Khubab Shaker
Yasir Nawab *Editors*

Engineering Materials

Fundamentals, Processing and Properties

Springer

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This work is dedicated to the researchers
working on materials,
Revolutionizing the world,
into a better place to live.

Preface

Engineering materials serve as a foundation stone for technological advancements. The applications of these materials range from towering skyscrapers to the sleek devices we carry in our pockets. Engineering materials define the very nature of the products we produce. This book offers a comprehensive exploration of this field and is designed for both aspiring and experienced material scientists. It delves into the fundamental principles that govern the behavior of materials, the diverse processing techniques used to shape them to our needs, and the resulting properties that determine their suitability for a wide range of applications.

This book is an invaluable resource for undergraduate students in engineering disciplines such as materials, polymer, chemical, and mechanical engineering. It is also equally suitable for engineering professionals seeking to refresh their knowledge of materials science. You will be well-equipped to contribute to the next generation of innovative materials and advancements, after going through the book. We commend the authors for creating this valuable resource and encourage readers to embark on this exciting journey into the world of engineering materials.

Faisalabad, Pakistan

Khubab Shaker
Yasir Nawab

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Editors and Contributors

About the Editors

Khubab Shaker is a distinguished researcher and academic in the field of textile and composite materials. He completed his doctoral studies at National Textile University in Faisalabad, Pakistan, in 2018. His postdoctoral studies at the Montan University, Leoben, Austria, further refined his expertise in the processing of composite materials. With an impressive track record, Dr. Shaker has established himself as one of the most productive researchers at National Textile University. He has authored 87 research papers with an impact factor of 232, that have garnered substantial recognition within the academic community. In addition, he has edited six books and contributed 26 chapters to various book publications. His expertise is further demonstrated through his participation in over 25 conference papers and keynote talks. Currently, he holds the esteemed position of Chairman of the Department of Materials at National Textile University. His research interests primarily revolve around natural fibres, biopolymers, and green composites. He is honored to be a fellow of the International Society of Development and Sustainability, based in Japan, highlighting his commitment to promoting sustainable development worldwide. e-mail: khubab@ntu.edu.pk

Yasir Nawab is a Professor at the National Textile University, Faisalabad, Pakistan. Currently, he is working as Dean School of Engineering & Technology and leading the Textile Composite Materials Research Group. His research areas are Composite Materials, 2D & 3D woven fabrics and Finite element analysis. He is the author of over 140 peer-reviewed journal articles, 5 books/book chapters and over 60 conference communications. He is the founding Director of National Center for Composite Materials. He received his Ph.D. from the University of Nantes, France in the domain of composite materials in 2012, which was declared as Remarkable Ph.D. in science & Technology in that year. In 2013, he did his postdoc from the ONERA (The French Aerospace lab) and University of Le Havre, France. e-mail: ynawab@ntu.edu.pk

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Introduction to Engineering Materials

Eslam Salama, Hassan Shokry, and Marwa Elkady

Abstract This chapter presents a brief introduction to the section on "engineering materials". Engineering materials are the fundamental building blocks of modern civilization, playing a pivotal role in almost every aspect of our daily lives. These materials are carefully designed and selected to meet specific performance criteria, ensuring the reliability and durability of various structures, machines, and devices. Engineering materials encompass a vast array of substances, each with unique properties and applications, and they can be broadly classified into metals, polymers, ceramics, and composites. Accordingly, this chapter will mainly focus on the raw materials and their types such as (e.g., ores, minerals, fossil fuels, biomass), extraction and processing, and refining of materials including refining process and techniques.

Keywords Engineering materials · Raw materials · Extraction and processing · Refining of materials

1 Introduction to Engineering Materials

Engineering materials refer to substances or compounds specifically chosen and designed for use in various engineering applications based on their unique properties and performance characteristics [84]. These materials are essential in constructing and manufacturing a wide range of structures, machines, devices, and systems across

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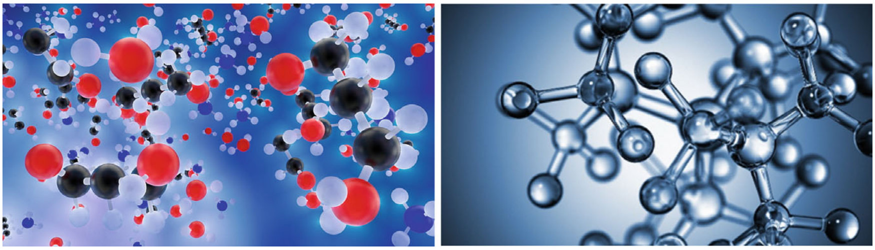


Fig. 1 Structure formulation of engineering materials

various industries, including aerospace, automotive, civil engineering, electronics, and more [78]. On the other hand, engineering materials are a vital component of the field of engineering, serving as the foundation for designing and building structures, machinery, and technologies that shape our modern world [49]. The selection, modification, and application of these materials are fundamental aspects of engineering practice, and advancements in materials science continue to drive innovation and progress in various industries [67] (Fig. 1).

1.1 Key Aspects of the Proper Selection of Engineering Materials

Engineering materials are not randomly chosen but are carefully selected based on the requirements of a particular application. Engineers consider factors like strength, stiffness, durability, electrical conductivity, thermal properties, corrosion resistance, and many other properties to make informed decisions about which material to use [91]. These materials often undergo modification, processing, or alloying to achieve specific properties that are essential for their intended use. For example, steel can be heat-treated to increase its hardness, or polymers can be blended to enhance their flexibility [90]. Engineering materials encompass a wide range of substances, including metals, polymers, ceramics, composites, and more. Each material type has its unique set of properties and applications, making it suitable for specific engineering needs [55].

Engineering materials are employed for various purposes, such as structural support, electrical conductivity, thermal insulation, or chemical resistance. The selection of a material depends on its compatibility with the desired function and environment [53]. The development and utilization of engineering materials often involve overcoming engineering challenges related to manufacturing processes, material testing, and quality control. Engineers and materials scientists continually research and innovate to create new materials or improve existing ones [15]. Engineers also consider the entire lifecycle of materials, from extraction or synthesis to disposal or recycling. Sustainable practices in material selection are becoming increasingly important to minimize environmental impact [64]. Engineering materials must meet specific performance criteria to ensure safety, reliability, and application longevity. These criteria may vary widely depending on the field and application, requiring materials to exhibit properties that suit the intended purpose [36].

2 Classification of Engineering Materials

Engineering materials can be classified into several categories based on their properties, composition, and intended applications. These classifications help engineers and materials scientists select the most suitable materials for specific tasks [86]. The primary classifications of engineering materials include metals, plastics, polymers, ceramics, composites, semiconductors, biomaterials, smart materials, and nanostructured materials (Fig. 2).

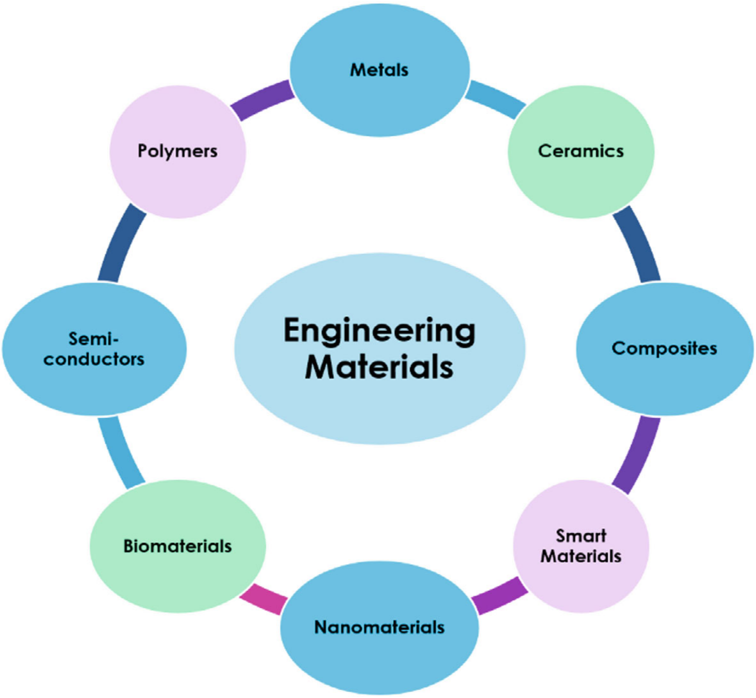


Fig. 2 Classification of engineering materials

2.1 Metals

2.1.1 Ferrous Metals

These metals contain iron as the main constituent. Common ferrous metals include steel and cast iron. They are known for their high strength and durability, making them suitable for structural applications, machinery, and tools [26, 41, 71, 72].

2.1.2 Non-ferrous Metals

Non-ferrous metals do not contain iron as their primary component. Examples include aluminum, copper, and brass. They are valued for their lightweight properties, electrical conductivity, and corrosion resistance. Non-ferrous metals are used in electrical wiring, transportation (e.g., aircraft), and architectural applications [41].

2.2 Polymers (Plastics)

2.2.1 Thermoplastics

Thermoplastics can be melted and reformed multiple times without significant degradation of their properties. Examples include polyethylene, polypropylene, and PVC. They are used in packaging, automotive parts, and consumer products [22, 27, 57].

2.2.2 Thermosetting Plastics

These plastics undergo a chemical reaction during curing, making them rigid and resistant to heat and chemical changes. Examples include epoxy, phenolic resins, and melamine. They are used in composite materials, electrical insulators, and high-temperature applications [9].

2.3 Ceramics

2.3.1 Traditional Ceramics

Traditional ceramics like porcelain, clay, and pottery are known for their hardness, brittleness, and resistance to heat and corrosion. They find applications in pottery, tableware, and building materials [50].

2.3.2 Advanced Ceramics

Advanced ceramics, such as silicon carbide and alumina, exhibit exceptional properties, including high-temperature stability and wear resistance. They are used in cutting tools, ball bearings, and electronic components [70, 92].

2.4 Composites

2.4.1 Fiber-Reinforced Composites

These materials combine fibers (e.g., carbon, glass, or aramid) with a matrix material (usually a polymer or ceramic) to create composites with enhanced properties. They are used in aerospace, automotive, and sporting goods [27, 73].

2.4.2 Particulate Composites

Particulate composites incorporate small solid particles (e.g., metal or ceramic) into a matrix material. These materials are used in brake pads, engine blocks, and various structural components [74].

2.5 Semiconductors

Semiconductors, such as silicon and gallium arsenide, are materials with electrical properties between conductors and insulators. They are critical for electronic devices like microchips, transistors, and diodes [33].

2.6 Biomaterials

Biomaterials are materials designed for use in medical and biological applications. Examples include titanium alloys for implants, biodegradable polymers for drug delivery, and hydrogels for tissue engineering [1].

2.7 Smart Materials

Smart materials, like shape memory alloys and piezoelectric materials, can change their properties in response to external stimuli (e.g., temperature, pressure, or electric fields). They are used in sensors, actuators, and adaptive structures [32].

2.8 Nanostructured Materials

Nanostructured materials have features at the nanoscale. They offer unique properties and are utilized in fields like nanoelectronics, nanomedicine, and nanocomposites [26, 72]. These classifications provide a framework for engineers and scientists to understand the properties and behavior of different materials, aiding in the selection and design of materials for specific engineering applications. The choice of material depends on factors such as strength, durability, electrical and thermal conductivity, cost-effectiveness, and environmental considerations [27]. Advances in materials science continue to expand the possibilities for creating new materials and optimizing existing ones for diverse engineering challenges.

3 Raw Materials and Utilities for Industrial Engineering

Raw materials are the basic substances or natural resources that are used to create various products through manufacturing, processing, or construction processes. They are the essential building blocks of industry and play a crucial role in the global economy. Raw materials encompass a wide range of materials, from natural resources like minerals and agricultural products to synthetic materials like chemicals and polymers [16]. Here are some key aspects to consider when discussing the types of raw materials (Fig. 3).

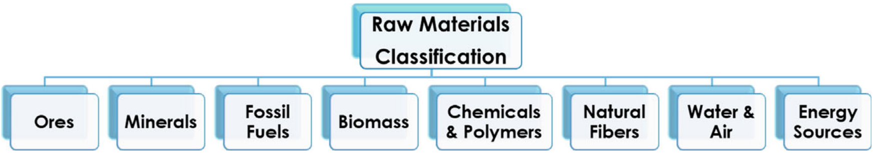


Fig. 3 Raw materials classification

3.1 Ores

Ores are natural deposits of minerals that serve as valuable sources of various elements and metals essential for human civilization. These raw materials play a crucial role in numerous industries, ranging from construction and manufacturing to technology and energy production [20]. Ores are typically mined from the Earth's crust and undergo various processes to extract the desired components. Ores come in diverse forms, each containing a specific mineral or combination of minerals. Common types of ores include metallic and non-metallic ores. Metallic ores contain metals like iron, copper, gold, silver, and aluminum. Where, non-metallic ores comprise minerals used in construction and manufacturing, such as limestone, gypsum, and phosphate [14].

The extraction of ores involves mining, a process that can take different forms depending on the nature of the deposit. Open-pit mining and underground mining are two primary methods. Once extracted, ores undergo beneficiation processes to concentrate the valuable minerals and remove impurities [12]. Ores are indispensable raw materials that fuel various industries and contribute to the foundation of modern life [89]. Balancing the extraction of these resources with environmental sustainability is crucial for ensuring a responsible and enduring supply of essential materials for future generations.

3.2 Minerals

Minerals are naturally occurring inorganic substances with a distinct chemical composition and crystal structure. They are the building blocks of rocks and play a fundamental role in the Earth's geology. Minerals are not only integral to the planet's structure but also have significant applications in various industries, scientific research, and everyday life [81]. Minerals form through various geological processes, including crystallization from molten rock (igneous rocks), precipitation from solution (sedimentary rocks), and metamorphism (alteration of existing rocks under heat and pressure). The conditions under which minerals crystallize determine their characteristics. Minerals are classified into several categories based on their chemical composition and crystal structure [38]. The Dana and Strunz classification systems are widely used, grouping minerals into classes, subclasses, and groups. Silicate minerals comprise the majority of Earth's crust, silicates contain silicon and oxygen. Quartz, feldspar, and mica are common examples. On the other hand, non-silicate minerals include oxides, sulfides, carbonates, and more. Examples include hematite (an oxide), pyrite (a sulfide), and calcite (a carbonate) [62].

Minerals are essential for various industries. Some minerals, such as iron ore and bauxite, are crucial for the production of metals like iron and aluminum. Others, like quartz and feldspar, are used in the glass and ceramics industries [35]. Rare minerals, including certain metals and gemstones, hold high economic value.

Minerals like limestone, gypsum, and granite are used in construction materials such as cement, plaster, and dimension stone. Minerals like coal, oil, and natural gas are vital sources of energy. Electronics rely on minerals like copper, gold, and tantalum for circuitry and component manufacturing. Studying minerals provides insights into Earth's history and geological processes [17]. Mineralogists analyze their physical and chemical properties to understand conditions during their formation, contributing to our knowledge of the planet's evolution. Certain minerals, when cut and polished, become gemstones prized for their beauty and rarity. Examples include diamonds, rubies, sapphires, and emeralds. Gemstones have cultural, aesthetic, and economic significance. Mining activities to extract minerals can have environmental impacts, including habitat disruption, soil erosion, and water pollution [11]. Sustainable mining practices aim to minimize these effects, emphasizing conservation and restoration. Minerals also play a role in space exploration. Understanding the mineral composition of other celestial bodies, such as the Moon and Mars, contributes to our understanding of the solar system's history [51]. In summary, minerals are essential components of the Earth's structure, with profound implications for industries, scientific research, and our daily lives. Balancing the extraction of minerals with environmental considerations is crucial for sustainable resource management and the well-being of the planet [25].

3.3 Fossil Fuels

Fossil fuels are hydrocarbons, primarily coal, fuel oil, or natural gas, formed from the remains of ancient organisms [47]. These energy-rich resources have powered human civilization for centuries, playing a pivotal role in industrialization, transportation, and electricity generation. However, their widespread use has raised environmental concerns due to the release of greenhouse gases and other pollutants. Fossil fuels are created through the decomposition of organic matter over millions of years. The process involves the accumulation and burial of plant and animal remains in sedimentary layers. Over time, heat and pressure transform these organic materials into fossil fuels. Fossil fuels can be divided into three main parts coal, oil (petroleum), and natural gas. Coal Formed from the remains of plants in swampy environments, coal is a solid fossil fuel and has been a primary energy source for centuries [85].

Oil (Petroleum) is derived from the remains of marine microorganisms; oil is a liquid fossil fuel and is crucial for transportation and the petrochemical industry. Natural gas is composed mainly of methane, natural gas is formed similarly to oil and is used for heating, electricity generation, and as a fuel for vehicles. Fossil fuels have been the dominant source of energy globally for several decades, meeting the majority of energy demands in transportation, electricity generation, and industrial processes [93]. However, this dependence has contributed to environmental challenges, including climate change. Greenhouse gas emissions which produced from burning fossil fuels and release carbon dioxide (CO_2) and other greenhouse gases, contributing to global warming and climate change. Moreover, the combustion of fossil fuels produces pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NOx), and particulate matter, leading to air quality issues and respiratory problems. Also, accidental spills during oil extraction, transportation, or refining can have devastating effects on marine ecosystems. On the other hand, growing awareness of environmental issues has prompted a shift toward renewable energy sources [23]. Governments, businesses, and individuals are increasingly investing in wind, solar, hydroelectric, and other sustainable alternatives to reduce reliance on fossil fuels and mitigate climate change. In conclusion, while fossil fuels have been crucial in powering human progress, their environmental impact has spurred a global transition toward cleaner and more sustainable energy sources. Balancing the need for energy security with the imperative to address climate change remains a complex challenge that requires coordinated efforts from governments, industries, and individuals worldwide.

3.4 Biomass Derivatives

Biomass refers to organic materials derived from living or recently living organisms, and it serves as a versatile and renewable source of energy and raw materials. These organic materials can be converted into various forms to produce heat, electricity, fuels, and other valuable products. Biomass plays a significant role in the transition toward more sustainable and environmentally friendly energy and manufacturing practices. Types of biomasses can include woody biomass, crop residues, energy crops, and organic waste. Woody biomass results from trees and shrubs, woody biomass includes logs, wood chips, and sawdust. Wood is used in construction, furniture production, and paper manufacturing [5]. While crop residues are agricultural byproducts such as corn stalks, rice husks, and sugarcane bagasse. Furthermore, the energy crops dedicated to crops like switch grass and miscanthus are grown specifically for energy production [45]. On the other hand, organic waste can be produced from municipal solid waste, food scraps, and animal manure as examples of biomass.

Biomass can be converted into bioenergy through processes like combustion, gasification, and anaerobic digestion. Bioenergy is used for heating and electricity generation and as biofuels for transportation. Anaerobic digestion of organic waste produces biogas, primarily composed of methane. It can be used as a clean-burning fuel for cooking or electricity generation [30]. Moreover, bioethanol which is prepared from the fermentation of sugars in crops like sugarcane and corn, bioethanol is a renewable fuel additive used in gasoline. Biodiesel is also produced from vegetable oils or animal fats, biodiesel is a renewable alternative to conventional diesel fuel [21]. Biomass can be processed to create a variety of bioproducts, including bio-based plastics, chemicals, and materials, reducing dependence on fossil fuels for manufacturing. Wood fibers from biomass are a key raw material in the production of paper and related products. However, biomass is considered carbon–neutral because the carbon dioxide emitted during its combustion or conversion is roughly equal to the carbon dioxide absorbed by the plants during their growth. This cycle maintains a balance in the carbon cycle and helps mitigate the impact of greenhouse gas emissions. Ongoing research focuses on improving biomass conversion technologies, exploring new feedstocks, and developing advanced bioenergy and bioproducts to enhance the sustainability and viability of biomass as a raw material [4]. In conclusion, biomass offers a renewable and versatile source of energy and raw materials, contributing to a more sustainable and environmentally conscious approach to energy production and industrial processes. As technology advances and sustainable practices are prioritized, biomass is likely to play an increasingly important role in the global shift toward a more sustainable and circular economy.

3.5 Chemicals and Polymers

Chemicals, including petrochemicals, are used as raw materials in various industries such as pharmaceuticals, plastics, and agriculture. Common examples include ethylene, propylene, and benzene [37]. Polymers like polyethylene, polypropylene, and PVC are raw materials for the production of plastics and plastic products [75].

3.6 Natural Fibers

Materials like cotton, wool, and jute are natural fibers used in the textile industry for making clothing, upholstery, and other fabric-based products [48].

3.7 Water and Air

Water is a critical raw material for industries like agriculture, food processing, and semiconductor manufacturing [31]. Air is used as a source of oxygen and nitrogen in various industrial processes [80].

3.8 Energy Sources

Electricity and heat are essential for many industrial processes and are often considered raw materials in industries like metal smelting, food processing, and electronics manufacturing [29].

3.9 Geographical Dependence

Raw materials are often found in specific geographic regions, leading to global trade and supply chain complexities. Countries may have abundant reserves of certain raw materials, which can impact their economic development and geopolitical dynamics [43].

3.10 Environmental Concerns

The extraction and processing of raw materials can have significant environmental impacts, including habitat destruction, pollution, and greenhouse gas emissions. Sustainable practices and resource conservation are increasingly important considerations in the use of raw materials [19]. In conclusion, raw materials are the foundational components of the global economy, impacting industries ranging from manufacturing and construction to energy and agriculture. Their availability, sustainability, and responsible use are essential considerations as societies seek to balance economic growth with environmental and resource conservation goals [7].

4 Extraction and Sustainable Technologies for Developing Engineering Materials

The extraction of engineering materials involves the process of obtaining raw materials from natural sources or converting primary materials into usable forms for manufacturing, construction, and various engineering applications. The extraction process can vary significantly depending on the type of material being sought and its source [76]. Here are some common methods and considerations for the extraction of engineering materials such as mining, quarrying, and natural-based extracted biomaterials (Fig. 4).

4.1 Mining

4.1.1 Metal Ores

Mining is a primary method for extracting metals like iron, copper, aluminum, and gold. It involves digging into the Earth to access ore deposits, which are then processed to separate the valuable metal from the surrounding rock and impurities [2].

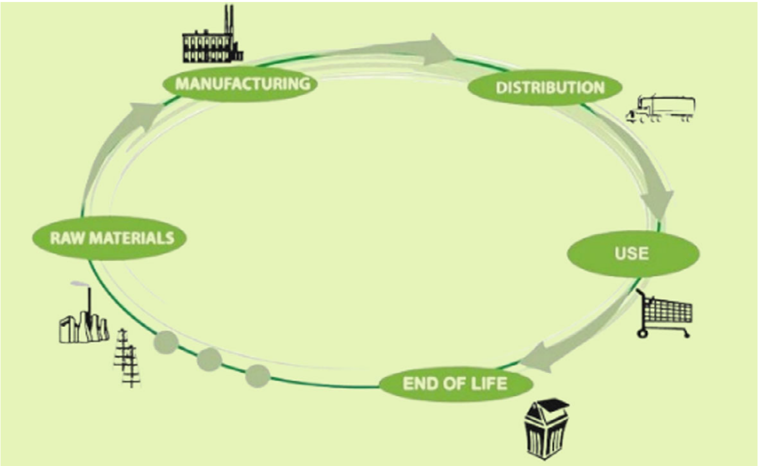


Fig. 4 Life cycle of raw materials

4.1.2 Mineral Resources

Minerals such as limestone, gypsum, and salt are extracted through mining. The extraction process may involve drilling, blasting, and crushing the rock to obtain the desired minerals [13].

4.2 Quarrying

Quarrying is the extraction of non-metallic materials from the Earth's surface, typically for construction purposes. This includes the extraction of materials like sand, gravel, granite, and marble. The process usually involves drilling, blasting, and crushing to obtain suitable sizes and shapes for construction.

4.3 Biomass Extraction and Petrochemicals

The extraction of petroleum (crude oil) and natural gas involves drilling wells into underground reservoirs. Once extracted, these raw materials undergo refining and processing to obtain various petroleum-based products, including fuels, plastics, and chemicals [40].

4.4 Forestry and Timber Extraction

Timber and wood products are extracted from forests through logging and forestry practices. Trees are felled, transported to sawmills, and processed into lumber and wood products for construction, furniture, and paper production [66].

4.5 Agricultural Cultivation

Some engineering materials, such as cotton and various crops, are obtained through agricultural practices. These materials are grown and harvested on farms and undergo further processing to become textiles, food products, or biofuels [18].

4.6 Renewable Resources

Renewable engineering materials, like wind and solar energy, are harnessed through technologies such as wind turbines and solar panels. These materials are essential for clean energy production and sustainability efforts [69].

4.7 Recycling and Reclamation

Recycling is an important aspect of materials extraction and conservation. It involves collecting and processing used materials (e.g., metals, plastics, paper) to create new products. Recycling reduces the demand for virgin resources and minimizes waste [8].

4.8 Environmental and Social Considerations

The extraction of engineering materials can have significant environmental and social impacts. Sustainable practices and responsible resource management are essential to minimize habitat destruction, pollution, and social disruptions associated with extraction activities [56].

4.9 Technology and Innovation

Advancements in technology play a crucial role in improving the efficiency and environmental sustainability of materials extraction processes. New methods, such as remote sensing and automated mining, help optimize resource extraction while reducing environmental impacts [56]. In conclusion, the extraction of engineering materials is a critical step in the supply chain for various industries. Balancing the need for raw materials with responsible environmental stewardship is an ongoing challenge, and innovations in extraction methods and materials recycling are central to achieving sustainable resource management.

5 Processing of Engineering Materials

The processing of engineering materials is a crucial step in converting raw materials into finished products with specific properties and shapes suitable for various engineering applications. This processing can involve a wide range of techniques and technologies, depending on the type of material and the desired end product [3] (Fig. 5).

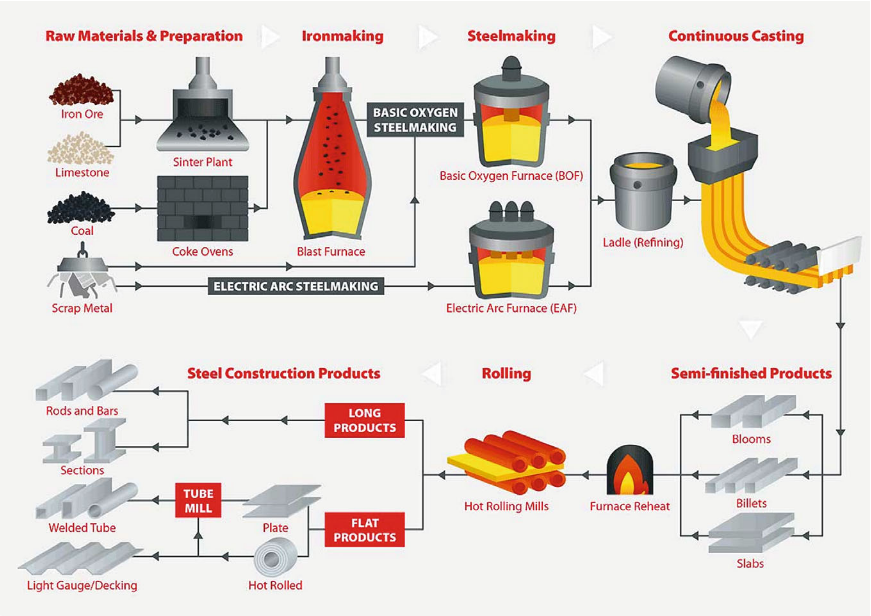


Fig. 5 Processing of raw materials for steel production. *Source* Vepica.com

Here are some common methods and considerations in the processing of engineering materials:

5.1 Metal Processing

5.1.1 Casting

Casting involves pouring molten metal into a mold to create a desired shape as it cools and solidifies. This method is used for manufacturing complex metal components like engine blocks and turbine blades [87].

5.1.2 Forming

Forming processes include techniques like forging, rolling, and extrusion, which manipulate metals at elevated temperatures to shape them into specific forms. Forging, for example, is used to create strong, lightweight components for the aerospace and automotive industries [83].

5.1.3 Machining

Machining processes such as turning, milling, drilling, and grinding are used to remove material from a workpiece to achieve precise shapes and dimensions. This is common in manufacturing components like gears, shafts, and engine parts [44].

5.1.4 Welding and Joining

Welding and joining methods are used to fuse or bond materials together. Techniques include arc welding, resistance welding, and brazing. Welding is essential in constructing structures like bridges and in manufacturing pipelines and aerospace components [79].

5.1.5 Heat Treatment

Heat treatment processes, including annealing, quenching, and tempering, are used to alter the mechanical properties of metals. This can improve hardness, toughness, and heat resistance, making materials suitable for specific applications [46].

5.2 Additive Manufacturing (3D Printing)

Additive manufacturing techniques build up materials layer by layer to create complex structures. This method is revolutionizing the production of custom or intricate components in the aerospace, medical, and automotive industries [63].

5.3 Polymer Processing

Polymer materials are processed through techniques like extrusion, injection molding, and blow molding. These processes are used to create plastic products, packaging, and components for various applications [60].

5.4 Ceramic Processing

Ceramics undergo processes like powder compaction, sintering, and glazing. These methods are used to manufacture ceramic tiles, electrical insulators, and advanced ceramics for aerospace and electronics [58].

5.5 Composite Manufacturing

Composite materials, such as carbon-fiber-reinforced composites, are manufactured using techniques like layup, filament winding, and resin infusion. These materials are used in aerospace, automotive, and sports equipment [52].

5.6 Surface Treatment

Surface treatments like coating, plating, and anodizing are applied to improve corrosion resistance, aesthetics, and wear properties of materials. This is common in industries like automotive and electronics [6].

5.7 *Quality Control*

Throughout the processing of engineering materials, rigorous quality control measures are implemented to ensure that the final products meet the required specifications and standards. This includes inspections, testing, and non-destructive evaluation techniques [61, 77].

5.8 *Environmental and Safety Considerations*

The processing of engineering materials often involves the use of hazardous chemicals, high temperatures, and energy-intensive processes. Ensuring worker safety and minimizing environmental impacts are essential considerations in material processing [34]. In summary, processing engineering materials is a critical phase in turning raw materials into functional products used in various industries. The choice of processing method depends on factors like material type, desired properties, production volume, and cost considerations. Advancements in processing technologies continue to drive innovation in materials engineering, allowing for the creation of more efficient and sustainable products [3].

6 Refining of Engineering Materials

Refining engineering materials is a crucial step in the manufacturing process, especially for materials derived from raw sources like metals, minerals, and petrochemicals. The goal of refining is to purify and enhance the properties of these materials, making them suitable for specific engineering applications [39] (Fig. 6).

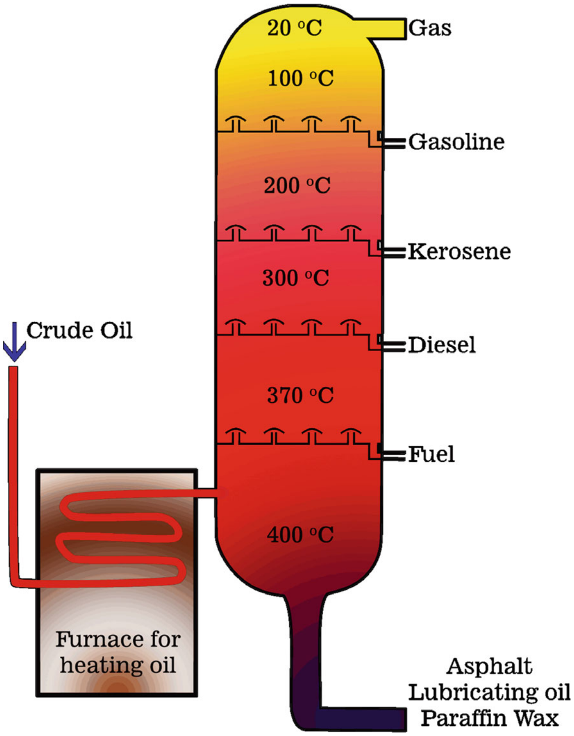
Here, the refining processes commonly used in various industries will be briefly explored:

6.1 *Metallurgical Refining*

6.1.1 Smelting

Smelting is the process of extracting metal from its ore through high-temperature heating and chemical reactions. It removes impurities like sulfur, carbon, and other non-metallic elements, leaving behind the desired metal. Common smelting methods include blast furnaces for iron and reverberatory furnaces for copper [10].

Fig. 6 Schematic of oil refining and gas processing



6.1.2 Electrorefining

Electrorefining is used to further purify metals like copper, aluminum, and lead. In this process, an electric current is passed through the metal in a solution, causing impurities to dissolve or migrate to the anode, leaving a purer metal at the cathode [28].

6.1.3 Zone Refining

Zone refining is a method to purify semiconductors and other high-purity materials. A molten zone is passed along a material rod, and impurities are selectively incorporated into the molten zone and moved to one end, resulting in a purified material [24].

Fig. 7 Petrochemical refining

6.2 *Petrochemicals Refining*

6.2.1 Crude Oil Refining

Crude oil is refined in oil refineries to separate it into various products like gasoline, diesel, jet fuel, and petrochemical feedstocks. This involves distillation, cracking, and other processes to isolate and upgrade different fractions [88] (Fig. 7).

6.2.2 Natural Gas Processing

Natural gas is refined to remove impurities like water, sulfur compounds, and heavy hydrocarbons. Processing includes gas sweetening and fractionation to produce natural gas liquids (NGLs) [82].

6.3 *Minerals Processing*

6.3.1 Froth Flotation

Froth flotation is used to separate valuable minerals from their ore by making use of their hydrophobic and hydrophilic properties. It's commonly used in the mining industry for minerals like copper, lead, zinc, and gold [68].

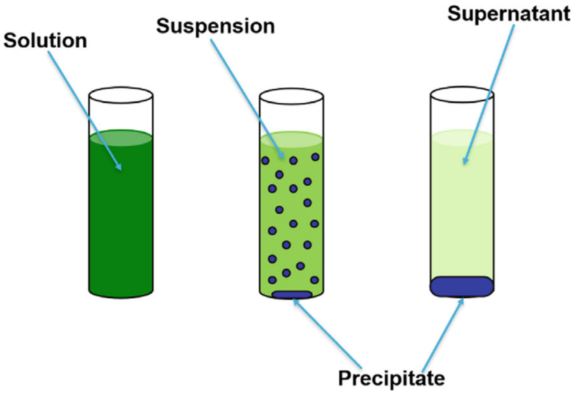


Fig. 8 Chemical precipitation of impurities

6.3.2 Magnetic Separation

Magnetic separation is employed to extract magnetic materials from non-magnetic ones. It's used in the separation of iron ore and recycling processes [42].

6.4 Chemicals Refining

6.4.1 Chemical Precipitation

In chemical refining, impurities are chemically converted into insoluble compounds that can be easily separated from the desired material. This process is often used in the refining of metals and chemicals [10] (Fig. 8).

6.4.2 Solvent Extraction

Solvent extraction is a technique to selectively remove impurities or separate components from a mixture using solvents. It's used in the extraction of certain metals from ores and the refining of edible oils [54] (Fig. 9).

6.5 Bioprocessing

In bioprocessing, biological organisms like bacteria or enzymes are employed to break down impurities or convert raw materials into valuable products. This is commonly used in the food industry for processes like brewing, fermentation, and cheese production [59].

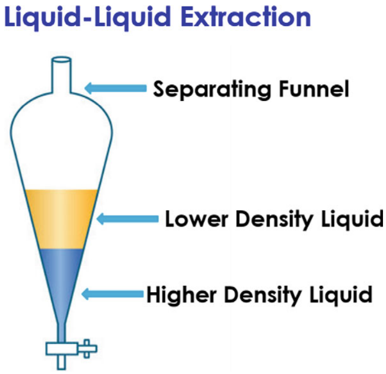


Fig. 9 Liquid–liquid extraction

6.6 *Quality Control*

Throughout the refining process, quality control measures are essential to ensure that the refined materials meet the required specifications and standards. This includes inspections, chemical analysis, and testing. Refining engineering materials is a critical step in ensuring that the final products meet the desired quality, performance, and safety standards. Advances in refining technologies continue to drive efficiency, sustainability, and the production of high-quality materials for a wide range of engineering applications [65].

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Fundamentals of Materials

H. M. Fayzan Shakir and Huzaifa Rushan Aziz

Abstract Materials science and engineering is an interdisciplinary field that deals with the study of the relation between the structure and the property of materials. Coming from historical roots in ancient metallurgy, the field today encompasses a vast range of different materials, including metals, ceramics, polymers, and composites. Fundamentally, material science is a study in which the link between synthesis and processing methods, the structure, and the properties of materials is identified. One of the principal goals is to relate macroscopic properties to those at the atomic- and molecular-level. A crystallographic (or crystal structure) perspective illustrates how atoms are stacked in crystalline solids, and is critical to understanding the relationship between the structures of materials and the resultant properties. Materials are categorized based on how they behave. The need for newer, more advanced materials has led to the idea of designing and customizing the properties of materials to meet specific requirements or needs. The above interplay between microstructure development and resulting properties, and processing techniques, is also necessary in materials science. It has enabled a vast array of innovative materials applications from aerospace to healthcare. By including theory, characterization, and application while taking a complete view, materials science continues to radically transform countless technological fields and is innovations that continue to shape our world.

1 Introduction

The basic ideas in materials science, like how atoms are bonded together and the structure of crystals, are really important for understanding the properties and behavior of crystals. These concepts come down to the atoms themselves and the complex way the forces between them work. These atoms interact with each other and arrange themselves in specific patterns to create the stable, solid materials we use every day.

Atomic bonding refers to the forces of attraction that hold atoms together to form molecules and solid materials. These bonds are responsible for the stability, strength,

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and other physical and chemical properties of substances. The three major types of atomic bonding include ionic bonding, covalent bonding, and metallic bonding [1].

Ionic bonding happens when one atom gives one or more electrons to another atom. The resulting positive and negative ions are attracted to each other via strong electrostatic forces to create a lattice-like structure. This type of bonding is commonly found in compounds made from both metals and nonmetals, like sodium chloride (table salt) or calcium carbonate (limestone).

In contrast, covalent bonding occurs when electrons are shared between atoms. The sharing of outer shell electrons between two or more atoms makes the outer electron shells of both atoms more stable so it's a win for all parties. Covalent bonds usually happen between nonmetal elements and compounds like water (H_2O) or methane (CH_4). The strength of covalent bonds depends on the number of shared electrons and the distance between the atoms involved [2].

Metallic bonding is unique to metals and is characterized by the number of delocalization of valence electrons. In a metal, the outermost electrons of individual atoms are free to move throughout the crystal, forming a "sea" of electrons. It is this 'sea' of electrons that allows for high electrical and thermal conductivity that we observe in metals. It is also this flow of electrons that allows for properties such as malleability and ductility to exist. In these cases, positive metal ions can slide past one another without actually losing the crystal structure, because the electrons that are delocalized can move in between the energies of the metal ions [3].

Crystal structure states the proper and ordered arrangement of atoms or ions in a solid creating a crystal lattice. This proper arrangement of atoms or ions goes in 3 dimensions and affects the material's core properties like mechanical behavior, optical properties, and electrical and thermal properties. There are various types of crystal structures depending on the atomic size, bonding nature, and crystal structure. Atomic arrangements and crystal structures can be determined using X-ray diffraction. it is crucial to understand the crystal structure and atomic bonding in materials science that allows one to tailor the structure and properties in specific areas for application in various industries. By mastering these concepts of materials science, scientists can explore the secrets of modern materials that can benefit the world a lot [4].

2 Atomic Structure and Bonding

2.1 Fundamental Concepts

The fundamentals of atomic structure and bonding are the foundation for understanding the performance and properties of materials. This includes the construction of atoms, how electrons are found inside an atom, and what forces grip atoms composed to form molecules and solids.

The fundamental of atomic structure is to comprehend the nature of the atom itself. Atoms have a fundamental region, the nucleus, which consists of protons and neutrons that are surrounded by electrons as shown in Fig. 1. This nucleus has a positive charge because of the occurrence of protons whereas electrons, which revolve around it in diverse orbits based on energy levels, have negative charge.

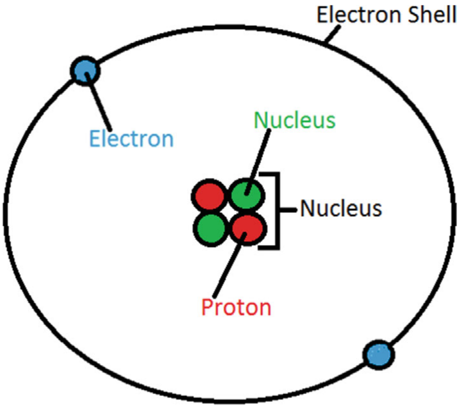
According to the model, electrons in an atom are organized into shells or energy levels, each shell has a particular capacity of electrons. The electronic configuration of an atom determines its chemical properties and behavior. The filling of electron orbitals is governed by a set of rules called the Aufbau principle, the Pauli exclusion principle, and Hund's rule.

Bonding forces and energies are responsible for how atoms interact with each other to form molecules and solids. The two main types of bonding are ionic and covalent bonding. Ions are formed by the transfer of electrons and these ions are held together by electrostatic forces to form ionic bonds. In covalent bonding, an electron pair is shared between atoms to form a stable electron configuration [5].

In addition to primary bonds between atoms and molecules, secondary bonding or van der Waals forces also contribute. These include dipole–dipole interactions, hydrogen bonding, and London dispersion forces, which are the result of temporary fluctuations in electron density. The importance of understanding atomic structure and bonding can be understood through the significance of water. Water molecules are held together by polar covalent bonds, resulting in unique properties, such as surface tension, cohesion, and adhesion. The volume expansion of water upon freezing is caused because of hydrogen bonds being formed between water molecules in the solid.

In general, atomic structure and bonding are the basic principal frameworks for understanding properties, behavior, and interactions of materials at molecular levels. If these ideas are not mastered, design materials or the structure could result in materials with undesired properties for specific applications in science and technology.

Fig. 1 Atom and its basic components



2.2 Electrons in Atoms

Understanding how electrons behave within an atom is crucial, as it forms the foundation for understanding chemical bonding, electronic properties, and the behavior of materials. Electrons, which have a negative charge, can be thought of as occupying specific energy levels or orbitals around the atomic nucleus as shown in Fig. 1. These energy levels are quantized, in such a way that electrons can only exist in discrete energy states.

As mentioned earlier, the rules that electrons within an atom have to follow. According to the Aufbau principle, electrons fill the lowest energy levels first, then occupy higher energy levels. That means level 1 will be filled first by electrons. If level 1 has free space for the electron, then the electron cannot go to level 2. It has to fill the 1st level first. The Pauli exclusion principle says that no two electrons in an atom can have the same set of quantum numbers, which means that their spins and orbital quantum numbers have to be unique for each electron. Hund's rule states that electrons fill orbitals of the same energy level separately before they start grouping in an orbital, just so they can maximize their electron spin and minimize their electron–electron repulsion.

The number of electrons in an atom determines its chemical properties and behavior. The distribution of electrons determines valence electrons, which are involved in chemical bonding and interactions with other atom's electrons. For example, noble gases have a full outer electron shell and are chemically inert, while elements with incomplete outer electron shells are more reactive and likely to form chemical bonds with other atoms to achieve a stable electron configuration.

Electrons exhibit both wave-like and particle-like properties, as described by the wave-particle duality principle. This duality is key to understanding electron behavior in atoms, where electrons are described by wave functions that represent the probability density of finding an electron in a particular region of space.

How the electrons in atoms behave is important for determining a material's electronic structure and properties. This includes whether it conducts electricity well, how it interacts with light, and whether it has magnetic properties. The electronic structure of a material can be deliberately changed by modifying the arrangement of its electrons. This can be done by adding other elements (doping), combining materials (alloying), or applying external influences. By altering the electronic structure in this way, we can customize the properties of the material to meet specific needs for things like semiconductor devices, sensors, and other electronic parts [5].

2.3 The Periodic Table

The Periodic Table (Fig. 2) is a fundamental tool in chemistry and materials science. It organizes elements based on their atomic number, electron configuration, and chemical properties. In 1869, Dmitri Mendeleev developed the first Periodic Table, for arranging the known elements at that time in order of increasing atomic mass and grouping them based on similar chemical properties.

The modern Periodic Table arranges the elements in rows and columns, known as periods and groups, respectively. Elements within the same group share similar chemical properties due to their identical outer shell electronic configurations. The periodic table consists of metals, nonmetals, and metalloids, each of which occupies a distinct region based on their characteristic properties.

The arrangement of the periodic table illustrates periodic trends in the properties of the elements: atomic size, ionization energy, electron affinity, and nuclear reactivity increase as you move from left to right and from top to bottom. There is a gradual increase across a period as nuclear charge is increased; a gradual decrease down a group as electrons are added; and a gradual increase across a period as nuclear charge is increased and a general decrease down a group.

Electronegativity also increases across a period and decreases down a group. Chemical reactivity also shows similar trends; the left side of the periodic table (the alkali metals and alkaline earth metals) are highly reactive, whereas the noble gases on the far right have little or no reactivity.

The periodic table is an indispensable tool for the understanding of the properties and behavior of the elements and their compounds. Through the predictive power of periodic trends, researchers can design new materials with tailored properties—such as semiconductors for electronic and optical applications, catalytic materials for chemical processing, and structural materials for aircraft, automobiles, and ships. In summary, the periodic table is a foundational resource for chemical and materials science. It provides a systematic basis for organizing the elements so that their properties and trends can be fully documented and understood. Through the lens of the

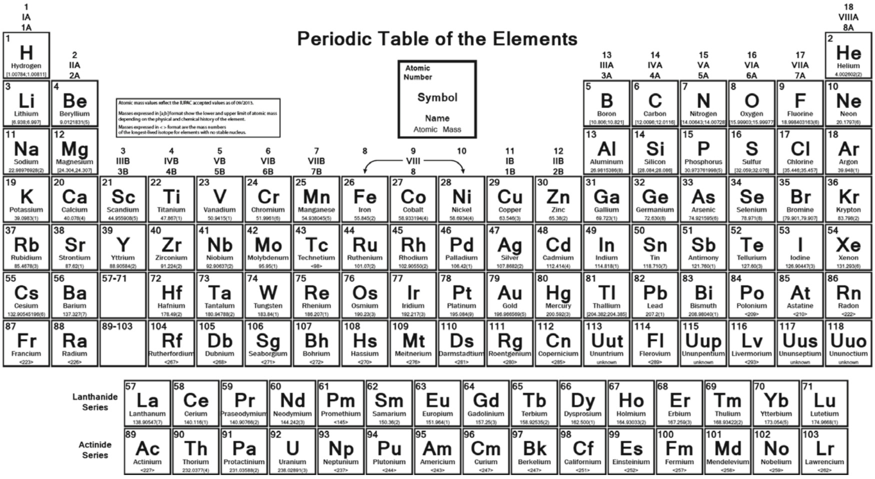


Fig. 2 Periodic table

materials scientist and engineer, the periodic table of the elements is the ideal example of “form and function” [6].

2.4 Bonding Forces and Energies

Bonding forces determine the stability, structure, and properties of the materials. These forces come from interactions between atoms and molecules and are responsible for making them stick together in chemical bonds. A grasp of bonding forces and energies is ineluctable if you want to predict the behavior of materials and design new compounds with selected properties.

The way atoms and molecules bond and the way that bonding forces and energies dictate how they interact is what ultimately determines a material’s properties—how strong it is, how dense, what electromagnetic properties it may have, how it conducts heat, flows as a liquid and in some cases even as it generates electricity, through the flow of electrons.

Understanding these forces, and being able to predict, tune, and apply them under any desired conditions is a challenge to scientists and engineers working to formulate and optimize new materials as well as perfect existing ones from a wide array of options for many diverse applications.

2.4.1 Primary Interatomic Bonds

Primary interatomic bonding is robust forces that hold atoms together. These types embrace both small changes (ionic bonds) and larger adjustments (covalent bonds). All such changes will lead to the compound’s ionic nature if left alone for long enough—it needs a while to accumulate. The fundamental forces that hold atoms together within a molecule or crystal lattice are called primary interatomic bonds. These bonds regulate the form and stability of compounds and play a crucial role in the properties, structure, and performance of materials. The three types of primary interatomic bonds are ionic, covalent, and metallic.

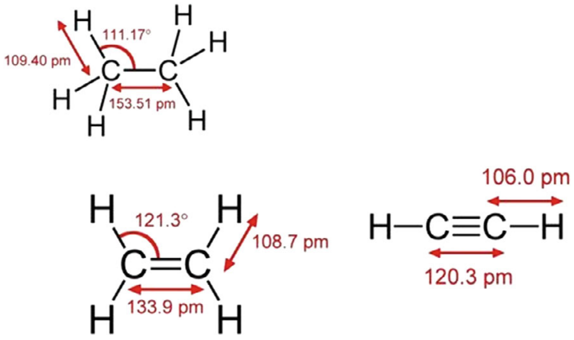
One of the most important types of bonding forces is the covalent bond, which involves the sharing of electron pairs between atoms as displayed in Fig. 3. The strength of a covalent bond depends on factors such as the number of shared electrons and the distance between the nuclei of the bonded atoms. The bond energy (E) of a covalent bond can be calculated using the formula:

$$E = (4 \times k \times e2 \times ZA \times ZB)/\mathrm{d}$$

where:

- k is Coulomb’s constant (8.99×10^9 N m^2/C^2),
- e is the elementary charge (1.6×10^{-19} C),

Fig. 3 Covalent bond illustration



- ZA and ZB are the atomic numbers of the bonded atoms,
- d is the distance between the nuclei of the bonded atoms.

Ionic bonds are another type of bonding force that occurs between ions with opposite charges. In an ionic bond, one atom donates electrons to another, resulting in the formation of positively and negatively charged ions that are attracted to each other as can be seen in Fig. 4. The strength of an ionic bond is influenced by the magnitude of the charges and the distance between the ions. The bond energy of an ionic bond can be estimated using Coulomb's law:

$$E = k \times |Q1 \times Q2|/d$$

where:

- k is Coulomb's constant,
- $Q1$ and $Q2$ are the charges of the ions,
- d is the distance between the ions.

Fig. 4 Ionic bonding illustration

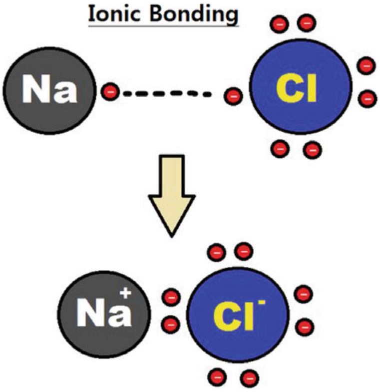


Fig. 5 Metallic bonding illustration

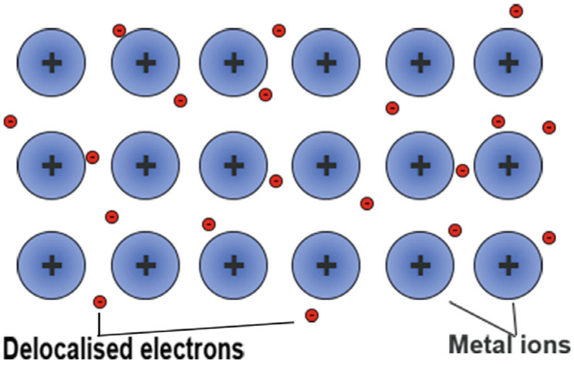
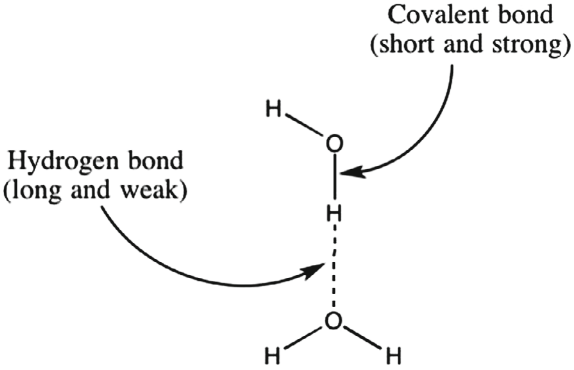


Fig. 6 Hydrogen bonding



Metallic bonds occur in metals and alloys, where positively charged metal ions are held together by a sea of delocalized electrons as illustrated in Fig. 5. These electrons are free to move throughout the metal lattice, creating a strong attractive force that holds the metal ions together. Metallic bonds are responsible for the unique properties of metals, such as high electrical conductivity, malleability, and ductility.

Hydrogen bonding is a special type of intermolecular force that occurs when a hydrogen atom covalently bonded to a highly electronegative atom (such as oxygen or nitrogen) interacts with another electronegative atom's hydrogen bonding is illustrated in Fig. 6. Hydrogen bonding is responsible for many unique properties of substances like water and DNA. The strength of hydrogen bonds is typically weaker than covalent or ionic bonds but still significant in determining the properties of materials [7].

2.4.2 Secondary Bonding or Van Der Waals Bonding

Each type of primary interatomic bond exhibits distinct characteristics and strengths, influencing the properties and behavior of materials. Ionic bonds are typically strong and brittle, while covalent bonds are strong and directional, leading to the formation of distinct molecular structures. Metallic bonds are characterized by their delocalized nature, allowing for the flow of electrons and the formation of metallic properties such as conductivity and ductility.

Secondary bonding, also known as van der Waals bonding, refers to the weak intermolecular forces that occur between atoms or molecules. Unlike primary interatomic bonds (such as ionic, covalent, and metallic bonds), which involve the sharing or transfer of electrons, van der Waals forces arise from temporary fluctuations in electron density within atoms or molecules.

The van der Waals forces encompass several types of interactions, including dipole–dipole interactions, London dispersion forces, and induced dipole interactions. These forces are collectively responsible for various physical properties observed in materials, such as cohesion, adhesion, and surface tension.

Dipole–dipole interactions occur between polar molecules, where the positive end of one molecule interacts with the negative end of another molecule. This interaction arises due to the unequal distribution of electrons within the molecule, resulting in a permanent dipole moment as illustrated in Fig. 7.

London dispersion forces, also known as induced dipole-induced dipole interactions, occur between nonpolar molecules or atoms. These forces result from temporary fluctuations in electron density, creating instantaneous dipoles within the molecules or atoms. These induced dipoles induce similar dipoles in neighboring molecules, leading to a weak attractive force between them. Induced dipole interactions occur when a polar molecule induces a temporary dipole moment in a neighboring nonpolar molecule. This induced dipole interaction is weaker than dipole–dipole interactions but still contributes to the overall attraction between molecules (Fig. 8).

Van der Waals forces are relatively weak compared to primary interatomic bonds, such as covalent or metallic bonds, van der Waals forces are illustrated in Fig. 9.

Fig. 7 Dipole–dipole interaction

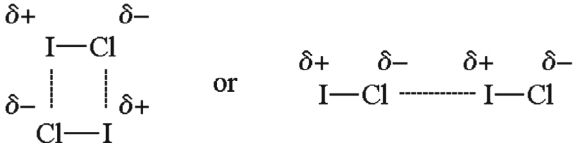
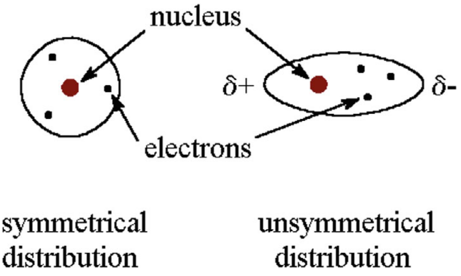


Fig. 8 Induced dipole forces



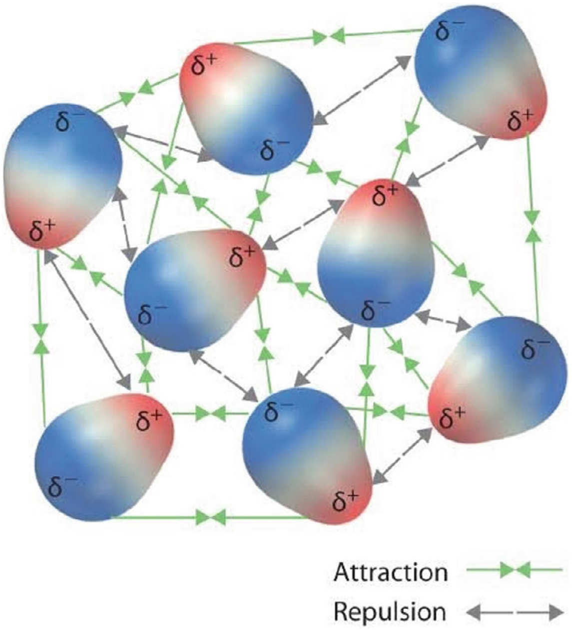


Fig. 9 Cluster of atoms and molecules showing van der walls forces

However, they can collectively influence the physical properties of materials, such as melting and boiling points, viscosity and solubility. They are especially notable in molecular solids, gases and liquids, where intermolecular interactions predominate the behavior of the material.

The understanding and manipulation of van der Waals forces is of paramount importance for the design and control of new materials with specific properties for a variety of applications in coatings, lubricants, and adhesives, and also to account for the specific interaction mechanisms in the context of biomolecular interactions including protein folding and molecular recognition that are important in biochemistry and biophysics [3].

3 Crystal Structure

3.1 Fundamental Concepts

Fundamental concepts in crystal structures are essential to understanding the arrangement of atoms or ions in crystalline solids. These concepts provide insights into the symmetry, packing, and properties of crystals, which are crucial in materials science and engineering. Some of the key fundamental concepts include:

Lattice: A lattice is an imaginary three-dimensional grid that represents the repeating pattern of points in a crystal structure. It provides a framework for describing the arrangement of atoms or ions in the crystal. The lattice can be primitive (simple cubic, body-centered cubic, or face-centered cubic) or non-primitive (obtained by subdividing the primitive lattice).

Unit Cell: The unit cell is the smallest repeating unit of a crystal lattice that, when stacked in three dimensions, reproduces the entire crystal structure. There are seven types of unit cells, classified based on their symmetry: primitive cubic, body-centered cubic, face-centered cubic, hexagonal, rhombohedral, monoclinic, orthorhombic, tetragonal, and triclinic. Each crystal lattice can be described by one of these unit cells.

Bravais Lattice: A Bravais lattice is a mathematical concept that describes the periodic arrangement of lattice points in a crystal structure. There are 14 Bravais lattices in three-dimensional space, classified based on their symmetry properties.

Crystal System: The crystal system categorizes crystals based on their symmetry and the lengths and angles between their lattice vectors. There are seven crystal systems: cubic, tetragonal, orthorhombic, hexagonal, trigonal (or rhombohedral), monoclinic, and triclinic. Each crystal system has unique characteristics that dictate the shape and symmetry of crystals.

Miller Indices: Miller Indices are a symbolic notation system used to describe the crystallographic planes and directions of a crystal lattice. They represent the reciprocals of the intercepts of a plane or direction with the crystallographic axes. They are a fundamental tool for characterizing the crystallographic features that are essential for understanding the phenomena such as crystal growth and the deformation of surfaces.

Symmetry Operations: Symmetry operations are a set of operations that leave the crystal structure unchanged. The set includes translation, rotation, reflection, inversion and glide reflection. The comprehension of these operations becomes the foundation for the analysis of the symmetry properties of crystals, and therefore in predicting the physical properties of the crystals. It is, therefore safe to say, that by understanding these basic concepts, scientists and engineers can interpret and manipulate the structural properties of crystals, which can eventually lead to breakthroughs—in material design, semiconductor technology, mineralogy, and many more scientific and engineering fields.

3.2 Unit Cells

Unit cells are the smallest repeating structure in a crystalline material and the fundamental building block of crystal studies. It describes the smallest repeated pattern of atoms or ions within a crystal lattice when they are stacked on top of each other up into 3D. A knowledge of unit cells is important for understanding the structure, symmetry, and properties of crystalline materials.

There are seven types of unit cells, one for each of the seven crystal systems. This figure shows a cubic unit cell. Its three parameters, a, b, and c are the edge lengths of the cube. Its three angles internally are α, β, and γ. The type of unit cell, and therefore the unit cell geometry used for crystal structures can depend on the crystal system and the symmetry of the crystal structure being studied.

In a tight space called the unit cell, lattice points represent the position of atoms, ions, or molecules in a crystal structure. Lattice points for different types of unit cells ending on, or inside, a unit cell will reside at corners, faces, or the center of a unit cell, depending on its type and atom arrangement. Researchers can find lattice points and with them unit-cell scales, locating symmetrical patterns in the lattice dimensions or other characteristics of the way a crystal structure has been arranged.

A unit cell allows us to describe materials' crystallographic properties, and it can help us predict how materials will behave under different conditions. By examining the arrangement of atoms within unit cells, materials scientists can learn valuable information about the mechanical, thermal, electrical, and optical properties of crystalline materials. They provide the basis for crystallographic calculations, such as for determining the atomic packing factor of a material, for calculating its density, and for analyzing its behavior during processes such as crystal growth and deformation [8].

3.3 Metallic Crystal Structures

The atomic arrangement in metallic solids is called a metallic crystal structure. Metals are characterized by their high electrical conductivity, malleability, and ductility (a property of metals that indicates that they can be worked, i.e. shaped, in different ways without breaking). They are also lustrous. In a metallic crystal, a large number of atoms are held together by metallic bonds, which result from the delocalization of a small number of electrons to form a "sea" of electrons. The most common crystal structures (and their abbreviations) for metals are:

Body-Centered Cubic (BCC): Each atom is located at the corners of a cube and there is one atom in the center of the cube, which is shared by the eight adjacent unit cells. For example, α-Fe (at high temperatures) is BCC.

Face-Centered Cubic (FCC) structure, each atom is located at the corners and the center of each face of a cube. Thus, there are a total of four atoms per unit cell. Metals such as Aluminum, copper, and gold have FCC crystal structures.

Hexagonal Close-Packed (HCP) structure, atoms are located in layers of a hexagonal arrangement and each layer is stacked on top of the previous one in an ABAB… sequence. This structure has a hexagonal unit cell with two atoms per unit cell. Metals such as zinc, magnesium, and titanium commonly adopt an HCP structure.

Individual metallic crystal structures are distinguished by unique combinations of packing efficiency, coordination number (the number of nearest neighbors that each atom has), and stacking sequence (i.e., the regular or random way in which close-packed planes of atoms are stacked upon one another). These structures offer metal systems unique mechanical, thermal, and electrical properties, which are exploited by engineers in applications across multiple industries such as aerospace, automotive, electronics, manufacturing, and construction.

The crystal structure adopted by a metallic material will depend on the size and shape of the atoms that comprise the metal, the presence of alloying elements, and processing conditions. Understanding the arrangement of atoms in metallic crystal structures and how to manipulate these structures to yield specific properties for given performance requirements helps scientists and engineers to continue to advance and employ metallic materials in countless applications within engineering, materials science, and manufacturing.

3.4 Density Computations

Materials science and engineering Density calculations are the amount of substance per unit volume determined by the Material. Density is a basic property of matter that can be used to distinguish between the matter. However, it can tell us something about how closely packed atoms and/or molecules are with a material. The density of the material is measured with units like kilograms per cubic meter (kg/m3) or grams per cubic centimeter (g/cm3) with the latter being the most common.

The formula for calculating density (ρ) is:

$$\rho = m/V$$

where:

- m is the mass of the material,
- V is the volume occupied by the material.

The computation of the density of a material requires an accurate measure of its mass and its volume. The mass is typically determined using a balance or scale. The volume must be determined in a material-appropriate manner. The volume of an object with straight edges can be determined using geometric formulas. The volumes of irregularly shaped objects are less obvious to determine and are typically done using the displacement of water or by methods such as Archimedes' principle.

Density computations are important for numerous applications in materials science. They are used to characterize and compare materials. The purity of a material may be measured using its density, or density could be used to judge the suitability of a material for a particular application. A material's density is indicative of its structural integrity, mechanical behavior, and even its chemical composition.

Materials with higher densities typically have better mechanical properties than those with lower densities. Applications such as lightweight vehicles, additive manufacturing, and thermal insulation use computations of density to gain insight and compare materials. The density of a material is also critical for the manufacturing of components since being able to control the material properties is essential to being able to achieve the desired performance in the final component. Engineers can also measure and control the density of materials with precision so that they can properly operate their manufacturing processes, (casting, forging, machining, etc.) to produce components of the highest quality and performance [2].

3.5 Polymorphism and Allotropy

Polymorphism and allotropy are frequently encountered and related concepts in chemistry, materials science and solid-state physics. These occur when the same substance can have distinct crystalline forms or structures. Polymorphism denotes the ability of a material to exist in more than one crystal form and has the same chemical composition, where each crystal form is referred to as a polymorph.

Different polymorphs of a substance arise from the phenomenon where atoms, ions, or molecules are arranged differently within the crystal lattice. Commonly encountered substances that exist in multiple allotropes include the element carbon (graphite, diamond, fullerene), sulfur (which has multiple allotropes), solid oxygen, and quartz (which can exist as α-quartz and β-quartz).

Allotropy is a special case of polymorphism that applies to elements. Allotropes are the different crystal structures or physical forms that an element can take. Allotropes of a given element can have very different physical and chemical properties, but the element's atoms are always the same kind. Carbon is an example of an element with allotropy (it can exist as diamond, graphite, or graphene, among other forms). Oxygen can exist in several allotropes, but the O_2 molecule is its most stable form; ozone (O_3) is another well-known allotrope.

The polymorphism and allotropy of a material can be attributed to several factors. Some of the most important include temperature, pressure, and the presence of impurities. Here, small changes in these parameters can result in one polymorph or allotrope transitioning into another, typically resulting in a wide range of interesting, and potentially very useful properties. Understanding these kinds of phenomena is of great importance to materials scientists and engineers, as different polymorphs or allotropes can result in dramatic changes in mechanical, electrical, thermal, or optical properties. The topic also has implications in such fields as pharmaceuticals, in which a drug's bioavailability, and the stability of drugs that are polymorphs, can determine the effectiveness and efficiency of treatments, and nanotechnology, where the properties of nanomaterials can be influenced by the control of their crystal structures.

3.6 Crystal Systems

Crystal systems are a method of classifying crystalline substances based on the unit cell lengths and angles and are divided into seven general categories. Despite differing in many disciplines, they tend to overlap, as each system has its characteristics, typical of a lot of things discovered and developed in different disciplines around the same time.

1. Cubic System: The cubic system is the most symmetrical crystal system, characterized by three mutually perpendicular axes of any length. There are three variations, simple cubic, body-centered cubic, and face-centered cubic, only the latter will be considered in these examples.
2. Tetragonal System: The tetragonal system consists of three axes, any two of which intersect at right angles with the third axis, of a different length, perpendicular to the plane they lie in. The angles between the axes are all 90°.
3. Orthorhombic System: The third crystal system is the orthorhombic system characterized by a set of three axes of different lengths, all perpendicular to all others.
4. Hexagonal System: This system consists of four plain axes; three of the axes intersect the plane at an angle of 12°, and the fourth axis is perpendicular to the other three and has a different length.
5. Trigonal System: This system is also known as the rhombohedral system which has three axes equal in length, which intersect at angles of 60°. However, the angles between the axes are not 90°.
6. Monoclinic System: This system has three axes of different lengths. Two of the axes intersect at an angle of something other than 90° and the third axis is perpendicular to the plane defined by both axes.
7. Triclinic system: It is the least symmetrical crystal system, which has three axes of different lengths. None of the angles between the axes are 90°.

Each system is characterized by its distinct symmetry properties, which in turn determine the geometry of the crystal lattice. Understanding the crystal systems is key for characterizing and analyzing the structure and properties of crystalline materials for a variety of scientific and engineering applications.

3.7 Materials of Importance—Tin (Its Allotropic Transformation)

Tin is a useful metal employed in a range of industrial applications, which undergoes a very weird phenomenon called allotropic transformation where at some temperatures, it can have two entirely different crystal structures: Below about 13.2 °C (55.8°F), it is in a non-close-packed lattice and is known as the gray, or α-phase—here, the tetragonal arrangement of atoms means it has significant interatomic spacing, so it is very brittle, and has awful mechanical properties. This is what is often referred to as "gray tin."

When cooled again, they may revert to the gray tin phase—although this doesn't happen quite as easily as it once did, due to a phenomenon known as tin pests. Earlier this month, my colleague Ben Benoy gave a great account of exactly what tin pests is and where it's come up before, so I'll point you there for more information on the subject. Let's just say that at temperatures below 13.2 °C, it's tough to be a tin atom.

This allotropic transformation is very significant in many industries, especially the fabrication of tin-based alloys, solders, and coatings, as controlling precisely when and how the transformation takes place is critical for the reliability and performance of tin-containing products. The transition between gray and white tin often completely alters the material's properties and structural integrity. Moreover, researchers are eager to be able to manipulate the allotropic transformation to fine-tune the properties of tin-based materials for various applications, ranging from electronics to packaging to corrosion protection.

4 Crystallography

4.1 Point Coordinates

Point coordinates in crystallography serve various functions in defining the positions of lattice points lying within the cell of a crystal structure. Generally, they provide a means of defining the spatial location of an individual atom, ion, or molecule to a reference frame that is established by the crystallographic axes. Point coordinates consist of a set of three numerical values which refer to the distances along the three crystallographic axes.

These are expressions for the set of coordinates for each lattice point describing its location within the unit cell. The coordinates, dependent on the crystal system's symmetry properties and the chosen unit cell parameters, can be fairly complicated. Exactly what the conventions are and which type of coordinate system (Cartesian, fractional coordinates…) is used is dependent on the particular crystallographic convention one is working under at the time.

For instance, if you had a cubic system, these coordinates might be (x, y, z), where the coordinates x, y, and z represented fractional distances along the crystallographic axes a, b, c respectively (where each would range from 0 to 1 and represent the fraction of the unit cell length parallel to each axis).

For a description of how atoms or ions are arranged in a crystal lattice, the coordinates of points in space are critical and, when analyzed, provide important structural properties of crystalline materials. The symmetry, coordination, and bonding environment of atoms in the crystal structure are all found by examination of these points, and they provide some of the most useful information for understanding the behavior and properties of the material.

4.2 Crystallographic Directions

In crystallography, crystallographic directions are the directions in the lattice space. The crystallographic directions can be obtained using the principle of Miller indices.

Crystallographic directions are useful for representing the path along which atoms/ions/lattice planes are arranged with crystal structure.

The Miller indices are enclosed within square brackets [hkl] and represent the reciprocals of the intercepts of the direction with the crystallographic axes a, b, and c (in that order). They are obtained as follows: The intercepts along the three axes are so determined that these intercepts are integral. The reciprocals of these intercepts are then written. These fractions are then multiplied by a common factor to make the resulting three numbers integral; these are the Miller indices.

Try another few examples. A direction that intercepts the a-axis at 2/3 of its length, the b-axis at 1/4 of its length, and the c-axis at 1/2 of its length, will have [312] as its Miller indices, found by taking the reciprocals of the intercepts (3/2, 4, and 2) and multiplying by a common factor (2) to obtain integers (6, 8, and 4).

Crystallographic directions are immensely important. They describe the orientation of crystallographic features such as atomic rows, atomic planes, and lattice defects (for example, a void packed in a crystal lattice). By analyzing them, researchers can understand the symmetry, arrangement, and mechanical properties of materials, shedding light on how these materials operate so that we can design and characterize materials that have superior or special properties for scientific or engineering applications [6].

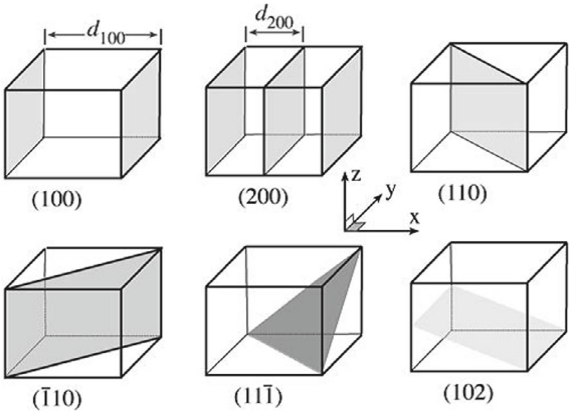
4.3 Crystallographic Planes

Crystallographic planes are the imaginary surfaces that represent the layers of atoms in a crystal lattice system. Similar to directions and points, these planes also use Miller indices, as shown in Fig. 10. The orientation and spacing of crystallographic planes determine many material properties, including mechanical, optical, and electrical behavior.

4.4 Linear and Planar Densities

Linear and planar densities are measures of the “packing efficiency” of atoms in a crystal lattice. Linear density is the number of atoms per unit length along a specific crystallographic direction and is determined by: Planar density is the number of atoms per unit area in a specific crystallographic plane, and is determined from: These parameters are used to predict or correlate several other material properties

Fig. 10 Miller indices



including mechanical strength (ductility, yield strength, tensile strength, hardness) and electrical conductivity [4].

4.5 Close-Packed Crystal Structures

Close-packed crystalline structures are unities in which atoms are closely packed to maximize atomic contact without violating atomic bond requirements. The most common of the close-packed structures are the face-centered cubic (FCC) and the hexagonal close-packed (HCP) Fig. 11, which lists the common Crystal structures found in nature. These structures are efficient means of packing and are important in understanding such properties of materials as hardness and deformation.

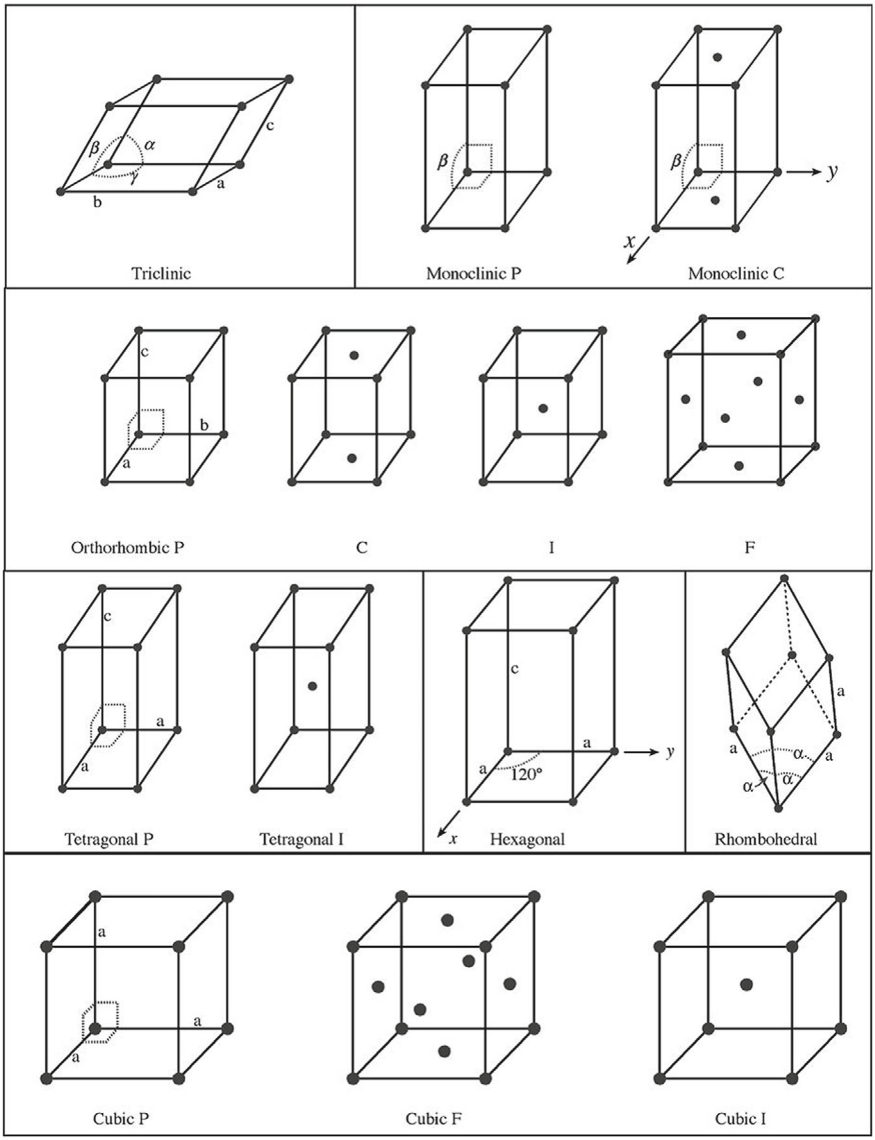


Fig. 11 Crystal structures

5 Conclusion

Atomic bonding and crystal structure are fundamental principles that underpin the behavior and properties of materials. By studying the forces that hold atoms together and the arrangement of atoms in a solid, scientists and engineers can gain insights into the diverse range of materials found in nature and develop new materials with tailored properties.

The three primary types of atomic bonding—ionic, covalent, and metallic—each contribute to the unique characteristics of different substances. Ionic bonds form by the transfer of electrons between atoms and result in the formation of oppositely charged ions, while covalent bonds include the sharing of electrons among atoms, leading to the formation of molecules. Metallic bonding, considered by the delocalization of valence electrons, gives rise to the characteristic properties of metals.

A crystal structure describes the periodic arrangement of atoms/ions in a material. The particular crystal structure of a material impacts its chemical, mechanical, and physical properties. By understanding the crystal structure, experts can manipulate the performance of materials, allowing developments in various fields, from microchip technology and aerospace to medication and renewable energy.

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Polymeric Materials

Zakariya Zubair, Muhammad Umar Iqbal, and Tahir Shah

1 Introduction

The building blocks of life, polymers, have existed from the beginning of time. However, their nature and potential was not fully comprehended until the middle of the 20th century. This adventure began with the quest to find billiard ball substitutes other than ivory, which resulted in the discovery of cellulose nitrate (celluloid) in 1868. In 1909, Bakelite, the first entirely synthetic plastic was developed. This opened the door for the quick creation of new materials including cellulose acetate, nylon, and PVC.

Early research was laborious and mostly concerned with the molecular makeup of polymers. But in the early 20th century, there was a change toward an appreciation of their structure. Long chain molecules were first conceptualized by researchers like Hermann Staudinger and Wallace Carothers, who also categorized polymers into different types, such as addition or condensation polymers. Between 1925 and 1950, a wave of novel polymeric materials, such as acrylic resins, polystyrene, and melamine resins, were produced as a result of this newfound knowledge.

Polymer research was significantly expedited during World War II due to the demand for synthetic rubber and improved insulating materials. Thermosetting polyesters, ABS plastic, and polyethylene were invented during this period. Even more progress was made in the years following World War II with the creation of stereo-specific catalysts that enabled customized polymer characteristics. The emergence of engineering thermoplastics, polycarbonates, and acetal offered improved strength and thermal stability. New developments for commercial and aerospace uses, such as high-barrier nitrile resins, thermoplastic polyesters, and high-temperature plastics, were introduced in the 1960s and 1970s. The idea of a custom-made polymer

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is now a reality due to the advancements in polymer science and novel polymerization methods. Certain properties can be engineered into polymers, enabling them to outperform traditional materials or perhaps even develop wholly novel material properties.

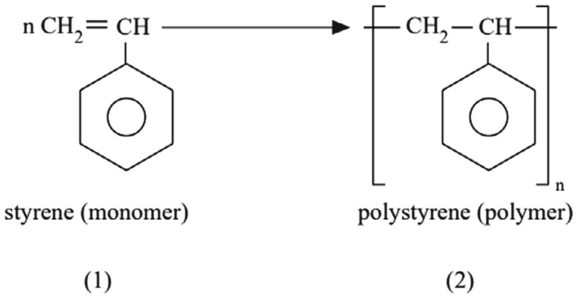
From solid plastics to fibers, elastomers, and foams; the polymer form possibilities are endless. They can be tough materials or flexible, thin films or coatings, porous or nonporous, heat-resistant or melt-able. Some even shield spacecraft from re-entry heat, while others form life-saving bulletproof armor. The future of polymers is bright, fueled by continuous development, modification of existing materials, and improved fabrication techniques. As we address environmental challenges, recycling and blending of plastics will further diversify the landscape of this remarkable class of materials [1–3].

1.1 Basic Concept and Definition

The Greek words poly, which means “many,” and meres, which means “parts,” are the roots of the word polymer. Consequently, a polymer is a large molecule (macromolecule) that is created by repeating smaller chemical building blocks. Figure 1 depicts the synthesis of the polymer polystyrene to illustrate this point.

There is a double bond in the styrene molecule (1). Chemists have developed strategies to break this double bond, forming connections between literally thousands of styrene molecules. The structure that results is polymer polystyrene (2), and it is denoted by square brackets. As any molecule that may be combined with other molecules of the same or different kind to form a polymer, styrene is referred to as a monomer. The repeating unit is the unit denoted by square brackets [4].

Fig. 1 Polymerization of styrene monomer



2 Classification of Polymers

There are numerous ways to classify polymers. The most evident division is between natural and synthetic polymers according to their origin. Other polymer classifications are based on the preparation methods, thermal behavior, polymer structure, or polymerization mechanism [5, 6].

2.1 Classification Based on Source of Availability

2.1.1 Natural Polymers

Natural polymers are those derived from plants and animals in the natural world. To survive, these polymers are necessary. They include: (a) Starch, which is a polymer of glucose that serves as a plant's food store. (b) Cellulose: another glucose-based polymer, which is the primary structural component of plants. From the glucose produced during photosynthesis, plants make both cellulose and starch. (c) Proteins; these are polymers of α-amino acids that typically contain 20–1000 α amino acids arranged in a highly ordered fashion. These are the fundamental components of living organisms and are also constituents of our diet. (d) Nucleic acids are polymers made up of different nucleotides and are common constituents of both DNA and RNA.

2.1.2 Synthetic Polymers

Synthetic polymers are defined as those that are created in laboratory settings. Another name for these is man-made polymers. Some examples of synthetic polymers are Teflon, Bakelite, Terylene, PVC, Nylon, Polyethene, and synthetic rubber.

2.1.3 Semisynthetic Polymers

Most of these polymers are created chemically from naturally existing polymers. For instance, cellulose is a naturally occurring polymer that forms cellulose diacetate polymers, which is prepared by acetylation of cellulose with acetic anhydride in the presence of sulfuric acid. Cellulose diacetate is utilized in the production of thread, films, glasses, etc. Another example of a semisynthetic polymer used to make tires and other products is vulcanized rubber. Cellulose nitrate is used to make explosives, which is commonly called "gun cotton."

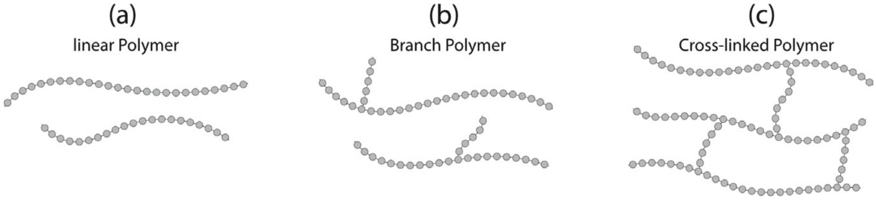


Fig. 2 Classification of polymers based upon structure. **a** Linear polymer, **b** branch polymer, **c** cross-linked polymer

2.2 *Classification Based Upon Structure*

2.2.1 Linear Polymers

These polymers, as seen Fig. 2a, are composed of monomeric units joined to form a linear chain. These linear polymers have high densities, high tensile (pulling) strengths, and high melting temperatures due to their densely packed structures. Common examples of linear polymers are polyester, PVC, PAN, nylon, and polyethylene.

2.2.2 Branched Chain Polymers

These polymers have long chains with side chains or branches of varying lengths formed by the joining of monomers Fig. 2b. Because of their uneven packing, branched chain polymers have lower melting points and tensile strengths than linear polymers. Typical examples of branched polymers are low density polythene, glycogen and starch.

2.2.3 Cross-Linked Polymers

These polymers are made up of monomers that have been cross-linked to create a three-dimensional network Fig. 2c. Because of their network structure, these polymers are brittle, hard, and rigid. Common examples of cross-linked polymers are melamine formaldehyde resin, Bakelite, etc. [7].

2.3 *Classification Based Upon Molecular Forces*

2.3.1 Elastomers

Elastomers are polymers with elastic properties, such as rubber. An elastic substance is one that can revert to its former shape after being stretched. Weak intermolecular forces hold the polymer chains together in elastomers. The polymers are easily stretched by modest amounts of tension due to the existence of weak forces, and then return to their original shape when the stress is released. Natural rubber is the primary example of elastomeric polymer.

2.3.2 Fibers

Strong intermolecular interactions exist between the chains of these polymers. Dipole–dipole interaction or hydrogen bonding are these forces holding the fiber structure together. These forces cause the chains to be densely packed in fibrous structure, resulting in their reduced elasticity and increased tensile strength. Fibers have high melting points as a result. These polymers structures may be woven into fabric because they are long, thin, and thread-like. Some common examples of fibers are silk, Dacron, and nylon 66.

2.3.3 Thermoplastics

These are the polymers whose properties do not change greatly, when heated and cooled, as a result they can be easily softened and hardened again. The intermolecular forces in thermoplastic polymers fall somewhere between those of fibers and elastomers. The chain is not connected by any crosslinks. Since there are no cross-links involve, the polymer chains can move more easily, causing the softening to happen. Thermoplastics melt when heated and create a fluid that can be shaped into any shape and then cooled to get the desired result. Typical examples of these polymers include Teflon, PVC, polystyrene, and polythene.

2.3.4 Thermosetting Polymers

Thermosetting polymers are those polymers that are transform permanently when heated. Upon heating they are hardened and turn into infusible materials, which cannot be softened again. Semifluid materials with a low molecular mass are typically used to prepare thermosetting plastics. They generate hard, insoluble, and strongly cross-linked compounds when heated. The molecules are held in place by the cross connections, preventing them from moving freely when heated. Consequently, a thermosetting plastic becomes cross bonded and irreversibly stiff [8, 9].

2.4 Classification Based upon Mode of Synthesis

Polymerizations are categorized based on the kinds of reactions that take place during synthesis. Three primary types of polymerizations exist [10, 11].

2.4.1 Addition Polymerization

The addition polymerization is also known as chain-growth polymerization. It involves the addition of new monomer units to a growing polymer molecule, one at a time through double or triple bonds in the monomer. Therefore, this techniques is typically used for unsaturated monomers such olefins, acetylenes, aldehydes, etc. As a result of the recognized step-by-step progression of reactions via reactive intermediates, it is also known as chain-growth polymerization. Since the polymerization process converts a π-bond in the monomer to a sigma bond in the polymer, the process is often exothermic by 8–20 kcal/mol. A very high molecular weight polymer is rapidly produced because of the nature of the process. The addition reactions are the most frequent and thermodynamically preferred chemical transformations of olefins. In general, bulk, solution, suspension, and emulsion polymerization methods can be used to create these polymers. Monomers with two double bonds can also occasionally be used to achieve cross-linking. Thermoplastics of the addition type include many commonly used polymers as illustrated in Fig. 3 [12].

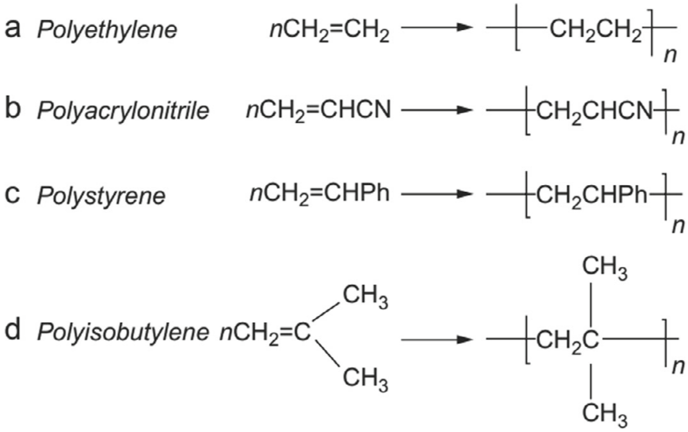


Fig. 3 Common examples of addition polymerization

2.4.2 Condensation Polymerization

In this method, water, ammonia, methanol, and HCl are eliminated in order to unite two distinct monomers. One other name for condensation polymerization is step-growth polymerization. The amount of monomer functional end groups that can react determines the kind of product that is produced during a condensation polymerization. The monomers utilized in addition polymerization and condensation polymerization are different. These monomers share two primary features: each monomer has two or more reactive sites, and they lack double bonds in favor of functional groups like -OH, -NH_2, or -COOH. Only at high conversion rates can a high molecular weight be achieved in this method. Since the majority of reactions have significant activation energy (ΔE_a), heating is typically necessary.

One reactive group in a monomer causes a developing chain to break, resulting in reduced molecular weight end products. Monomers with two reactive end-groups are used to generate linear polymers, and monomers with more than two end-groups result in cross-linked three-dimensional polymers. Joining monomers with a -OH group and a readily ionizable H on either end—such as a hydrogen from the -NH_2 in nylon or proteins—is a common step in dehydration synthesis. Typically, the reaction involves the employment of two or more distinct monomers. Water is released when the bonds between the hydroxyl group, the hydrogen atom, and their individual atoms break, separating the hydroxyl, hydrogen, and polymer. Ester connections between monomers, involving functional groups like carboxyl and hydroxyl (an organic acid and an alcohol monomer), are what makes a polyester. Another popular condensation polymer is nylon, which is made by reacting carboxyl derivatives with diamines. Dicarboxylic acid is the derivative in this instance, although buta-diacyl chlorides are also employed. The reactivity of bifunctional monomers with one carboxylic acid group and one amine group on the same molecule is another strategy that is employed. Figure 4 shows a typical reaction for the formation of condensation polymer.

A peptide bond, also called an amide group, is created when amines and carboxylic acids combine. Condensation polymers formed from monomers of amino acids are known as proteins. Condensation polymers like glucose and galactose are the building blocks of carbohydrates. Simple hydrocarbons can occasionally be formed through condensation polymerization. But because this process is costly and ineffective, ethene addition polymer, or polyethylene, is typically utilized instead. Contrary to addition polymers, condensation polymers could degrade naturally. Bacterial enzymes or acid catalysts can hydrolyze the peptide or ester bonds connecting monomers, severing the polymer chain into smaller segments.

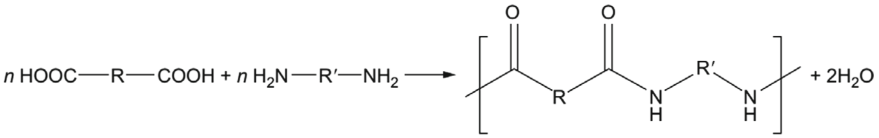


Fig. 4 Example of condensation polymerization

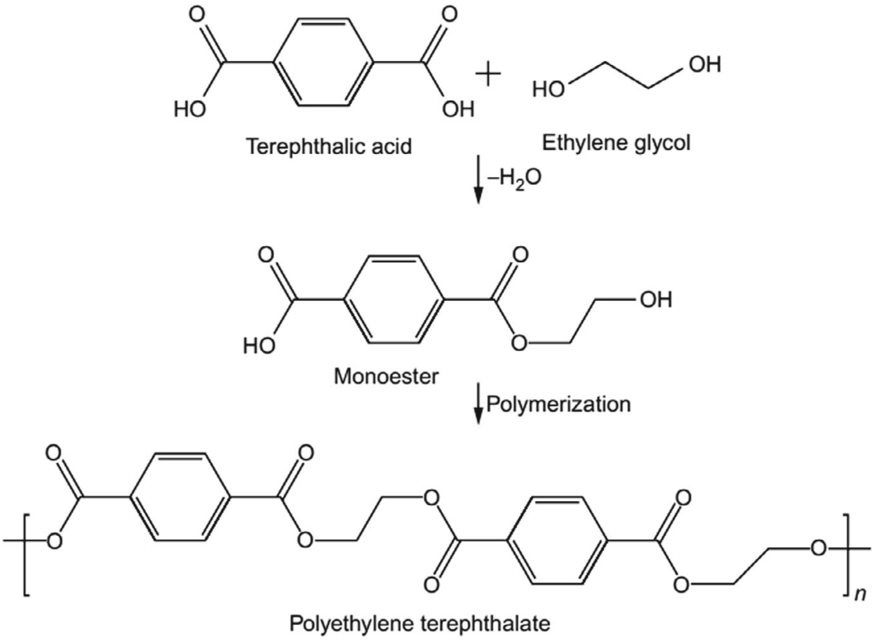


Fig. 5 Preparation of polyethylene terephthalate as an example of condensation polymerization

Proteins and textiles like nylon, silk, or polyester are the most well-known examples of condensation polymers. It is possible for an ester bond to develop between an alcohol and a carboxylic acid monomer, which is followed by the loss of a water molecule. The resulting monoester combines with another monoester to make polyethylene terephthalate (PET) through further reactions (Fig. 5).

2.4.3 Metathesis Polymerization

The process of breaking the carbon–carbon double bond in an olefin and then rearranging the molecules statistically to form a polymer is known as olefin metathesis. The carbon–carbon double bond does not stay in the polymer backbone in other polymerization procedures once vinyl monomer is transformed into polymer. The carbon double bond does, however, stay in the polymer backbone chain after metathesis polymerization; these polymers are known as polyalkenamers. Figure 6 shows the mechanism of metathesis polymerization. Chauvin proposed the widely recognized mechanism for the olefin metathesis reaction. An intermediate metallacyclobutane is created by a [2 + 2] cycloaddition process between the olefin and the transition metal alkylidene complex. After that, this metallocycle disintegrates in an opposite way to produce a new olefin and alkylidene. Eventually, an equilibrium mixture of olefins will be produced if this process is repeated [13].

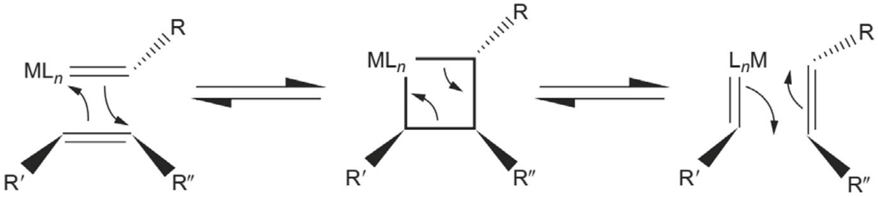
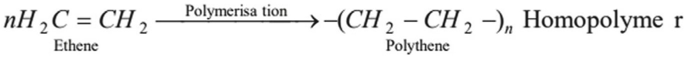


Fig. 6 Mechanism of metathesis polymerization



$$\underset{\text{Ethene}}{nH_2C = CH_2} \xrightarrow{\text{Polymerisa tion}} \underset{\text{Polythene}}{-(CH_2 - CH_2 -)_n} \text{ Homopolyme r}$$

Fig. 7 Example of homopolymer synthesis

2.5 Classification Based upon the Nature of Monomers

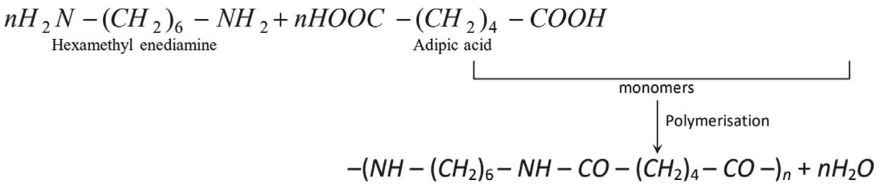
There are two different kinds of polymers based on the nature of the monomers used for their synthesis. These commonly called copolymers and homopolymers, as described below [14].

2.5.1 Homopolymers

Homopolymers are polymers that have just one type of repeating unit within their molecules. On the other hand, chemists have created methods for creating polymer chains with multiple repeating units. One example of homopolymer, based on monomer ethane, is polythene, which is illustrated in in Fig. 7.

2.5.2 Copolymers

A polymer formed from two or more different monomers is called copolymer or mixed polymer. For example, nylon-66 is a polymer of two types of monomers: hexamethylenediamine and adipic acid (Fig. 8).



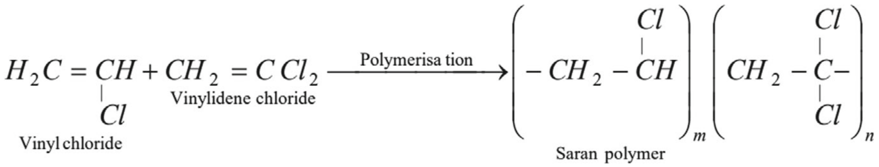
$$\underset{\text{Hexamethyl enediamine}}{nH_2N - (CH_2)_6 - NH_2} + \underset{\text{Adipic acid}}{nHOOC - (CH_2)_4 - COOH}$$

$$\underbrace{\qquad\qquad\qquad}_{\text{monomers}}$$

$$\Big\downarrow \text{Polymerisation}$$

$$-(NH - (CH_2)_6 - NH - CO - (CH_2)_4 - CO -)_n + nH_2O$$

Fig. 8 Nylon-66 polymerization



$$\underset{\text{Vinyl chloride}}{H_2C = \underset{\displaystyle Cl}{\underset{|}{C}}H} + \underset{\text{Vinylidene chloride}}{CH_2 = C\,Cl_2} \xrightarrow{\text{Polymerisa tion}} \underset{\text{Saran polymer}}{\left(-CH_2 - \overset{\displaystyle Cl}{\overset{|}{C}}H \right)_m \left(CH_2 - \overset{\displaystyle Cl}{\overset{|}{\underset{\displaystyle Cl}{\underset{|}{C}}}} - \right)_n}$$

Fig. 9 Saran Polymer an example of copolymer

Copolymers are commercially more important. For example copolymerization of vinyl chloride with vinylidene chloride (1, 1 dichloroethane) in a 1: 4 ratio forms a copolymer known as saran (Fig. 9).

Copolymerization of monomer mixtures often leads to the formation of polymers which have quite different properties than those of corresponding homopolymer.

The composition of the copolymer depends on the proportion of the monomers and their reactivity. It may be noted that some monomers do not polymerise at all but copolymerise. For example, maleic anhydride does not polymerise as such. However, it copolymerizes with styrene in a highly symmetrical manner to form styrene maleic anhydride copolymer.

It may be noted that many types of copolymers can be obtained depending upon the distribution of monomer units in the chain. Two monomers can combine in either regular fashion (although this is rare) or random fashion. For example, if monomer A is copolymerized with monomer B, the resultant product may have a random distribution of the two units throughout the chain or it might have alternated distribution.

(– A – B – A – B – A – B – A – B –) Alternating copolymer.

(– A – A – A – B – A – B – B – A – B –) Random copolymer

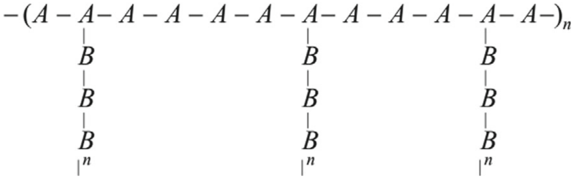
The exact distribution of monomer units depends on the initial proportion of the two reactant monomers and their reactivities. Most copolymers have varying distributions. Two other types of copolymers that can be prepared under certain conditions are called block copolymers and graft copolymers.

(a) Block copolymers are those in which different blocks of identical monomer units alternate with each other as

(– A – A – A – A – B – B – B – B – A – A – A – A – B – B – B – B –)n

These are prepared by initiating the polymerization of one monomer as if growing a homopolymer and then adding an excess of second monomer to the active reaction mixture.

(b) Graft polymers are those in which homopolymer branches of one monomer units are grafted on the homopolymer chains of another monomer units as (Fig. 10).



$$-(A-\underset{\substack{|\\B\\|\\B\\|\\B\\|^{n}}}{A}-A-A-A-A-\underset{\substack{|\\B\\|\\B\\|\\B\\|^{n}}}{A}-A-A-A-\underset{\substack{|\\B\\|\\B\\|\\B\\|^{n}}}{A}-A-)_n$$

Fig. 10 Example of graft polymer

These are prepared by radiation of γ-rays on a completed homopolymer chain in the presence of the second monomer. The high energy radiation knocks hydrogen atoms of the homopolymer chain at random points resulting radical sites for initiation of the added monomer. By careful control of the polymerization reaction, we can produce copolymers of desired properties by combination of different monomers in various ratios and geometric arrangements.

3 Mechanical Properties

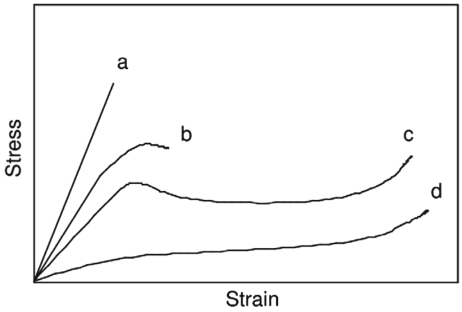
Polymers are often used in many stress-related applications. For example, housing, gears, ropes, constructions, composite materials, etc. are made of different types of polymers. In these applications polymers are subjected to different levels of stresses and strains. Prior to employing polymers in load-bearing applications, it is important to understand their mechanical properties. Many tests are used to characterize the mechanical properties of polymeric materials and structures.

3.1 Stress–Strain Analysis

In order to carry out stress strain analysis on polymeric materials, coupons are made of these materials, which are then subjected to tensile tests. Steadily increasing stress is applied and the resulting strain is measured. The results are plotted in the form of a stress–strain curve, as illustrated in Fig. 9. The first thing to look at is a tensile stress–strain curve obtained by tugging in a single direction. Poisson contraction effects cause the cross-sectional area to alter as the sample lengthens. It is necessary to define the “true” stress and “true” strain in terms of the dimensions of the sample tested. This is referred to as engineering stress, which is obtained by dividing the total load by the initial cross-sectional area of the specimen. The entire elongation divided by the initial length is known as engineering strain. Figure 9 shows some typical stress–strain curves used in polymer engineering. For a linear elastic polymer, curve ‘a’ is used. Up to the point of final failure, the stress grows linearly (or very nearly linearly) with strain (Fig. 11).

Deviations from linearity are indicative of yielding. Yield stress in metals is frequently described as a set percentage of linearity deviation. This method is

Fig. 11 Typical stress–strain curve, **a** linear elastic; **b** nonlinear with yield; **c** yielding followed by necking and high elongation; **d** rubber-elastic curve



frequently ineffective when dealing with polymers, because yield stress is typically the peak stress. Peak stress is not usually evident, however it is evident in curve ‘c’ and very slightly in curve ‘b’. Curve ‘c’, thus, represents a material that gives before continuing to elongate. A neck will form after yielding. The neck area then expands or elongates, occasionally to several hundred percent strains. The polymer chains will eventually align in the necked area. The material will stiffen and eventually break upon alignment. The stress–strain behavior of rubbers and other rubber-like materials is illustrated by the curve ‘d’. There is no necking and a high recoverable extension in rubber elastic deformation. The chains of the polymers can align and crystallize at the maximum elongations. Before failure, these processes will lead the curve to turn up and stiffen.

4 Polymerization Methods

The two main categories of polymerization procedures are homogeneous and heterogeneous. When using a homogeneous method, pure or diluted monomers are added directly to one another, and the reaction takes place in the media that is produced when the reactants are mixed. A phase boundary that serves as an interphase where the reaction takes place is present in heterogeneous processes are given in Fig. 12.

4.1 Solution Polymerization

A monomer is dissolved in a nonreactive solvent containing a catalyst in this polymerization method. Both the monomer and the final polymer are soluble in the solvent. The solvent absorbs the heat produced during the reaction, which lowers the reaction rate. Excess solvent must be eliminated in order to produce the pure polymer after the maximum or intended conversion is achieved. Because chain transfer may occur, the compounds produced by this process have relatively low molecular weights. Because the extra solvent is difficult to remove and the solvent is occluded, securely trapping

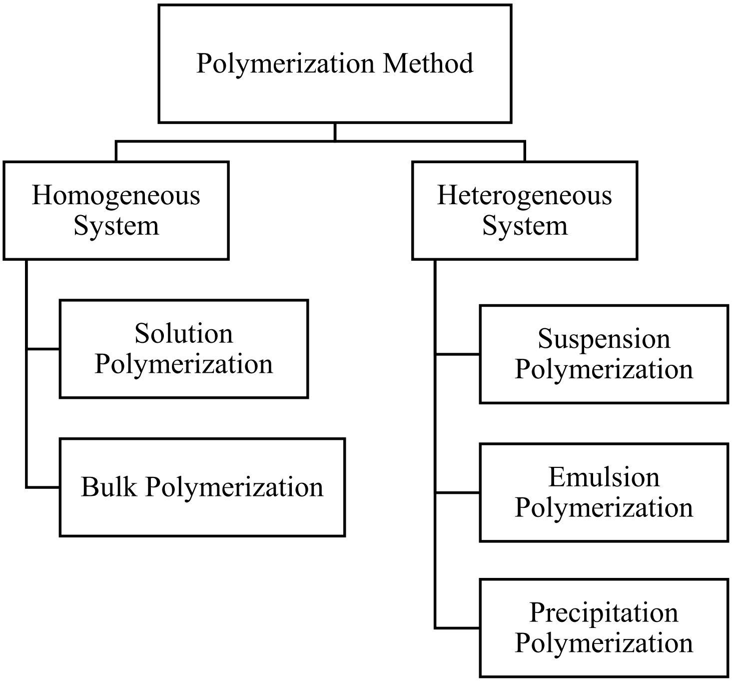


Fig. 12 Different type of polymerization methods

the polymer. This technique works well for producing wet polymers. Therefore, when polymer solutions are needed (for ready-made usage) for technical applications like surface coatings, adhesives, and lacquers, this polymerization procedure is used. Neoprene, which is used in wet-suits and disposable diapers; and sodium polyacrylate, a superabsorbent polymer, are often produced using this procedure. This process is also used for the production of polymers such as polytetrafluoroethylene, polyacrylic acid, and polyacrylonitrile (PAN).

4.2 Bulk (Mass) Polymerization

Under the influence of heat or light and chemicals such as initiators, transfer agents and catalysts, the monomers undergo internal bulk polymerization. Due to the highly exothermic nature of this polymerization process, which makes it difficult to control, the resulting polymer typically has a wide molecular mass distribution. However, using a chain transfer agent makes it simple to alter the molecular-weight distribution. Characteristics of the finished polymer can also be controlled by adjusting the temperature and pressure of the reaction. The polymer is obtained as a powdery or porous solid if it is insoluble in its monomer. Since the monomers make up most of the recipe, pure polymers are generally obtained using this method of polymerization. This works well with liquefiable or liquid monomers that can be handled in batch or continuous production. Higher optical clarity makes the resultant product ideal for casting, particularly clear products (like polymethyl methacrylate (PMMA) sheets). This process can also be used to create low-molecular-weight polymers for use as lubricants, plasticizers, and adhesives.

4.3 Suspension Polymerization

The process of suspension polymerization is heterogeneous. In this method, stirring is plays an important part to disperse the monomer, which contains the initiator, modifier, etc., in a solvent (usually water). Due to their insolubility in the liquid phase, the initiator and monomer combine to create beads in the liquid matrix. Typically, a suspension agent like PVA or methyl cellulose is added to stabilize the monomer droplets and prevent their agglomeration. The volume ratio of the monomer to liquid phase in the reaction mixture is typically between 0.1 and 0.50. A significant advantage of this method is that heat transfer is quite effective, making reaction control simple. Typically, the reactions take place in a stirred tank reactor, which uses viscous shear forces or turbulent pressure to continually mix the solution. The churning action keeps the monomer droplets apart and produces a more homogeneous suspension, which results in final polymer beads with a narrower size distribution. The term pearl polymerization for this method comes from the formation of the beads' resembling to pearls. Because of their propensity for agglomerations, sticky polymers like elastomers cannot be polymerized with this method. Numerous commercial resins, such as PAN, PMMA and polyvinyl chloride (PVC), are produced using this technique. Styrene resins such as expanded polystyrene, high-impact polystyrene are also prepared using suspension polymerization method.

4.4 Precipitation Polymerization

Precipitation polymerization is a heterogeneous process that starts off as a homogeneous system in the continuous phase when the initiator and monomer are fully soluble. However, the produced polymer is insoluble and precipitates as soon as it is initiated. The precipitated polymer can be separated by simple filtration or centrifugation into a gel or powder. Since heat dissipation is not an issue, high degree of polymerization can be achieved. Hydrocarbons are used as solvents in the commercial production of precipitation polymers such as polyvinyl and polyacrylic esters. However, for the production of PAN, water is used as a solvent.

4.5 Emulsion Polymerization

In this method of free radical polymerization, an emulsion is produced when the liquid monomer is distributed throughout an insoluble liquid. The reaction takes place in three distinct steps; initiation, propagation and termination.

An oil-in-water emulsion, in which droplets of the monomer (the oil) are emulsified (with surfactants) in a continuous phase of water, is the most prevalent kind of emulsion polymerization. Emulsifiers and stabilizers can also be made from water-soluble polymers, such as hydroxyethyl celluloses and certain polyvinyl alcohols. During the initial phase of the process, latex particles that spontaneously develop undergo polymerization. These latex particles are composed of numerous distinct polymer chains and have an approximate size of 100 nm. Because the surfactant, or soap, surrounds each particle and repels other particles electrostatically due their charge, the particles cease to coagulate with one another. The repulsion between particles occurs when water-soluble polymers are employed as stabilizers rather than soap. This is because the water-soluble polymers produce a hairy coating surrounding a particle, which repels other particles because pulling the particles together would compress these chains. Since the polymer molecules are confined within the particles, the reaction medium's viscosity does not rely on the molecular weight and stays relatively close to that of water. High monomer to polymer conversion is the intended aim at the operating temperature for emulsion polymerizations. There may be a large chain transfer to the polymer as a result. However, removal of water from dry (isolated) polymers requires a lot of energy (Fig. 13).

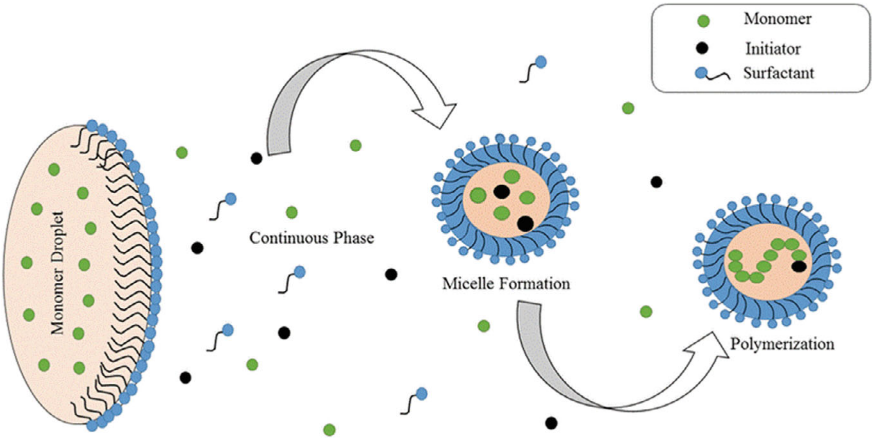


Fig. 13 Basic mechanism of emulsion polymerization [16]

5 Processing of Polymers

In order to transform polymeric materials into useable products—with the appropriate shapes, characteristics, and dimensions—a variety of polymer processing technologies are used. The kind of polymer, the intended use, and the desired properties of the finished product determine the selection of particular processing methods. In the following sections some common techniques for processing of polymers are briefly described [17].

5.1 Fabrication of Polymer Films

Polymer films possess distinct characteristics such as a high aspect ratio, remarkable flexibility, physical adherence to various surfaces, and visually appealing structural colors. Biocompatible and biodegradable polymer materials can be used to create films. Owing to their prospective uses in medicine, which include scaffolds for tissue engineering and biocompatible implant coatings, these films have received a lot of attention. Numerous techniques can be used to produce polymer films. The following text discusses the key techniques.

5.1.1 Solution Casting

This approach involves dissolving the polymer in an appropriate solvent to create a viscous solution, which is then applied to a surface that is either flat or lacks stickiness. The dry coatings can be scraped (peeled) off the flat surface by allowing the solvent to evaporate or be removed. In order to prevent weak conglomerates from forming in the polymer solution, a larger molecular weight is necessary. The solvent needs to be sufficiently volatile to evaporate at room temperature or slightly higher than this in order to facilitate solution casting. Furthermore, the solvent should not evaporate too quickly since this could lead to bubble formation or a semicrystalline precipitate. In addition to cooling the film, the quick volatilization also raises the possibility of crazing or atmospheric water condensation. Typically, solvents with boiling points between 60 and 100 °C are required to produce high-quality films.

In most cases, filtration of the polymer solution is necessary prior to casting, and pressure techniques—as opposed to gravity or vacuum filtration—must be used for filtration. Figure 14 illustrates how to make a small-scale, uniformly thick polymer film in a laboratory by simply spreading the polymer solution over the glass surface and rolling it with a glass rod.

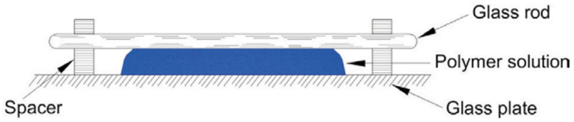


Fig. 14 Laboratory-scale preparation of film by solution casting

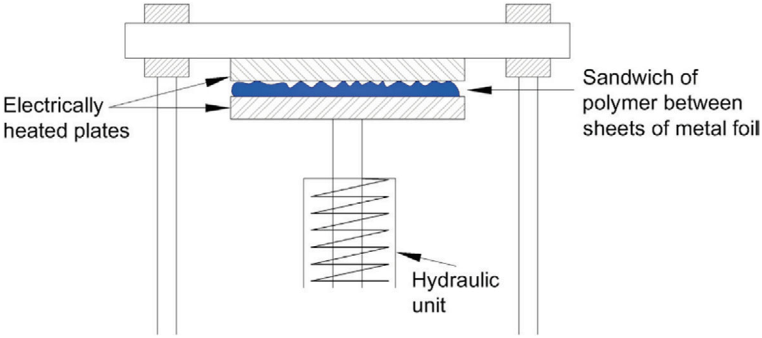


Fig. 15 Preparation of films by melt pressing

5.1.2 Melt Pressing

For polymers that are thermally stable, this technique works well. Due to the discontinuous nature of the procedure and difficulty in preparing large films, this technology is more frequently employed in laboratories than in industrial facilities. Two platens that are heated electrically make up this method. An electric hand pump or hydraulic device can be used to press one platen up against the other. Sandwiching the polymer powder between two aluminum or copper foil sheets, it is then placed between the two heated plates. For roughly 30 s, a hydraulic pressure of between 2000 and 5000 psi is applied. After the sandwich has cooled, it is taken out and the foil and film are separated. In order to obtain the desired quality of the film by this process, you have to experiment to find the right pressure and temperature. Overheating causes the polymer to just pour out of the sandwich. If it is too low, insufficient fusion may cause the film to be weak or opaque (Fig. 15).

5.1.3 Melt Extrusion

Continuous procedures are generally recommended for the commercial production of products. Melt extrusion, being a continuous process, is more commonly used for bulk production. Using this process, as illustrated in Fig. 12, the polymer powder or pellets are fed into a screw extruder, which uses a rotating screw spindle to heat the polymer. The molten polymer is pushed into the die, where it cools below its melting temperature and forms a flat sheet that is collected by a revolving drum. The

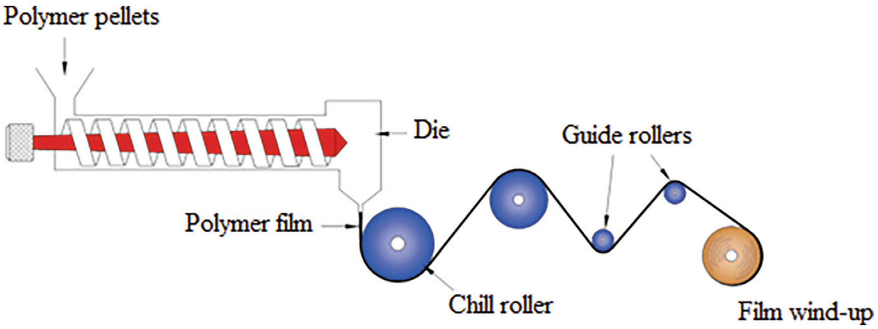


Fig. 16 Preparation of film by melt extrusion

chilling effect and alignment process are finished by the next set of rollers. Using this process, a film with a thickness ranging from 0.01 to 0.1 mm can be generated (Fig. 16).

5.2 Spinning Industrial Polymers

The earliest forms of fiber spinning were based on natural materials like flax and wool. However, the development of synthetic polymers has opened up new possibilities for synthetic fiber production. Today, synthetic fiber spinning technology continues to evolve, enabling the production of a wide range of high-performance materials for various applications. These polymers are spun into fibers using different spinning processes. Each process has unique benefits and is appropriate for a particular use case [18, 19]. Various polymer spinning processes are briefly described in the following sections.

5.2.1 Solution Spinning

In the solution spinning process, polymers are dissolved in a suitable solvent to create a solution, whereas in the melt spinning process, polymers are heated until they are in a molten state. Despite this difference, both processes involve extruding the polymer (whether as a solution or molten material) through a spinneret, a specialized plate with extremely fine holes used to form fibers. Solution spinning can be further categorized into three distinct types.

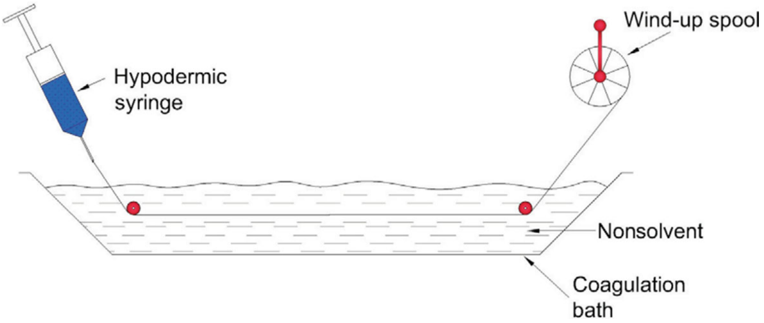


Fig. 17 Laboratory scale for wet spinning of fibers

5.2.2 Wet Spinning

This process involves injecting a viscous polymer solution into a coagulation bath that contains a nonsolvent using a hypodermic syringe, and then extruding the mixture as a continuous filament as depicted in Fig. 17. The viscous solution solidifies or precipitates as a fiber during the nonsolvent process, and it is then be wrapped up onto a spool. Because of the irregularity in the jet, droplets may occur during the wet spinning process rather than a continuous filament. Increasing the viscosity of the polymer solution will help prevent this happening.

The viscous polymer solution is pushed into a coagulation bath containing a nonsolvent on a large scale using a motor-driven syringe pump. There, the polymer solution precipitates and can be removed and wound up using a roller.

5.2.3 Electrospinning

Nanotechnology has advanced recently and is being widely used in many biomedical sectors, especially in tissue engineering, drug delivery, and enzyme immobilization, where scaffolds are being created for tissue engineering. The creation of biological replacements that preserve, enhance, or restore tissue functions has been greatly aided by tissue engineering. This results from the electrospinning technique's production of nanofibers. Because of this, electrospinning is a crucial procedure in the current era of technology. By selecting an appropriate polymer solution, an electrical charge is utilized in this procedure to draw fine (usually micro- to nanoscale) fibers. This method assures that no solvent may be carried over into the final product and produces fine fibers from polymer solution without the need for a coagulation bath or high temperatures. This approach makes it possible to generate fine semicrystalline polymer fibers, like polyethylene, PET, and polypropylene, which would be difficult or impossible to produce with other spinning techniques (Fig. 18).

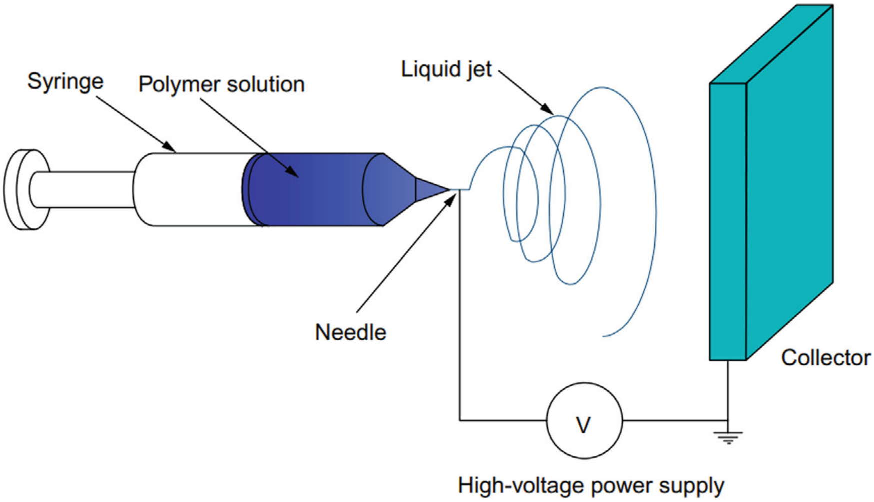


Fig. 18 Electrospinning setup for thin fibers

5.2.4 Dry Spinning

A polymer fiber is created utilizing the dry spinning technique without the need of a coagulation bath. Rather, the fiber is dried using hot air after it is extruded from the hypodermic syringe. The procedure is quite straightforward when applied to a laboratory scale, as Fig. 19 illustrates. The polymer solution is placed into a syringe, forced down into a vertical cylindrical tube, and hot air is concurrently blasted from the bottom to the top. A spool can be used to roll the flowing polymer solution into a solid thread when hot air is blasted into the chamber. However, the approach shown in Fig. 19 is used to carry out this process on a wide scale. Here, a spinneret is used to filter and pump a polymer solution that is more concentrated. A stream of heated air is directed through the chamber from the tube's bottom end as the fibers descend through a vertical chamber. After applying the drying process, the fibers are wrapped up on a spool.

5.2.5 Melt Spinning

Solid polymer pellets or chips are heated to melt in a melting grid in the large-scale process. By using a pump, the melt is filtered and pressed through a spinneret. To harden the fibers, a stream of cold air is passed over the fine threads as soon as they emerge from the spinneret. To obtain a consistent diameter for the fibers, the solid form of the threads is passed between two drums that rotate in opposition directions to one another. The fibers are then coiled onto a bobbin. The melt spinning process is a quick method for manufacturing fibers from thermoplastic polymers. The fibers produced have uniform circular cross-section and consistent mechanical properties.

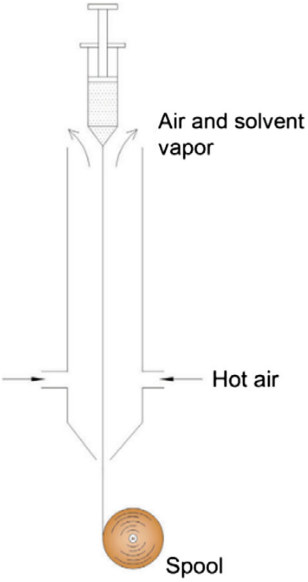


Fig. 19 Laboratory setup for dry spinning of fiber

However, the melt spinning process cannot be used for thermally unstable polymers. The process is illustrated in Fig. 20.

5.3 Fabrication of Shaped Polymer Objects

Various molding processes are used for the creation of three-dimensional items or shaped objects from polymer materials. The type of polymer, the finished object's desired characteristics, and the intended use are some of the features that influence choice of the fabrication technique. After the full curing process, the three-dimensional objects are frequently removed from the molds. A mold-releasing chemical is often applied in order to facilitate the removal of the product formed. There are various molding procedures [18–21]; and some of the most common processes are described in the following sections.

5.3.1 Compression Molding

It is common practice to employ the compression molding technique to create products using thermosetting resins. There are two halves to the mold: an upper half and a lower half. Typically, the upper halve has a projection that fits into the cavity created by the lower halve when the mold is closed. The molded device's shape is determined by the space between the lower chamber and the projected top half (Fig. 21).

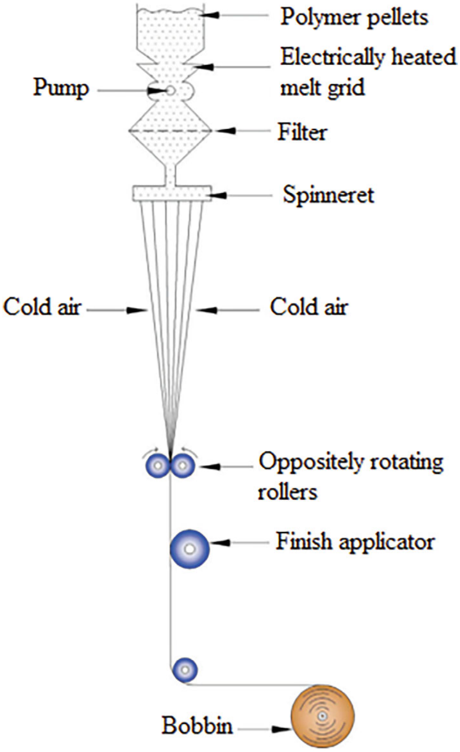


Fig. 20 Laboratory setup for melt spinning of fibers

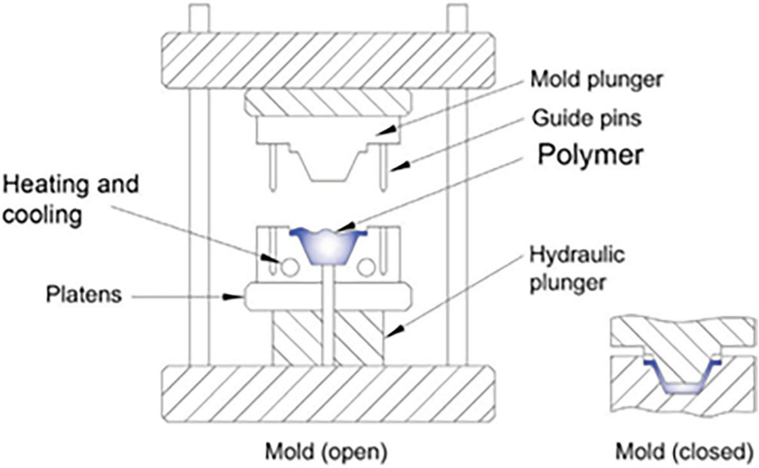


Fig. 21 Preparation of objects by compression molding process

The polymer material is subjected to both stationary and mobile parts of the mold during the compression molding process. When the mold is closed, pressure and heat are applied concurrently to the material to cause it to become plastic. The plastic then flows into the mold and homogenizes. However, depending on the polymer's thermal and rheological characteristics, the appropriate pressure and temperature are applied. The extra polymer material that is forced out of the cavity as a thin film at high pressure is referred to as the flash. The molds are kept together until the resin has completely set, which could take anywhere from a few seconds to many minutes. Next, the mold is opened, allowing the object to be released. In this technique metal molds, which are plated with chromium, are used. Typically, temperatures in the range of 150 °C and pressure of about 200 psi are employed.

5.3.2 Injection Molding

Both thermoplastic and thermosetting polymeric materials can be used to fabricate a wide range product using this high-speed molding method. The process is illustrated in Fig. 22. The polymer is loaded, in the form of liquid or powder resin, into the hopper and driven into a horizontal cylinder by means of electrically heated plates. The molten material is forced into a mold that is attached to the end of the cylinder by a hydraulically powered piston. A torpedo-like device aids in uniformly accelerating the plastic material around the hot cylinder's inner wall as it passes through its hot zone. This guarantees even heating throughout the substance. A nozzle is then used to inject the molten material from the cylinder into the mold chamber. After cooling or curing, the polymer solidifies, allowing the object to be removed in a specific shape. This cycle is repeated, and since the sequence typically takes just ten to thirty seconds, the method is excellent for large-scale production.

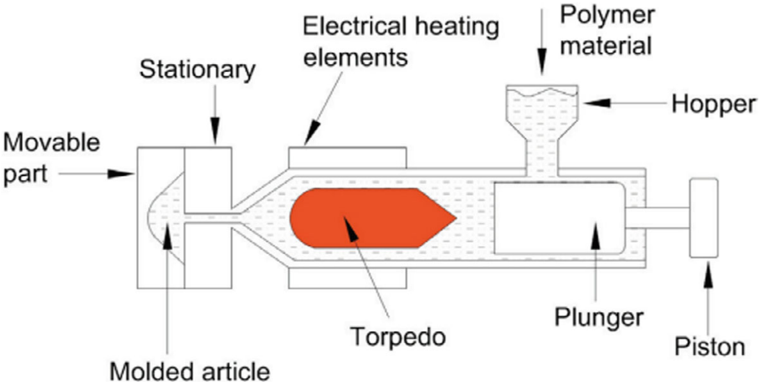


Fig. 22 Schematic representation of injection molding process

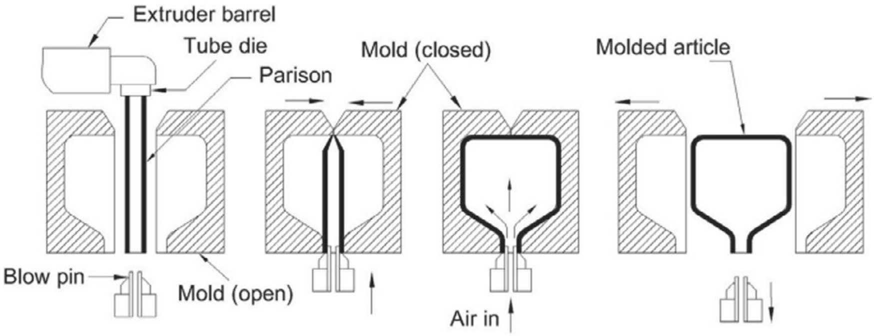


Fig. 23 Diagram of blow molding process

5.3.3 Blow Molding

This process is commonly used to produce the majority of hollow biomedical products. Historically, the blow molding process is related to the production of products using glass. Since it is a low-cost process and requires a very basic operation, it has also found use in the polymer industry. Using this technique, a segment of melted polymer tube, commonly referred to as parison, is appropriately inserted from an extruder between two mold halves. A blowing pin is placed at one end of the prison and the other end is squeezed, when the two sides of the mold are closed. A blowing pin is used to introduce compressed gas into the parison at a pressure of between 2 and 100 psi and heated parison is inflated like a balloon and continues to expand until it makes close contact with the hollow mold's relatively cool interior surface. The parison eventually takes on the form of the mold's hollow cavity when compressed. The mold is then cooled, and the product is removed by opening the mold. The process can be repeated as often as required. Figure 23 illustrates the principle of the blow molding process.

5.3.4 Extrusion Molding

This is a cost-effective technique for creating a wide range of polymer products in continuous lengths, such as sheets, tubes, rods, and filaments. The procedure, as illustrated in Fig. 24, involves feeding the polymeric material through a hopper into a cylinder. The material is then softened by using the electrical heating element of the cylinder. A spinning screw is used to move the molten material into a die. The plastic material goes through three different zones during processing, including the feed zone, compression zone, and material zone, as it moves from the hopper to the die.

Every zone makes a unique contribution to the overall extrusion process. The material from the hopper is sent to the feeding zone and the to the compression zone. In the compression zone, the material melts due to the heat applied, and then

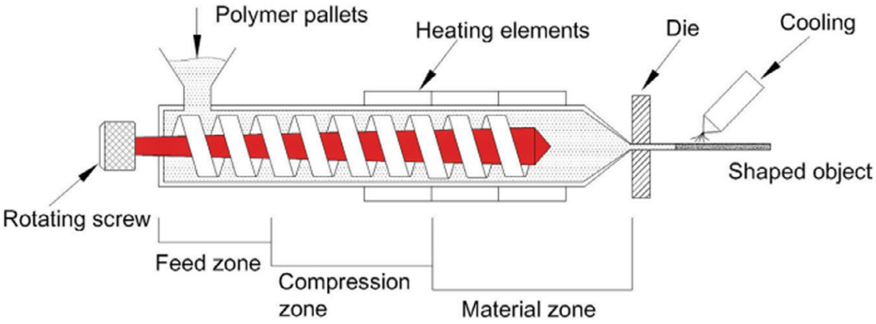


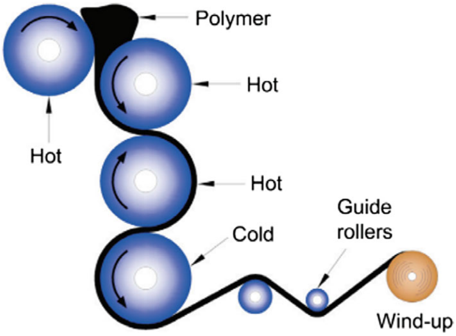
Fig. 24 Representation of extrusion molding process

compressed by the screw action. The molten material is then transferred to the material zone, where the screw's helical flight gives it a steady flow rate. The melt then enters the die and exit it with the desired profile due to the pressure limitations in this region. In order to maintain the required profile of the product, the die is quickly cooled down. The product is then either sliced to the required length or rolled up.

5.4 *Calendaring*

Calendaring is an important process for producing polymeric films and sheets. The process is depicted in Fig. 25, which shows passage of a plastic compound through a sequence of hot rollers. The sheet formed then passes through a series of cold rollers and a uniformly chilled sheet emerges from these rollers, which is then wound-up on a spool. Thickness of the sheet is controlled by maintaining the pressure and adjusting speed of the take-up rolls.

Fig. 25 Preparation of sheet/film by calendaring process



6 Applications

The polymer business is one of the fastest-growing industries in the world thanks to its rapid growth and diversification. These days, polymers are essential to thousands of items, such as adhesives, coatings, elastomers, and plastics. Polymers are therefore widely used in everything from high-tech aerospace applications to compact CD [22–25]. Some typical application areas of polymeric materials are shown in Fig. 26.

6.1 Space

Due to their superior mechanical, thermal, electrical, and thermo-optical properties over other materials, as well as their high strength and low weight, polymers are widely employed in aerospace and aircraft building. These polymers are essential to the construction of several spacecraft parts, including adhesives, instrument pieces, body panels, and windows. Prominent polymers that are employed for these uses are nylon, PVC, silicon, epoxy, etc. These polymers were selected because of their benefits over metals. Since silicon polymers greatly reduce airbag weight, NASA is also exploring silicon nanocomposite coverings for the Mars Exploration Rover airbags.

Electric motors and the interiors of airplanes also use PAE-TOR and PAE-COR because of their fire resistance. Rocket nose cones are made of silicon carbide and aluminum oxide fiber-reinforced polymers, whereas military aircraft parts and helicopter rotor blades are made of boron-fiber-reinforced polymer composites. Specifically, spacecraft in low Earth orbit are protected from the corrosive effects of atomic oxygen by using polyacrylene ether. Moreover, aircraft overhead passenger service modules use high-performance polymers such polysulfides.

6.2 Ocean

In marine applications, polymers are frequently used in place of metals because of their remarkable properties, which include high strength, low weight, and corrosion

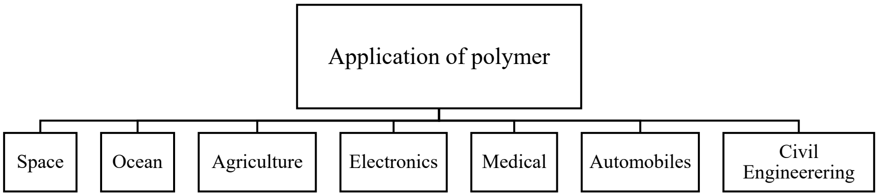


Fig. 26 Application of polymeric material in different field area

resistance. These materials are used to make gas masks, lifeboats, boat hulls, and passenger and naval vessels. Certain polymers fulfill a number of vital purposes: Glass/epoxy composites are used in cargo lines; PMMA is used as an optical fiber in the construction of underwater optical glasses; and PVC is used to make both fresh and saltwater pipes. Neoprene is essential to the manufacture of marine life-saving jackets. Ship propellers are also made of nylon and fiber-reinforced polymers, while ship hulls are made of epoxy resin reinforced with Kevlar fiber, which produces a lightweight composite with excellent rip resistance and impact strength [3, 26].

6.3 Agriculture

Polymers are often used in agriculture to improve the physical characteristics of soil and increase yield. These polymers, also referred to as soil conditioners, perform numerous vital roles. They lessen the need for frequent irrigation, stop soil erosion, and increase water efficiency. They also improve the performance of plants, especially during droughts. One typical soil conditioner is polyacrylamide (PAM), which is mostly used to stop soil erosion in its linear form. Conversely, cross-linked polymer–polymer (PAM) has the ability to absorb and release large volumes of water over time. Water retention granules, another name for gel-forming polymers, boost the soil's capacity to hold water, which lessens the need for regular irrigation. Another kind of polymer is hydrogel, which slowly releases water to plant roots after absorbing it. This increases the amount of moisture in the root zone and reduces the need for frequent irrigation. Hydrogels also lessen the amount of fertilizer that leaches. Soil conditioners soluble in water enhance the physical–chemical characteristics of soil, hence augmenting the total productivity of agriculture [27].

6.4 Electronics

Traditional polymers are usually not very good electrical conductors, but new developments have produced conducting polymers, which are more electrically conductive. Doping is a chemical process that converts polymers into their conductive state; oxidation and reduction processes are important in this approach. These conducting polymers are used in many different fields. For example, they are essential for the production of organic solar cells, which use sunlight to produce energy. They are also used in organic light-emitting diodes (OLEDs), which are frequently seen in digital cameras, watches, mobile phone displays, and television screens. In addition, the production of rechargeable batteries uses conducting polymers, providing a substitute for conventional lead-acid batteries. They also provide safe packaging for electronic circuitry, which is essential for the encapsulation of integrated circuits. Another kind of polymer used in liquid crystal displays (LCDs) seen in digital watches, televisions,

Table 1 Different type of polymer used in medical field

Sr No	Polymer	Application
1	Nylon	Used in sutures
2	Polyethylene	Disposable syringe
3	Polypropylene	Heart valves, blood filters
4	Silicone adhesives	Covering burns and making artificial skin
5	PMMA	Cosmetics surgery for reducing wrinkles and scars, dentures (color-matched to the patient teeth and gum tissue)
6	Acrylic Hydrogels	Grafting
7	PVC	Disposable syringe
8	PHEMA	Contact lenses
9	Polyurethane	Artificial heart, heart valves, blood filters

and other digital display devices is called liquid crystal polymer (LCP). These application areas highlight the importance of conducting polymers and other specialty polymers in contemporary technology [28, 29].

6.5 Medical

An important development in dental care occurred when gutta-percha was used as a filling material in the 19th century. Polymethyl methacrylate (PMMA) became a prominent substitute for artificial tooth fillings in 1909, providing improved functionality and durability. Synthetic polymers, such as polyester, polyamide, and polyethylene, proliferated in the 1930s and were shaped into a wide range of products, including fibers, adhesives, rigid structures, and soft compounds. These adaptable materials revolutionized healthcare practices around the world by opening up new avenues for medical applications, such as fillings, implants, and sutures [30] (Table 1).

6.6 Automobiles

The automobile sector has seen a notable increase in the use of polymers in a variety of components during the last century. These adaptable materials are now present in vital areas like body panels, windows, tires, engine parts, and instrument panels.

The remarkable combination of particular strength and stiffness that polymers display is one noteworthy benefit. This characteristic guarantees that structural elements remain strong while reducing weight, which enhances overall performance and fuel efficiency. Polymers also help in part integration, which makes it possible to combine several functions into a single component. This simplification improves overall efficiency while simultaneously lowering production complexity.

The ease of processing polymers is another important advantage. Polymers are very easy to mold and shape, unlike many metals, which allows manufacturers to create complex shapes and configurations. Additionally, their low density and subsequent lightweight nature enhance mobility and fuel efficiency. Another benefit that polymers provide is their affordability. Compared to some metals, polymers often imply reduced production costs, making them an economically viable choice for mass production in the automotive sector. Because of their low cost and high design and production flexibility, polymers are the material of choice for many different automotive applications.

A particular class of polymers called elastomers is essential to the production of tires. Tire performance can be improved by using a variety of variations, including Natural Rubber (NR), Polyisoprene Rubber (IR), Styrene Butadiene Rubber (SBR), and Polybutadiene Rubber (BR). These elastomers highlight the various uses of polymers in car engineering by enhancing traction, durability, and overall ride comfort [31, 32].

6.7 Civil Engineering

In addition to traditional building materials like metal, glass, wood, and stone, plastic materials are becoming more and more popular in the construction sector. Because of their outstanding performance qualities, they are now used in more building applications. Plastics are utilized in roofing materials, flooring systems, windows, doors, gutters, sealants, and adhesives, among other crucial building components. These adaptable materials are perfect for a variety of structural requirements because they are flexible and durable. Projects involving civil engineering also profit from plastics' adaptability. They are used in the construction of reinforced constructions, bridges, and sports and road surfaces. These infrastructure projects' lifetime and efficiency are increased by their sturdy qualities and lightweight design.

Innovations based on polymers broaden the range of uses for plastics in buildings. For roller shutters, gutters, and fences, PVC is reinforced with stabilizers and additives to provide durability under tough conditions. Insulation applications employ polystyrene extensively because it is thermally efficient and energy efficient. Plastic-infused composite materials are being used more often in construction projects for load-bearing applications because they combine strength and lightweight. Recycled plastics are also included in cement matrices to show a commitment to sustainability, minimizing environmental effects without sacrificing structural integrity. In cement, polymeric fibers work well as reinforcements to improve the durability and stability of the structure.

Polymer-based mortars and concretes are part of the protective coatings that shield buildings from environmental elements and prolong their service life. These developments highlight how plastics are influencing contemporary building methods and providing creative answers to the needs of the built environment [33, 34].

7 Technological Development and Future Trends

The future of polymers is inextricably linked to sustainability. Development and use of bioplastics derived from renewable resources, such as cellulose and algae, is increasing because of their biodegradable nature and are more sustainable alternatives to petroleum-based polymers. Furthermore, new technologies, such as carbon capture and utilization, are making strides in transforming CO_2 into polymer feedstocks, creating a potentially carbon–neutral industry. A considerable amount of research and industrial focus is on the improvement of recycling and upcycling techniques, in order to create a closed-loop system for polymer use and disposal.

Smart polymers, responsive to stimuli like temperature, light, or pressure, are paving the way for new applications. Imagine self-healing coatings, fabrics that adjust to temperature, or sensors embedded in medical devices using these materials. Nanocomposites, incorporating nanoparticles in polymers, can further enhance material properties such as strength, conductivity, and heat resistance. These advancements can revolutionize fields of aerospace, energy, and healthcare.

Polymer science is increasingly utilizing tools like computational modeling and 3D printing for precise design and control. This allows for the tailoring of polymer properties at the molecular level, creating materials with specific functionalities for targeted applications. Additionally, advances in micro and nanofabrication techniques are opening doors for miniaturized devices and structures made from polymers, pushing the boundaries of what's possible in fields like optics, electronics, and microfluidics [35].

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Ceramic Materials

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1 Ceramic Materials

Ceramics are in general compounds of non-metallic and metallic elements, including carbides, oxides, and nitrides. They are known for higher insulation, resistance to corrosion and environmental conditions, and capable of withstanding high temperatures. Unlike metals, ceramics materials generally display greater stiffness, lower electrical and thermal conductivity, and lower fracture toughness. A variety of ceramic materials are currently employed in industrial applications for their unique properties [1]. Table 1 shows the general classification of ceramic materials.

Traditional and advanced ceramics are two major ceramic materials, each with unique characteristics, properties, and applications. Traditional ceramics are typically composed of naturally occurring raw materials such as clay, silica, and feldspar. While advanced ceramics are generally termed technical ceramics as they are engineered with precise compositions of pure or synthetic raw materials, and processing methods to produce ceramic products with superior properties for a specific application [2].

Advanced ceramic materials show improved performance compared to metals and polymers in wear and high-temperature conditions due to their inherent resistance to chemical reactions. They are increasingly integrated into advanced engineering structures in various industries including energy, aerospace, biomedicine, and tool manufacturing due to their high hardness, strength, high heat dissipation, low thermal expansion, and biocompatibility.

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Table 1 General classification of ceramic materials

Ceramics	Conventional ceramics	Refractories (alumina, zirconia, magnesia)
		Abrasives (silicon carbide, boron carbide, aluminium oxide)
	Ceramic matrix composites	Enamels etc.
		Silicon carbide based CMCs
		Alumina based CMCs
		Mullite based CMCs
	Glass ceramics	Quartz
		Sapphire
		Zerodur
	Glass	Optical glass etc.
		Basic glasses
		Special variety glasses (float glasses, fibre glasses, alumina-silicate glasses etc.)

2 Ceramic Matrix Composites (CMCs)

Composites are multicomponent materials made of at least two or more constituent materials that have physical or chemical properties different from each other. The two main components of composites are matrix and reinforcement. The matrix provides shape and covers the constituents while the reinforcement contributes to the strength properties of a composite material. Based on Matrix, composite material can be classified into three major categories, i.e., Polymer Matrix Composites (PMCs), Metal Matrix Composites (MMCs) and Ceramic Matrix Composites (CMCs) [3].

Composite materials where the ceramic materials are used as matrix and reinforcements are called Ceramic matrix composites (CMCs). Ceramic materials generally display low-strength properties which are improved in CMCs with the addition of reinforcement. They are categorised as advanced materials and the preferred choice of material and design engineers where high-temperature stability, low thermal expansion, excellent mechanical properties, lightweight and resistance to wear and corrosion are requirements. CMCs can be classified based on the type of ceramic matrix, reinforcement, and manufacturing method. Table 2 shows the classifications of ceramic matrix composites [4, 5].

2.1 *Oxide-Based CMCs*

Oxide-based CMCs are primarily composed of oxide ceramic matrix reinforced with ceramic (alumina or zirconia) based fibre preforms to enhance their mechanical properties, including tensile strength and fracture toughness. Oxide-based ceramics

Table 2 Classification of ceramic matrix composites (CMCs)

Ceramic matrix composites (CMCs)	Based on ceramic matrix material	Oxide based CMCs
		Non-oxide based CMCs
	Based on reinforcement materials	Particulate reinforced CMCs
		Continuous fiber reinforced CMCs
		Staple fiber reinforced CMCs
		Whisker reinforced CMCs
	Based on manufacturing process	Chemical vapor infiltration (CVI)
		Liquid phase infiltration (LPI)
		Pyrolysis & polymer infiltration (PIP)
		Hot pressing
		Additive manufacturing

are known for their high-temperature stability and provide excellent thermal insulation properties. They are highly corrosion and thermal shock resistant and have found numerous applications in aerospace and power generation industries where the service conditions are harsh and operational temperatures are very high. Alumina (Al_2O_3), zirconia (ZrO_2), and mullite (Al_2O_3-SiO_2) based CMCs are the most common examples of Oxide-based CMCs [6].

Alumina-based CMCs offer high-temperature stability, low wear, and thermal shock resistance. They are commonly used in applications such as cutting tools, furnace components, and several aerospace components. ZrO_2 Matrix CMCs exhibit high-temperature resistance and unique phase transformation characteristics. They are used for thermal barrier coatings of turbine engines and fission reactors. Mullite-based CMCs are well known for their thermal shock resistance properties and have found applications as refractory materials. Yttria-stabilized Zirconia-based CMCs are valuable for their higher mechanical strength and toughness at elevated temperatures and have found applications in propulsion systems of aerospace structures [7].

2.2 *Non-oxide-Based CMCs*

Non-oxide CMCs are mainly composed of non-oxide matrices and reinforcements such as carbon, silicon nitride (Si_3N_4) and silicon carbide (SiC). These CMCs are known for their exceptional mechanical performance, low density, fracture toughness, thermal stability, and resistance to wear and corrosion at high operational temperatures [8].

SiC-based ceramics including SiC/SiC and C/SiC, are the most common non-oxide ceramics used in turbine engine components, including shrouds, nozzles, aircraft brakes, rocket nozzles and combustor liners. Si_3N_4-based non-oxide ceramics are valued for their outstanding toughness properties and have found several applications in aerospace components including blades, vanes, and engine parts. Boron Nitride (BN) based CMCs are known for high electrical insulation properties and are the preferred choice of material where high thermal conductivity and electrical resistance, such as in electronic components are required [9]. Aluminium Nitride (AlN) based CMCs exhibit improved thermal conductivity and electrical insulation and are used for electronic packaging and heat sink applications [10]. Titanium Diboride (TiB_2) display exceptional wear resistance and has found use in applications where the working temperatures are high and abrasive [11].

3 Reinforcements for CMCs

Ceramic materials require reinforcement due to their intrinsic brittleness and limited structural integrity in terms of mechanical strength. Reinforcement fibres are essential to avoid or obstruct cracks by deflecting them at the interfaces between the reinforcement and the matrix. Reinforced ceramics have gathered significant attention in automotive, aerospace and energy industries for their exceptional performance in extreme conditions. The reinforcement type and its distribution within the matrix influence the performance of CMCs. The selection of reinforcement and their placement design within the matrix is therefore of crucial importance. Different forms of reinforcing phases are used in CMCs such as particles, whiskers, platelets, continuous or short fibres [12].

For the selection of ceramic reinforcements, the criteria are generally based on factors including the mechanical, physical, and chemical behaviour of a reinforcement, its compatibility of with the matrix, processing method, availability, cost, operational conditions, end use and commercialisation. It is important to understand the matrix/reinforcement interaction as a weak interaction can hinder the load transfer between them resulting in poor mechanical performance of the CMCs [13]. Figure 1 shows a general criterion for the selection reinforcement for CMCs.

In ceramic matrix composites (CMCs), only the fibres that can withstand high process temperatures are used. Depending on the specific application, these fibres must display prolonged thermal stability, creep and oxidation stability. Organic polymeric fibres such as plant or animal fibres cannot be used in CMCs due to degradation at relatively lower temperatures (below 500 °C). Conventional glass fibres are also unsuitable as they melt or soften below 700 °C.

Reinforcements of ceramic, metallic, glass and polymeric nature are used in CMCs for various applications. These reinforcements can be of organic or inorganic nature.

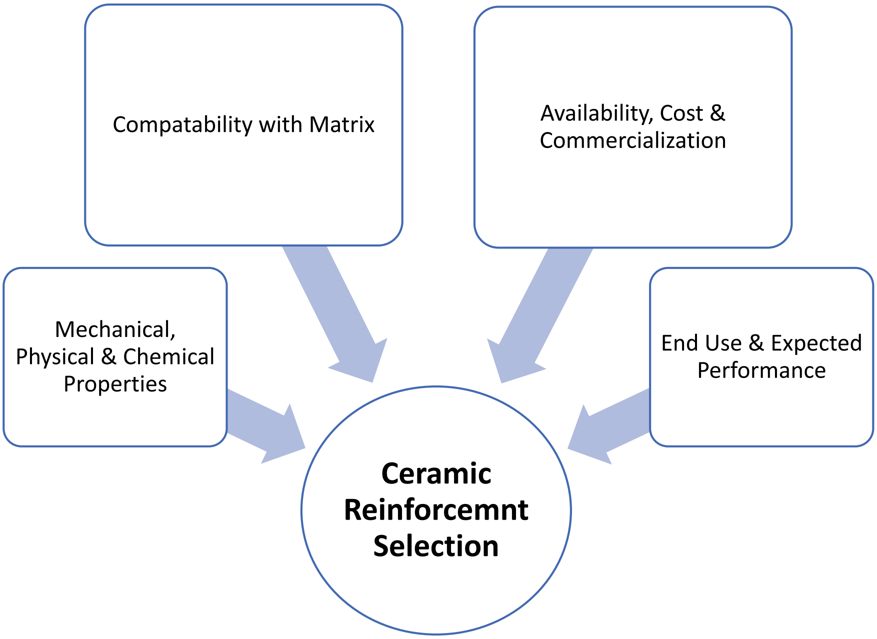

Fig. 1 Factors that are considered while selecting the reinforcement for Ceramic Composites

Organic materials are carbon-based compounds and can be found in natural, terrestrial, and aquatic environments. They are composed of organic compounds either derived from the remains or waste products of plants and animals or they can also be synthesized through chemical reactions without the involvement of life processes. Organic compounds-based reinforcement can be categorised into agricultural and industrial-based reinforcements. The ashes from coconut, ground nut shells, bagasse, eggshells, animal horns, tamarind leaves etc. are examples of organic reinforcement. Fly ash and red mud particles are examples of industrial-based organic reinforcements. These ashes from organic sources contain hard particles including Al_2O_3, SiO_2, Cr_2O_3, MgO, and Fe_2O_3 as major elements. The presence of hard phases enhances the hardness, thermal and strength properties of matrix material. Figure 2 shows the list of reinforcements that are generally used in various forms and shapes to reinforce ceramic materials. Polycrystalline or amorphous inorganic fibres and carbon fibres are suitable for reinforcing ceramic materials. "Ceramic fibres" refers to all non-metallic inorganic fibres (oxide or non-oxide) except those made by solidifying glass melts. Ceramic reinforcements such as oxides, carbides, nitrides, and borides contribute to higher modulus, strength, and wear resistance properties of the CMC [14].

Ceramic fibres produced through new routes such as sol–gel routes can be polycrystalline, partially crystalline, or amorphous in structure which has blurred the distinction between ceramic and glass fibres for CMCs. However, in terms of CMCs,

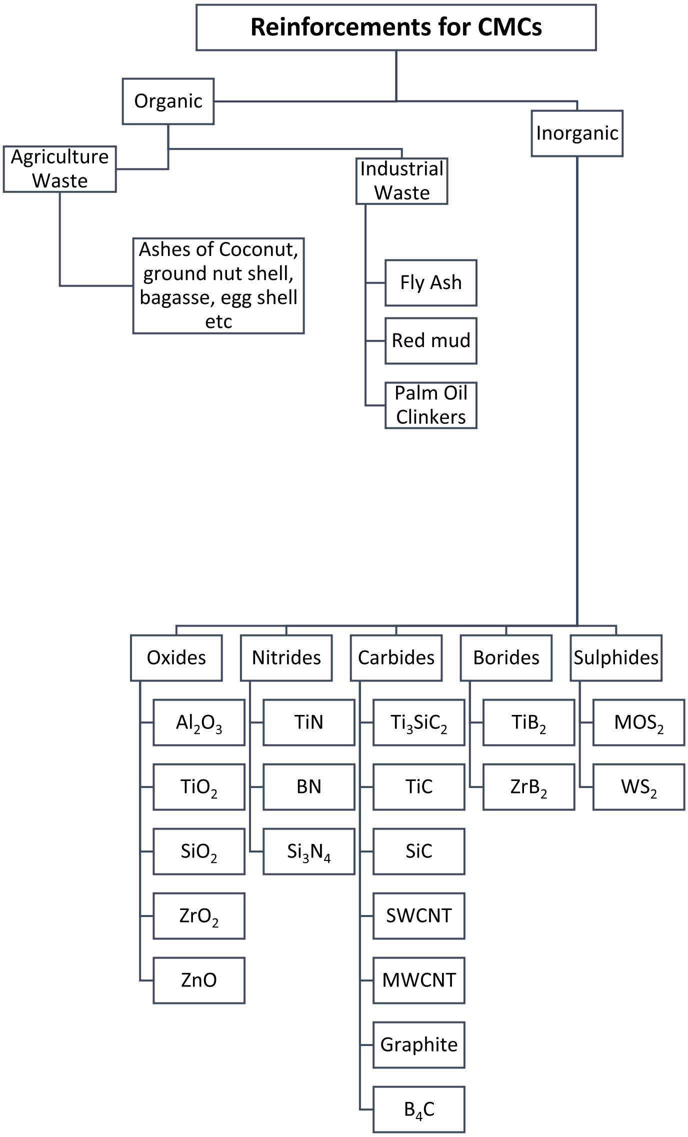

Fig. 2 Classification of reinforcements for ceramic matrix composites based on chemical nature [18]

the glass fibres refer to the fibres produced by solidifying typical glass melts based on silicate systems. They can also be differentiated from mineral fibres if the melts use minerals like basalt. Carbon fibres are used in CMCs under specific circumstances as they oxidise in ambient conditions above 450 °C, however, they remain stable in non-oxidizing conditions up to temperatures of 2800 °C. The use of carbon fibres in CMCs is an economical option and are protected using Environmental Barrier Coatings (EBC) to avoid degradation during processing and operation [15, 16].

Besides the fibre material, the structure of fibres also plays a vital role in the performance of fibres. Key manufacturing methods for high-performance fibres include melt spinning, dry spinning, and wet spinning, alongside variations of these processes tailored to specific requirements. The performance of fibres is highly influenced by the processing parameters such as spinning speed, dope concentration, draw ratio, PH, and temperature. For applications in CMCs, the oxide-based green fibres often require post-treatment before pyrolysis, annealing, and sintering to make them ceramic fibres. The ceramic of carbon fibres is generally coated with pyro-carbon or boron nitride as interphase between the fibre and matrix [15–17].

The mechanical performance of fibres is governed by three structural parameters including bond type, crystallinity, and molecular orientation. Within a fibre, compared to other bonds, ionic and covalent bonds can orient in one, two or three dimensions and have the highest energy content resulting in higher mechanical strength and modulus of the fibres. Based on bond type and spatial orientation, the ceramic and glass fibres with three-dimensional covalent or ionic bonds must have superior properties. However, these fibres are isotropic and lack molecular orientation, resulting in lower mechanical strength compared to carbon fibres. Carbon fibres have higher strength and modulus (moduli ~ 600 GPa and strength > 7000 GPa) due to their two-dimensional covalent bonds, pronounced crystallinity, and high molecular orientation within the fibre [16].

Practically, it is not possible to produce a perfect fibre structure that matches theoretical values. However, fibre spinning, and formation processes can be optimised to minimize structural flaws through improved process control. The high cost of ceramic and other high-performance fibres is mainly due to the complex manufacturing processes, not the raw material expenses.

The shape, form, and pattern of placement of reinforcements within the matrix play a crucial role in determining the mechanical, thermal, and overall performance of CMCs. Reinforcements can be used in the shape of continuous filaments, particulates, whiskers, and short fibres while they can be placed in random, unidirectional (UD), Bidirectional (2D) or multidirectional orientations. For laminated CMCs, the reinforcements are utilised in the form of UD, 2D, 3D woven, and nonwoven sheets [19].

Continuous filaments are preferred where superior strength and stiffness properties are required. SiC, Boron, Carbon and Alumina fibres are the most common ceramic reinforcements that are used in continuous filament form. Particulate reinforcements enhance properties like hardness, wear resistance, and toughness. Some of the most common particulate reinforcements used in CMCs are Silicon Carbide (SiC) particles, Silicon Nitride (Si_3N_4) particles, Zirconia (ZrO_2) particles, Aluminium Nitride (AlN) particles, Boron Carbide (B_4C) particles and Titanium Diboride (TiB_2) particles [20]. Table 3 shows the overview of shapes and orientation of reinforcements that are generally adopted in the manufacturing of CMCs.

Table 3 Classification of reinforcements for CMCs based on shapes and orientation in the ceramic matrix

Reinforcements for ceramic matrix composites (CMCs)	Shape	a. Particulates
		b. Laminates
		c. Continuous fibers
		d. Chopped fibers
		e. Whiskers
	Orientation	i. Unidirectional
		ii. Bidirectional
		iii. Multidirectional
		iv. Random
		v. Fabrics
	Form	i. Non-crimp UD/MD fabrics
		ii. Woven UD/MD fabrics
		iii. Nonwoven Mats
		iv. Rovings

CMCs can also be reinforced with ceramic reinforcements in the form of whiskers, which are short, single-crystal fibres. Alumina, SiC and Silicon nitride-based whiskers are generally used in CMCs to improve fracture toughness and wear resistance. Short ceramic fibres, such as SiC, Carbon and Alumina chopped fibres, are dispersed within the ceramic matrix. The resultant composites offer a balance between strength and toughness [19–21].

4 Manufacturing of CMCs

CMCs are set of composite materials aimed to address the issues of conventional ceramics, such as silicon carbide, alumina, silicon nitride, aluminium nitride, and zirconia, which tend to fracture when subjected to mechanical and thermo-mechanical loads. CMCs offer improved mechanical and thermal properties even sometimes surpassing conventional superalloys employed in advanced aeroengines. The CMCs are manufactured through sophisticated techniques which are based on the specific requirements of the product. Several factors are involved in the selection of a manufacturing technique for a CMC including material properties, type and form of matrix and reinforcement, complexity of shape, processing speed, density and porosity requirements, ceramic composition control, availability, cost, and the end use of the CMC product [20].

Chemical Vapor Infiltration (CVI), Liquid Phase Infiltration (LPI), Pyrolysis and Polymer Infiltration (PIP), Spark Plasma Sintering (SPS) and Hot Pressings are some of the major techniques that are currently in practice for the manufacture of CMCs.

4.1 Sol–Gel Infiltration

Sol–Gel infiltration is a ceramic matrix composite (CMCs) manufacturing process in which a chemical precursor is hydrolysed into a gel, which is then dried and fired to form a ceramic composition. Figure 3 represents the fundamental steps of the Sol–Gel process for the manufacturing of CMCs. This technique is preferred for improved homogeneity, near-net shape fabrication, and low processing temperatures (below 600 °C). However, it requires multiple infiltration cycles and intermediate heat treatments to overcome excessive shrinkage and porosity of the matrix and improve densification during sintering and drying.

In this process, a Sol is prepared, which is a liquid colloidal suspension of fine ceramic particles formed through a chemical reaction, forming nanoparticles within a liquid (water or organic solvent). The precursor materials are typically water, alcohols, and metal oxides which stabilize the colloids containing discrete ceramic particles. The hydrolysis reactions result in an organometallic solution with polymer chains that contain metallic ions and oxygen. This solution, Sol, forms amorphous particles, creating a rigid gel. To produce CMCs, the reinforcement preform is infiltrated with the liquid sol as a matrix material. The sol easily infiltrates the porous structure of a preform due to low viscosity. The infiltration process is sometimes assisted with a vacuum or pressure. The sol is subjected to thermal treatment at elevated temperatures (~150 °C) to form a gel [22].

At elevated temperature sols containing organometallic compounds (e.g., alkoxides) polymerise through polycondensation or hydrolysis and convert them into a gel. The gel is then dried at temperatures around 400 °C to remove water, alcohol, and organic volatile components. The process of infiltration-gelation-drying is repeated multiple times to get the desired densification and to overcome the effect of shrinks during the gel drying step. Moreover, to improve the volumetric yield of the ceramic content of a Sol–Gel and reduce the crack formation additional ceramic particles are added.

The perform impregnated with Sol, termed prepreg, is placed in a Mold to achieve the desired shape and to consolidate the matrix. The prepreg in the Mold is sintered at the firing temperature to form the final ceramic part [22, 23].

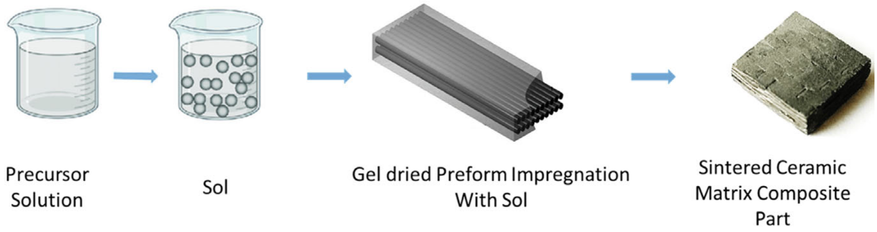

Fig. 3 Sol–gel infiltration technique to produce CMCs

4.2 *Electrophoretic Deposition (EPD)*

Electrophoretic deposition (EPD) is a well-known, simple, easy to adopt and cost-effective technique to manufacture fibre-reinforced ceramic matrix composites through the application of coatings on fibres or fabrics. Figure 4 represents the basic EPD apparatus for fabric coatings and composites fabrication. Aqueous or non-aqueous suspensions of submicron- or nano-sized ceramic particles are used to prepare the matrix in the EPD process. EPD is particularly effective for fully infiltrating tightly woven fibre preforms. It reduces processing times and improves control over the green body microstructure [24, 25].

During EPD, charged particles in a liquid medium move towards an oppositely charged electrode which creates a stable deposit through coagulation. In the case of non-conductive fibres, the fibre preform is placed in front of the deposition electrode, allowing the ceramic deposit to form on the electrode and grow around and through the fibre. EPD has been used in the manufacturing of various ceramic composites including laminated composites, composite coatings, whisker-reinforced composites, and functionally graded materials [26].

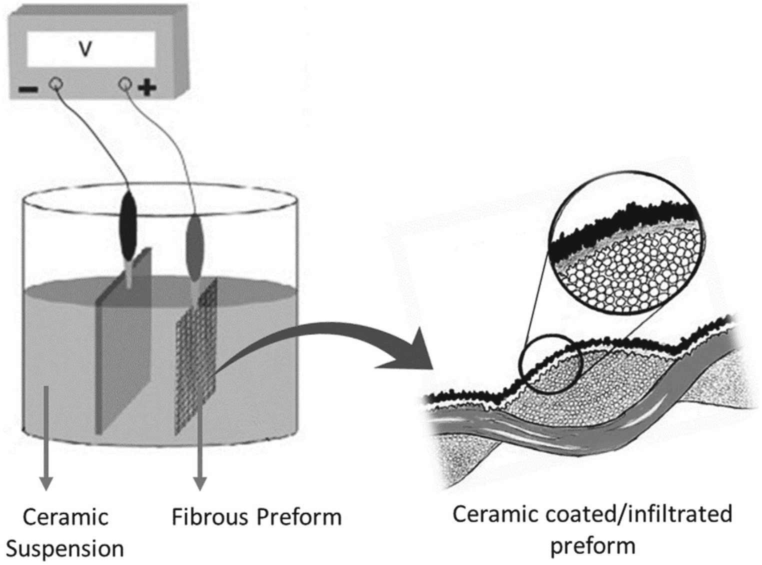

Fig. 4 EPD apparatus for fabric coatings and composites fabrication [25]

4.3 Chemical Vapor Infiltration (CVI)

CVI is a technique of fabricating a ceramic matrix in which reactive gases permeate and are deposited into a porous preform comprised of long continuous ceramic or carbon fibres. Before the introduction of the CVI technique, advanced ceramic composite manufacturing was limited to conventional processes such as castings and rolling where these processes have resulted in shrinkage and serious whisker damage. The CVI process is preferred in applications where the high control of the ceramic matrix composition, high-temperature performance, high purity, and complex part geometries are critical. In this process, matrix material in the form of gaseous precursor is infiltrated into the ceramic preform. The precursor reacts with solid preform and deposits as solid ceramic material under isobaric/isothermal conditions, covering the preform as a matrix [27].

The CVI process is generally used to produce silicon carbide matrix composites reinforced with continuous silicon carbide fibres which are termed SiC/SiC ceramic composites. Carrier gas streams such as H_2, Ar or He are used to deliver the vapour reagent to the preform. a mixture of Methyltrichlorosilane (MTS) as the precursor and hydrogen is used as the carrier gas to produce SiC matrix through the following reaction:

$$CH_3Cl_3Si \rightarrow SiC + 3HCl$$

The gaseous HCl is forced out by the carrier stream. To produce Carbon based matrix, methane (CH_4) precursor is used. The ceramic matrix deposition grows as long as the diffusing vapour reaches the reaction surface, filling the porosity with a solid ceramic matrix. With growing ceramic deposition, it becomes harder for the diffusion vapours to reach the inner spaces of the preform and eventually the precursor transportation is slowed down. The matrix densification stops when the preform surface pores are closed. The final residual porosity of the ceramic composites fabricated by the CVI method may reach 10–15% [28]. The following are the major variants of the CVI process:

- Isothermal/isobaric (I-CVI)
- Temperature gradient (TG-CVI)
- Isothermal-forced flow (IF-CVI)
- Thermal gradient-forced flow (F-CVI).

In the isothermal/isobaric (I-CVI) CVI process, the fibre preform is infiltrated at a uniform temperature and the reactant gas is supplied at a uniform pressure. This process is the most common CVI process but is slow-paced due to the low diffusion rate. In the temperature gradient (TG-CVI) process, the preform is kept at a temperature gradient during infiltration. The vapor precursor diffuses from the cooler surface to the hotter inner regions of the preform. Temperature gradient in preform is achieved by heating the top region of it when the bottom region is cooled.

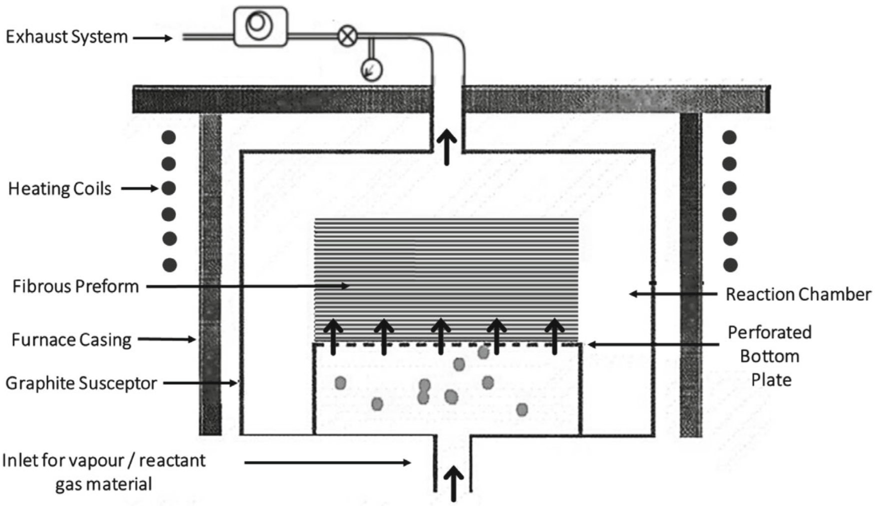

Fig. 5 Chemical vapor infiltration (CVI) Process Schematic [29, 30]

The gradient in temperature improves gas diffusion. The precursor gas decomposes in hot inner regions allowing the filling of inner regions first followed by the outer surfaces resulting in enhanced densification of CMCs. Isothermal-forced flow (IF-CVI) process employs forced flow through a pressure gradient to infiltrate the uniformly heated preform with the gas precursor to improve the densification of CMCs. The pressure gradient is determined by the difference in the pressures of the entering and exhausting gases. The thermal gradient-forced flow (F-CVI) process utilises the combined effect of temperature and pressure gradient to enhance the infiltration of the vapor precursor and achieve improved densification, Fig. 5.

The preform used in this process are generally porous ceramic fibres which serve as a structural framework for the desired ceramic composite while the gaseous precursor is based on the composition of the desired ceramic matrix and contains the elements required for the desired ceramic matrix formation. Organometallic compounds halides and common precursor gases are used in the CVI of CMCs.

A debonding interphase which is a thin (~0.1–1 μm) layer of pyrolytic carbon or hexagonal boron nitride (BN) is deposited on the fibre preform surface using the CVI method before the infiltration with a preceramic gaseous precursor. The preheated preform is placed in a CVI reactor and is infiltrated with the gas at temperatures ranging from 800 to 1200 °C. The deposition rate is governed by the parameters including gas flow rates, temperature, and pressure. At elevated temperatures, the precursor gases decompose into the constituent elements which react with the surface of the porous preform and deposit as a matrix material on the surface of preform till the surface pores of the preform are closed. The closed pores are machined to open the paths of the percolating network and allow the precursor gas to fill the pores and densify the matrix. To reach maximum densification, multiple reinfiltrating cycles followed by machining are employed. The final CMCs are coated with a protective layer to seal the surface pores to avoid penetration of environmental gases during service operation using the CVI method [31].

The disadvantages of the CVI process include low production rate, product size limited to the CVI chamber, resource intensive, high cost of equipment and complexity of precursor materials selection. However, CVI is a very versatile technique to process a wide range of ceramic compounds such as Carbon (C), Carbides (SiC, B_4C, and TiC), Nitrides (BN and Si_3N_4), Borides (TiB_2) and Oxides (Al_2O_3 and ZrO_2) [31, 32].

CVI processing materials find diverse applications across a broad spectrum of CMCs, including C/C, C/SiC, and SiC/SiC composites. These materials are valued for their exceptional attributes, such as high resistance to elevated temperatures and corrosive environments, damage tolerance, and toughness. As a result, they are used in various fields, encompassing heat exchangers, gas turbines, structural components within the aerospace industry, nuclear reactors, and heat engines [20].

4.4 Liquid Phase Infiltration (LPI)

The LPI process is cost-effective compared to CVI and allows the manufacturing of CMCs with complex shapes, controlled composition, uniformity, and improved density. Figure 6 represents the basic schematic of the LPI process. This process is also termed as Reactive Melt Infiltration (RMI) process. In this process, molten ceramic materials are infiltrated into the preforms under pressure, Fig. 6, or exploiting capillary forces as shown in Fig. 7.

The preform, composed of ceramic fibres or other reinforcement materials, is placed in the desired shape and orientation. The type and the placement of reinforcement define the shape, and the orientation of fibres influences the mechanical performance of the CMC product. The preforms have pores between the fibres or are

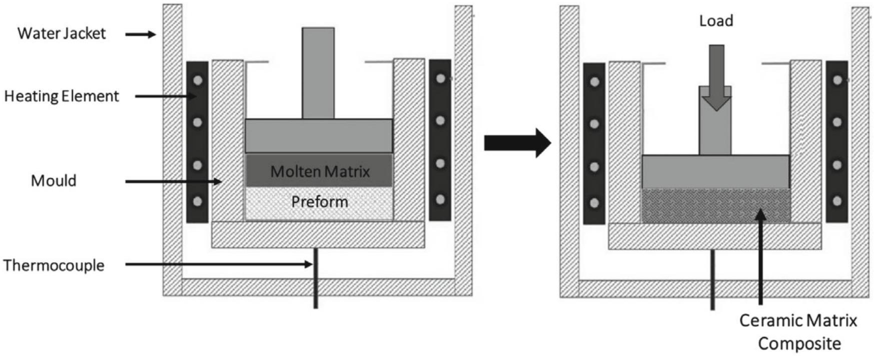

Fig. 6 Liquid Phase Infiltration (LPI) Technique Schematic [30]

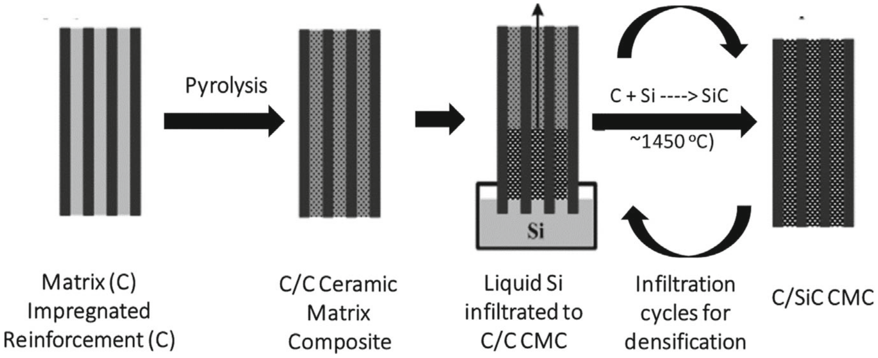

Fig. 7 Liquid Si Infiltration (LSI) Technique Schematic [30, 32]

imparted in the structure through weaving, knitting, braiding, layering etc. to receive the molten matrix [16, 33].

In the LPI process, a precursor material is prepared with the elemental composition desired for the matrix. The melting temperature of the precursor material is essentially lower than the selected reinforcement. The preform is placed in a high-temperature furnace and precursor material is added to the preform using pressure or sometimes through capillary action. The precursor material melts and liquefies at the elevated temperature and infiltrates into the preform through capillary action. The liquid precursor reacts with reinforcement fibres at their surface, fills the pores and develops the matrix component of the CMC. Upon cooling the liquid precursor solidifies, undergoes phase transformation, and forms a solid ceramic matrix.

To achieve the desired densification, multiple LPI cycles are adopted. Each cycle adds a new layer of matrix filling the unfilled spaces, increasing the density and integrity of the CMC. Post-LPI heat treatment or densification steps can be added to further improve the density and quality of CMC by removing the residual materials [33].

4.5 Polymer Infiltration and Pyrolysis (PIP)

The PIP process is a CMC fabrication technique that allows high-temperature pyrolysis of polymeric precursor infiltrated into the preform. The preform acts as a foundational structure for the ceramic composite and is typically composed of ceramic, metallic or other high-performance fibres. Polymer precursor, often in liquid slurry or solution form, is poured onto the preform to impregnate the reinforcement fibres. Figure 8 represents the general steps followed during the PIP process for CMCs.

The polymer precursor is selected based on the desired composition of the ceramic matrix and the end use of the CMC. Fibre preforms are impregnated with a soft preheated polymer and the solvent in the polymer precursor is allowed to evaporate or is

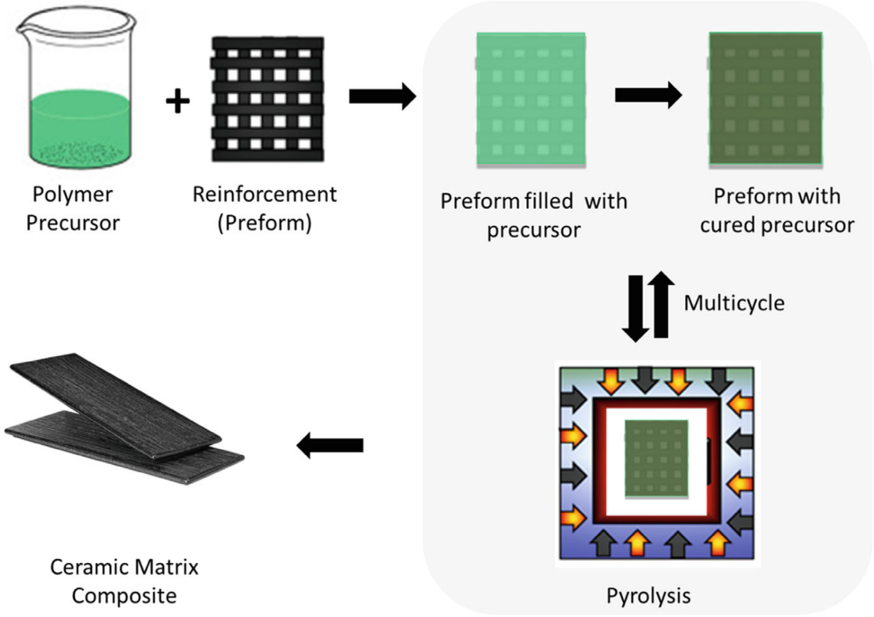

Fig. 8 Polymer Infiltration Pyrolysis (PIP) process for CMCs

cured allowing the polymer to solidify within the pores of the preform. The preform filled with solidified polymer precursor is subjected to high-temperature pyrolysis at 800–1300 °C in an inert or controlled atmosphere. During the pyrolysis process, the solid polymer precursor decomposes and converts into a material rich in carbon or ceramics. This process is also termed carbonisation, and it may involve the release of gaseous byproducts depending on the precursor composition. An inert atmosphere is maintained during the carbonization process to avoid oxidization or any unwanted reactions with air [34].

Pyrolysis causes shrinkage of the matrix material and formation of pores up to 40 vol.%. To avoid this problem, the PIP process in general requires multiple cycles of impregnation, solvent evaporation, and pyrolysis to achieve the desired density of the matrix in CMCs. CMCs produced with PIP may also require heat treatment to remove residual precursors and impurities. The PIP technique allows the fabrication of CMCs at relatively low temperatures and hence prevents fibre damage during the processing. Near net shape, CMCs with controlled matrix composition and microstructure can be produced with the PIP process. High production cost, high residual porosity, relatively longer production time and multiple infiltration-pyrolysis cycles are the major disadvantages of this process [35].

Applications for PIP-produced CMCs are found in the aerospace, automotive, energy, and industrial sectors. PIP-produced CMCs are used as engine components such as turbine blades, nozzles, aerospace structural components, thermal protection systems, and industrial components requiring high-temperature resistance and lightweight characteristics.

4.6 Hot Pressing

Hot pressing is a fabrication method to produce CMCs with relatively simple shapes through the consolidation of ceramic powders and fibres at high temperatures and pressure. Figure 9 illustrates the process steps involved in the hot pressing technique used to fabricate CMCs. Ceramic powders and reinforcement materials are carefully blended to achieve the desired composite composition. The powdered mixture is shaped into a preform using methods such as pressing, casting, or slip casting. This preform acts as the initial structure for the composite and is placed in a hot press where it is sintered. Sintering is carried out at high temperatures (ranging from 1000 to 2000 °C) and high pressures (often several MPa to GPa) in the hot press.

The sintering process allows the bonding of ceramic powders and reinforcement materials through a diffusion process resulting in a dense composite structure. The sintering process is followed by the solidification step which is achieved by slow cooling of the sintered part to room temperature ensuring the final form of the CMC [36], as shown in Fig. 9.

Hot-pressing fabrication of CMCs allows the manufacturing of high-density composites with fine microstructure, uniform composition, and high strength. The disadvantages of the hot press technique are the limitation to producing complex shapes, high equipment cost and high energy consumption. CMC produced with Hot pressing techniques has found applications in aerospace structures such as combustion chambers, nozzle throats, and heat shields in rocket engines, gas turbine components including turbine blades and vanes, High-temperature furnace parts like heating elements and crucibles, industrial cutting tools and Armor and protective systems [38].

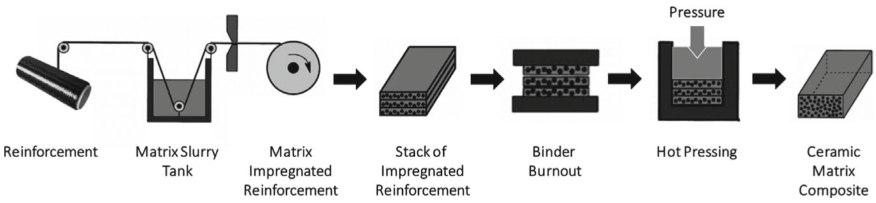

Fig. 9 Hot press (HP) technique schematic [37]

4.7 Spark Plasma Sintering (SPS)

Spark Plasma Sintering is an advanced technique to effectively bind fine-grained ceramic particles. It is an efficient process with rapid sintering times, higher heating rates, and lower sintering temperatures. Figure 10 presents the steps involved in the SPS method utilized for the manufacturing of CMCs. SPS techniques employ pulsed DC that passes through the ceramic powders, preform and the die generating sparks at the interfaces. The sparks cause a rapid increase in temperature allowing the sintering of ceramic powder. The spark effect pressure, electric field diffusion, and Joule heating promote the optimal particle densification in this process [39], as depicted in Fig. 10.

SPS is suitable for consolidating nano-powders, as its short sintering times avoid grain growth compared to conventional methods such as hot pressing, which require longer dwell times. CMCs produced with the SPS technique display improved densification consistency with ease of operation, reliability, safety, precise control of consolidation power, fast sintering rates, high heating rates, and lower

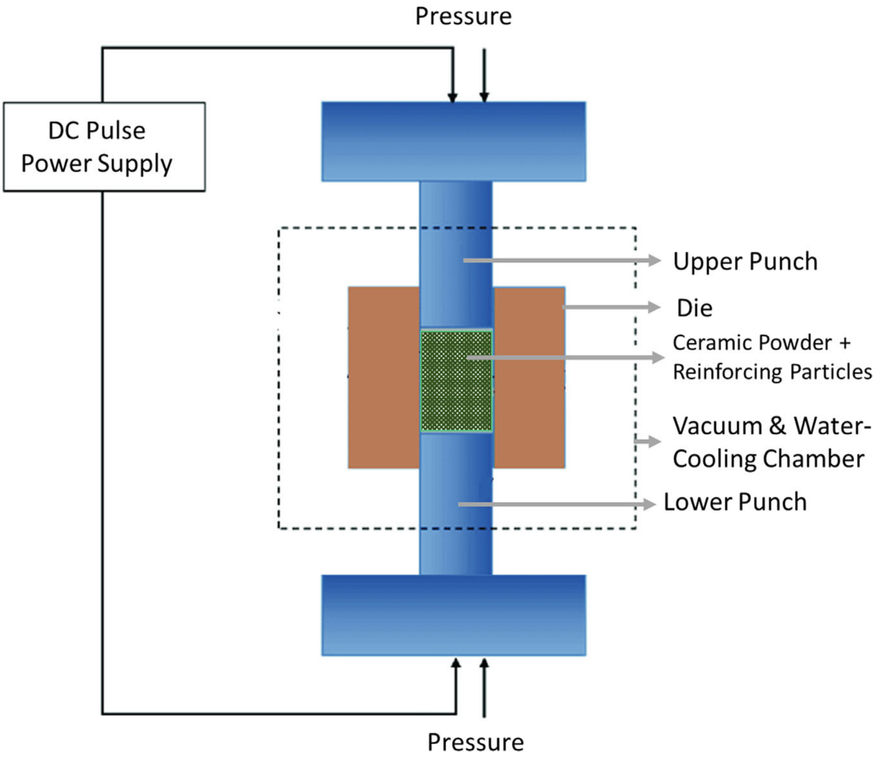

Fig. 10 Schematic for spark plasma sintering (SPS) technique [40]

sintering temperatures compared to other conventional ceramic manufacturing techniques[39, 41].

4.8 Additive Manufacturing (AM)

Additive manufacturing technologies, also known as 3D printing, or rapid prototyping, have been developing rapidly and have drawn and drawn great attention in the recent past. AM of CMCs has enabled the manufacturing of highly customized and complex parts with enhanced properties and functionality, compared to conventional CMCs. Different approaches are adopted by researchers for the additive manufacturing of CMCs.

The technologies for CMCs generally fall into two categories: Indirect Additive Manufacturing (Indirect AM) and Direct Additive Manufacturing (Direct AM). The indirect AM process is generally comprised of three steps: firstly, the template formation through AM methods followed by ceramic green body formation using traditional methods including slip casting, gel casting, slurry infiltration, PIP, CVI HP etc. The final ceramic composite is obtained by the sintering of green bodies. This approach reduces the cost of mold and allows the production of complex shapes that cannot be achieved with conventional techniques. Direct AM processes are used to produce SiC ceramic or green body through directly through additive manufacturing. The ceramic raw material is prepared, and part is produced through layer-by-layer addition of the raw material using the AM technique followed by debinding, sintering and consequent post-processing.

The Direct AM techniques are currently available in different configurations based on the state of raw materials. For powder-based raw material, selective laser sintering (SLS), Selective Laser Melting (SLM), Laser Powder Bed Fusion (LPBF), Binder Jetting (BJ), and 3D printing (3DP) methods are suitable. In the case of Wire or sheet-based raw materials, Fused Deposition Modelling (FDM) and laminated Object Manufacturing (LOM) are employed. For the paste-based raw material, robocasting, Extrusion Free Forming (EFF) methods are used. While for slurry or ink-based raw material, Stereolithography Apparatus (SLA), Digital Light Processing (DLP) and Direct Ink Writing (DIW) configurations are found suitable [42]. Some of these AM techniques are not yet commercially available for CMCs and are still in the development phase. Figure 11 represents the schematic drawings of SLS, SLM, LPBF and Binder Jetting additive manufacturing technologies for CMCs.

In the SLS method of additive manufacturing, ceramic powders are spread onto the forming platform. Product design is submitted through the AM program. A heat source (a laser or plasma) moves along a predefined path to irradiate the ceramic powders. The irradiation increases the temperature up to 60–70% of the melting point of the powder particles, causing sintering to occur. The ceramic powders are then spread layer by layer using a doctor blade and sintered sequentially, ultimately forming a 3D complex-shaped SiC ceramic component.

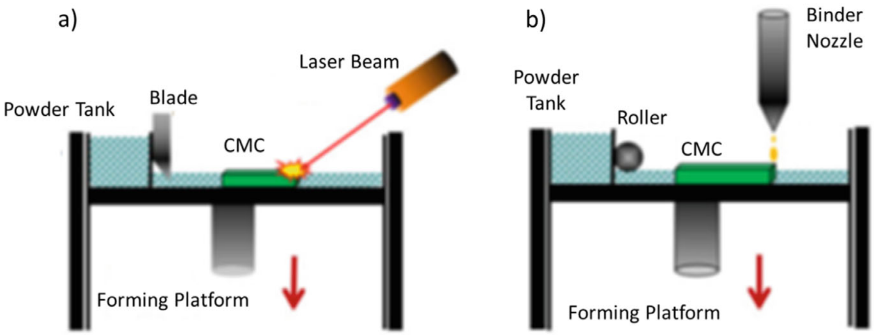

Fig. 11 Schematic drawing of various direct additive manufacturing technologies for CMCs: **a** SLS, SLM, LPBF; **b** binder jetting (BJ) [42]

The SLM method is very similar to SLS. The difference is that the temperature of the irradiated powders rises sharply to their melting point, causing them to melt and form a compact structure upon cooling. This process is also repeated layer by layer like the SLS until the final ceramic product is produced. Presently, SLM is limited to ceramics with low melting temperatures such as quartz and some oxide ceramics due to the limited power of heat source heads.

The LBPF method follows the same mechanism as SLS and SLM and involves a high-powered laser beam directed at the powder layer which selectively melts (or sinters) the powder particles, causing them to fuse. This method is also suitable for ceramic materials with low melting points.

The Binder Jetting (BJ) method involves the spreading of a layer of ceramic powder on the forming platform using a blade mechanism. An adhesive is sprayed through a nozzle onto selective areas of the powder layer as per the design. The forming platform is lowered slightly to allow a new layer of ceramic powder which is sprayed with adhesive at the designated points. The powder spreading and adhesive spraying cycles are repeated until a 3D green body of CMC is produced. The green body undergoes debinding to remove the adhesive followed by sintering at high temperature to achieve the final ceramic part.

The 3D printing process for CMCs involves the preparation of ceramic slurry with high solid content and specific viscosity with added binder material. The slurry is extruded through a nozzle of a specific diameter using mechanical or pneumatic force and is deposited on the forming platform. The movement of the nozzle follows the predefined path and allows the layer-by-layer deposition of slurry to produce a 3D ceramic green body. Debinding is carried out to remove the adhesive. The final ceramic product is produced after sintering. Figure 12 represents the schematic drawings of 3DP and FDM additive manufacturing technologies for CMCs.

In the FDM method, the ceramic powder is blended with a thermoplastic polymer material through extrusion and a thermoplastic polymer-ceramic filament wire with a defined diameter is produced. This wire is loaded into an FDM apparatus and extruded from a heated nozzle. The movement of the nozzle follows the designed path fed to

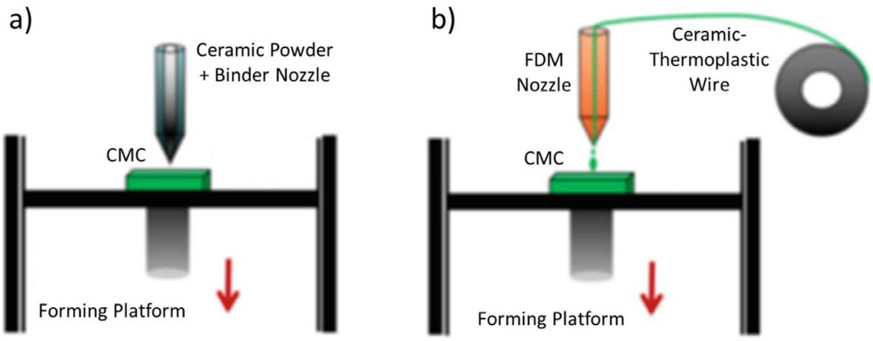

Fig. 12 Schematic drawing of various direct additive manufacturing technologies for CMCs: **a** 3DP, **b** FDM [42]

the FDM program and allows the layer-by-layer deposition of polymer-ceramic on the forming platform to produce a 3D ceramic green body. The thermoplastic-ceramic layers rapidly cool and solidify into a solid shape. This process is repeated through several fusion and deposition cycles as the forming platform gradually lowers. The final CMC component is obtained after debinding and sintering at high temperatures.

Figure 13 represents the schematic drawings of LOM, Robocasting, EFF and DIW additive manufacturing technologies for CMCs. The AM techniques, EFF and robocasting operate on similar principles. In this process, a ceramic paste with high solid content is prepared using ceramic raw materials mixed with solvents, dispersants, and other additives. The ceramic paste is extruded through a nozzle using mechanical extrusion or air pressure forming a 3D ceramic green body. The final CMCs are obtained through debinding and sintering at elevated temperatures.

Stereolithography (SL) technology for ceramics has emerged as a highly promising AM technique more recently. The process of SL for CMCs involves the preparation of photosensitive ceramic-resin slurry with high solid loading, low viscosity, and stable dispersion. Ceramic powders and dispersants are mixed with a resin system having photosensitive resin monomer and photoinitiator. The photoinitiator initiates the polymerisation of the photosensitive resin monomer and forms a cured polymer network to produce a 3D ceramic green body. The final CMC part is obtained after high temperatures debinding and sintering. Figure 14 represents the schematic drawings of SLA and DLP additive manufacturing technologies for CMCs.

SLA and DLP are the two variants of SL technology. The SLA process involves the use of a point light source to cure the resin. The light source is directed precisely to cure specific points in the resin layer by layer. DLP uses a space light source, similar to a digital projector, to project an entire image of the layer onto the resin. This allows the curing of a whole layer at once and makes the DLP process faster compared to SLA. The SLA method is slower as the light source traces the entire pattern for each layer which is time-consuming.

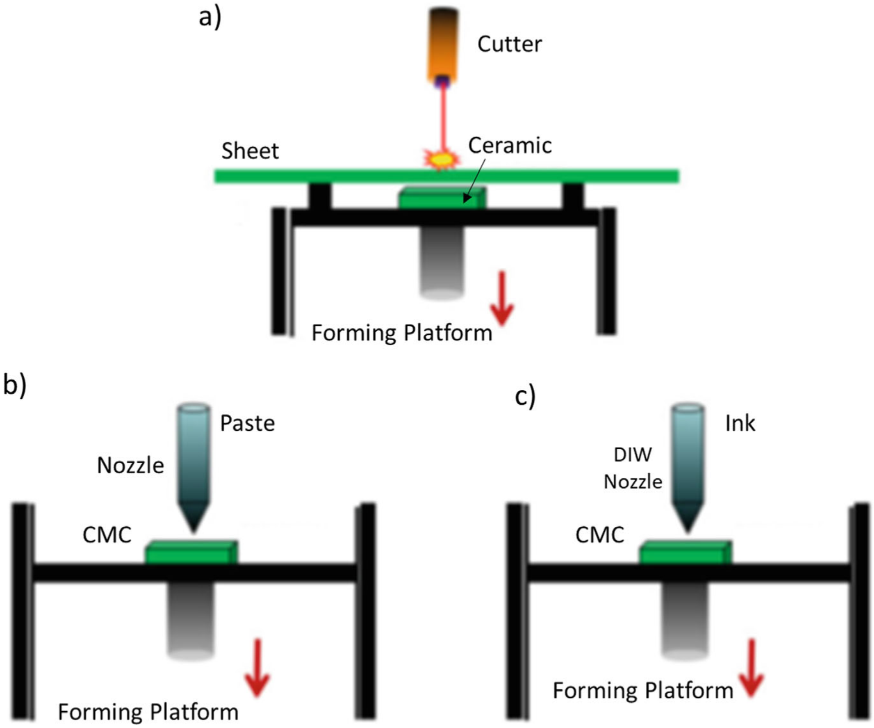

Fig. 13 Schematic drawing of various direct additive manufacturing technologies of SiC ceramic: **a** LOM, **b** robocasting, EFF; (c) DIW [42]

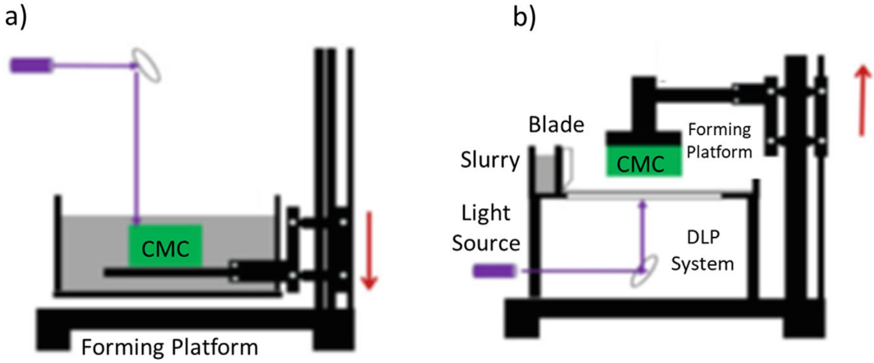

Fig. 14 Schematic drawing of various direct additive manufacturing technologies of SiC ceramic: **a** SLA, **b** DLP [42]

The DIW technique is similar to robocasting or Extrusion Free Forming (EFF). The robocasting and EFF use ceramic paste (with high solid content), while DIW uses ceramic ink (with low solid content). During the DIW process, ceramic ink is produced first by mixing a solvent and binder with ceramic powder. This ink is then printed through a nozzle to produce the desired 3D ceramic body. The structure is built layer by layer given the design. After the printing process, the ceramic body undergoes high-temperature debinding and sintering to produce the final CMC part.

5 Applications of CMCs

The ceramic matrix composites (CMCs) market is poised for remarkable growth, with forecasts indicating a substantial leap from USD 11.9 billion in 2022 to USD 21.6 billion by 2028, demonstrating an impressive Compound Annual Growth Rate (CAGR) of 10.5% [43]. Ceramic matrix composites (CMCs) are a unique innovation in material science and have found use in diverse industries. Through their distinctive combination of ceramic fibres and matrices, these materials have found extensive use not only in aerospace and energy but also in healthcare and other sectors. The remarkable attributes of CMCs, such as their ability to withstand high temperatures, exhibit robust mechanical strength, and resist corrosion, have catalysed a revolution in engineering and manufacturing solutions [41]. Figure 16 represents the images of CMC parts used in various industries. Following are some of the major application areas of CMCs.

5.1 Aerospace Industry

Ceramic Matrix Composites (CMCs) have gathered significant attention in the aerospace sector due to their unique properties tailored to meet the requirements of advanced aircraft and spacecraft structures. In aerospace operations, where components routinely operate at high temperatures, superior thermal stability and mechanical strength are vital for structural components. CMCs have become the preferred choice for critical components such as engine components and exhaust nozzles in aerospace vehicles. Aircraft components such as leading edges, wing flaps, and tail surfaces derive immense benefits from CMCs due to their lightweight nature and remarkable resistance to high-temperature environments. These materials are also useful in heat shields and thermal protection systems (TPS) for spacecraft, space shuttles, and re-entry capsules [44].

CMCs have shown a transformative impact on the aerospace industry, enabling the development of more efficient and dependable aerospace components. CMC-based aircraft brakes offer superior wear resistance, thermal stability, and enhanced braking performance. Nose cones constructed from CMCs are designed to withstand the frictional heating experienced at higher speeds by supersonic and hypersonic aircraft.

Fig. 16 Applications of CMCs in various industries [45]

CMCs are being explored for advanced propulsion systems, including scramjets and hypersonic engines. They have also found attention in the construction of exhaust nozzles for space launch vehicles and missiles, further highlighting their versatility.

In addition, CMCs are being considered for optical equipment in space missions, such as space telescopes, owing to their ability to maintain dimensional stability and optical performance in extreme space conditions. They are also instrumental in several satellite components, including communication antennas and solar array supports, as well as in space exploration missions, such as Mars rovers and lunar landers, where their exceptional capabilities play a pivotal role. The continued integration of CMCs into aerospace applications highlights their significance in advancing technology and enhancing the performance and reliability of aerospace systems [44, 45].

5.2 *Energy Industry*

CMCs are found effective in improving the efficiency, durability, and safety of energy production and utilization processes across various sectors, ranging from traditional power generation to renewable energy sources and nuclear power. Their ability to withstand extreme conditions and reduce maintenance requirements makes them a valuable asset in the energy industry.

In concentrated solar power (CSP) systems, ceramic matrix composites (CMCs) are utilized in solar concentrators and receivers to withstand the intense heat generated by concentrated solar radiation. These materials play a crucial role in enhancing the efficiency of CSP systems. Furthermore, CMCs find application in various components within nuclear reactors, where their high-temperature resistance and radiation tolerance are essential for ensuring safety and longevity. Specifically, they are employed in control rods, reactor fuel structures, and other critical parts within nuclear reactors. Additionally, CMCs are integral to the construction of industrial furnaces, kilns, and crucibles, where their ability to maintain structural integrity at high temperatures is vital for the longevity and performance of these high-temperature processing systems. In the realm of power generation, CMCs are utilized in boiler tubes that are exposed to extreme temperatures and pressures, owing to their exceptional resistance to thermal cycling and corrosion, making them a reliable choice for such applications [46].

CMCs are employed in advanced cooling systems for power plants, including high-temperature heat exchangers and cooling panels, contributing to improved energy efficiency within the power generation sector. Furthermore, CMC-based thermal insulation materials are employed in energy applications to minimize heat loss and enhance energy conservation in industrial processes and equipment. Additionally, CMCs are being investigated for potential use in wind turbine components subjected to high-temperature and mechanical stress, such as generator components and gearbox parts. Lastly, CMCs hold promise for applications in high-temperature electrolysis cells for hydrogen production, thereby contributing to the advancement of clean energy technologies.

5.3 Automotive Industry

The utilization of CMCs in automotive settings holds significant importance. These materials play vital roles in engine parts such as pistons, cylinder liners, and exhaust systems, contributing to weight reduction, improved fuel efficiency, and enhanced overall performance. Additionally, their application in high-performance brake systems serves to enhance thermal stability and decrease wear, consequently elevating the braking performance of vehicles [47].

5.4 Industrial Manufacturing

CMCs demonstrate versatile utility in industrial manufacturing, playing key roles across crucial sectors. They form integral components in high-temperature furnaces, kilns, and crucibles, exhibiting exceptional resilience in extreme thermal environments. In machining and metalworking, CMC-based cutting tools are essential, offering unparalleled resistance to wear and high temperatures, ensuring extended tool life and precision. CMCs also play a vital part in crafting chemical reactors, pumps, and valves, showcasing resistance to chemical corrosion and high temperatures, further cementing their significance in industrial settings [48].

5.5 Bio-medical Industry

CMCs have found several important applications in the medical sector, serving diverse needs. They are the preferred choice in orthopaedics and dental implants, offering biocompatibility, strength, and bone-like mechanical properties. Their durability and resistance make them valuable in dental prosthetics. CMCs also contribute to advanced medical imaging tech due to their resilience in harsh conditions, enhancing imaging capabilities. Additionally, their potential in crafting bioresorbable tissue engineering scaffolds offers hope for regenerative medicine [49].

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Metallic Materials

Azmah Hanim Mohamed Ariff and Dele-Afolabi Temitope Theophilus

Abstract Metallic materials play a pivotal role in various industrial sectors due to their exceptional properties and wide-ranging applications. This chapter provides an extensive analysis of the mechanical and physical qualities that come from the processing methods used to create metallic materials, as well as a thorough assessment of those methods. The processing techniques covered in this discussion include both liquid state and solid state modern procedures. The effects of each approach on phase composition, defect formation, microstructure, and grain size are assessed, as these factors have a major impact on the mechanical and physical properties of metallic materials. The purpose of this chapter is to help researchers, engineers, and practitioners understand the relationships between metallic materials' processing, structure, and properties. This will enable the development of advanced materials with customized properties for a range of applications in the engineering, aerospace, automotive, and other industries.

1 Introduction

The two main categories of metallic materials are ferrous and nonferrous. Ferrous materials are those with iron bases; nonferrous families comprise all other materials. Over half of the metallic materials division is made up of ferrous materials. Ferrous materials are classified into multiple subsections based on their significance and use in various applications. These include iron and steel, alloy steel, stainless steel, tool and die steel, and cast iron. Thermal treatments were usually applied to change the

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properties of these materials. The segmentation of the "nonferrous materials" family is once more determined by usage and significance. All other nonferrous materials are categorized under the nonferrous metals and alloys family, while aluminum, magnesium, and titanium metals and their alloys are classed under light metals and alloys. Several tiny groups fall under this subdivision: glass metals, solder materials, superalloys, noble metals, high temperature materials, and so on.

With a long history of use in industry, structural metal alloys are still very relevant today when it comes to creating multipurpose goods, parts, and structures. These include parts of airplane wings and fuselage, fuel, and cryogenic tanks, rocket bodies, wheel discs, engine mounts, vehicles, aluminum bridges and pipelines, air conditioners used in construction engineering, heat exchangers, railway car bodies, subterranean train frames and bases, and many more. The primary characteristic of these parts and assemblies is their ability to function over an extended period of time under specified loads; this is mostly dictated by the selection of an appropriate alloy that offers the required characteristics. The mechanical properties and overall performance of structures are not only determined by the alloy's chemical composition but also by a carefully chosen, superior processing technique. It is commonly recognised that adding alloying elements, metal fibres, or powders of different sizes and chemical compositions to metal parts can increase their strength [1–6].

The ability to include a variety of reinforcement materials and improvements in fabrication techniques allow metal matrix composites (MMCs) to be produced on a large scale for a wide range of applications. The MMCs are made of an alloy or metal matrix reinforced with ceramic, metallic, or organic compounds to improve their specific strength, stiffness, elastic modulus, resistance to wear and corrosion, thermal conductivity, and other qualities [7–11]. The amount of research conducted in the field of aluminum MMCs has increased significantly during the past ten years. At significantly lower production costs, these amalgamations are employed to replace metallic alloys in automotive parts like brake discs, drums, and pistons as well as aeronautical components like wings and fuselage [12, 13]. It is noteworthy that over the past forty years, a great deal of research has been done on MMCs, which has made it possible to overcome certain difficult technical problems such as matrix-reinforcement interfacial control, cost-effective processing, material design, and characterization [14, 15]. As a result, the military, ground transportation, electronics, and even certain leisure and infrastructure industries are using MMCs more regularly.

In this chapter, we will concentrate on the case of the metallic materials. The most recent details on the cutting-edge processing of various metallic materials, particularly metal matrix composites. The numerous characteristics of metallic materials are also covered in detail in this chapter. The chapter also discusses the numerous difficulties associated with metallic materials and their advanced application areas, along with technical advancements that address these issues.

2 Processing of Metallic Materials

With current technical developments, metallic materials can be produced using a variety of methods. The mechanical performance, including tensile strength, impact strength, hardness, fatigue, and cost-effectiveness, is significantly impacted by the fabrication procedures. After identifying some of the traditional methods for processing metallic materials such as casting, forging, extrusion, etc. this section offers an overview of the sophisticated methods that are now accessible for producing metallic materials, especially metal matrix composites. The fabrication procedures are categorized as illustrated in Fig. 1 based on the handling of the matrix in a solid or liquid state or others such as semiliquid or compo-casting.

2.1 *Solid State Processing*

Pure metals and their alloys can be produced via solid-state processing, and MMCs are also readily processed because of the bonding that occurs between the matrix and reinforcing materials as a result of mutual diffusion under pressure at high temperatures. MMCs produced via the solid-state approach can also be heated or cooled while being shaped by extrusion, forging, and other processes. The following discusses a few of the solid-state processing techniques that can be used to create MMCs.

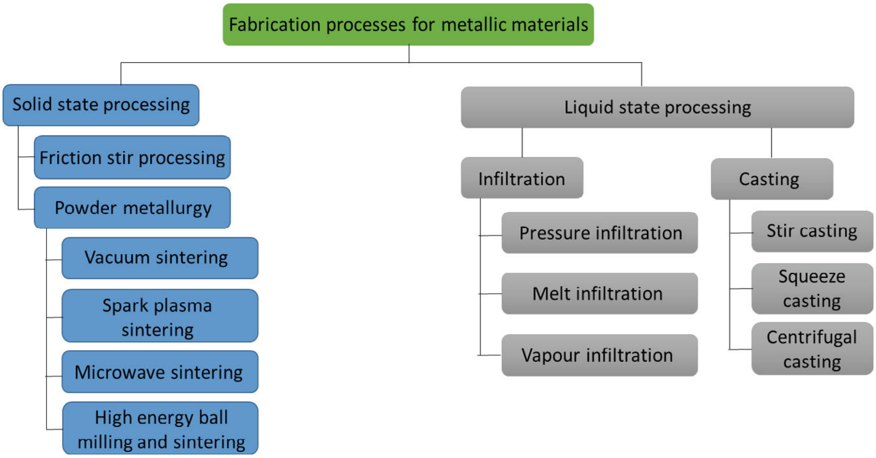

Fig. 1 Classification of fabrication processes for metallic materials

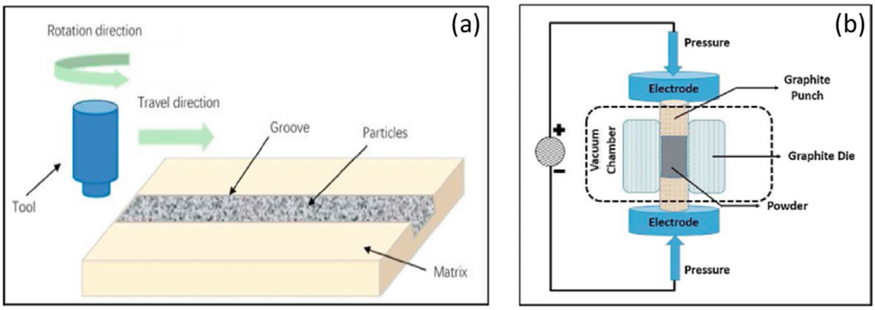

Fig. 2 Schematics for **a** friction stir processing, and **b** spark plasma sintering [16, 17]

2.1.1 Friction Stir Processing (FSP)

A recently discovered technique called FSP is utilised to prepare surface composites that result in finely tuned grain structures. Although it does not fuse two metal plates together, it is based on the idea of friction stir welding. It only provides an improvement in characteristics along with a change in microstructure. In FSP, a non-consumable tool with a pin and shoulder is agitated and inserted into the workpiece, creating a lot of friction in the process. The heat produced by the friction then causes the metals to become softer with plastic flow and finer grain refining. Friction stir processing is depicted in Fig. 2a. The alloy's strength and hardness rise as a result of the finely equiaxed recrystallized grains of uniform size that FSP develops into a subsurface gradient structure.

FSP has been used on aluminum [18–20] (Fig. 3), copper [21–23], titanium [24, 25], magnesium alloys [26, 27], steels [28, 29], and high-entropy alloys [30, 31] up to this point, based on data from the literature. The number of passes, traverse speed, and tool rotation rate all affect the FSP efficiency, which varies according to the kind of alloy. Using FSP, AA6061/Al_2Cu composites were created, and as a result of significant plastic deformation, the grain size became extremely small [32]. The AA7075/SiC nano- and micro-composites' hardness and tensile strength have increased, according to Kumar et al. [33]. The composites showed improved uniformity in the particle distribution and total elimination of pores as a result of the FSP. Grain refinement and nanostructure formation were noted by Wang et al. in pure copper during cryogenic friction stir processing, while high strength and electrical conductivity were attained by Bheekya et al. in Cu-Zr synthesized by FSP [34, 35].

2.1.2 Powder Metallurgy

The effective creation of Al-SiC composites using the spark plasma sintering (SPS) procedure was documented by Cavaliere et al. [36]. Aluminium particles are broken during heating by the SPS process' quick temperature and pressure rises, which results in localised metal-to-metal contact. There was a noticeable 34 and 26%

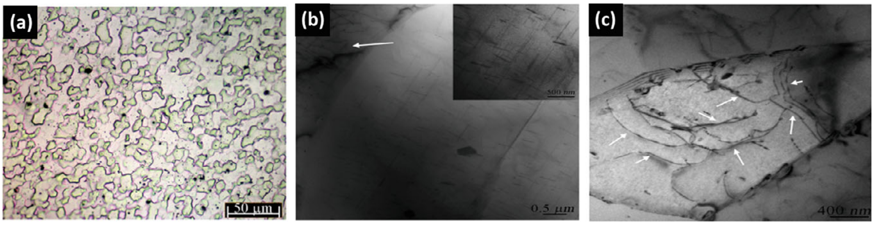

Fig. 3 **a** OM microstructure, and **b**, **c** TEM image of 6063 aluminum alloy processed using FSP [19]

increase in the hardness and tensile strength of the 6 weight percent SiC composites that were created. The three main factors that affected the SP sintering process were mechanical pressure, pulsed direct current, and quick heat transfer [37]. Figure 2b displays the schematic diagram for the spark plasma sintering procedure. According to Zhang et al. [38], at a specific temperature, vacuum sintering produced the best mechanical strength with the least amount of porosity. It was also discovered that the toughness and hardness of the sintered samples were influenced by the porosity and grain size.

A magnesium-based metal matrix composite (MgMMCs), namely Mg3Zn1Ca15Nb, was created using microwave sintering [39]. The authors also looked at the impact of a range of optimized microwave sintering conditions on the mechanical and physical characteristics of magnesium metal matrix composites. High energy ball milling was used to create the aluminum metal matrix composite reinforced with copper particles (3, 6 and 9 vol.%). Vacuum sintering (VS) and microwave sintering (MS) were then applied separately (Fig. 4) [40]. When compared to vacuum sintered specimens, the microwave sintered specimen showed superior mechanical properties and the highest hardness overall. Ball milling and sintering of Al–Mg alloy with SiO_2 particles were carried out by Bhatt et al. [41]. When comparing nano-composites to micro-composites, a higher hardness was noted. After twenty hours of mechanical alloying, it was found that the distribution of SiO_2 in the Al matrix was uniform and homogeneous.

2.2 Liquid State Processing

The liquid state method is widely used in many sectors to produce metallic products since it is simple and inexpensive. It consists of the solidification process after the reinforcing phase has been dispersed into the molten metal matrix for both alloys and composites. It can be broadly divided into two approaches: the casting method, which involves mixing molten metals directly with reinforced particles, and the infiltration method, which involves soaking the prepared reinforcement phase in the molten matrix.

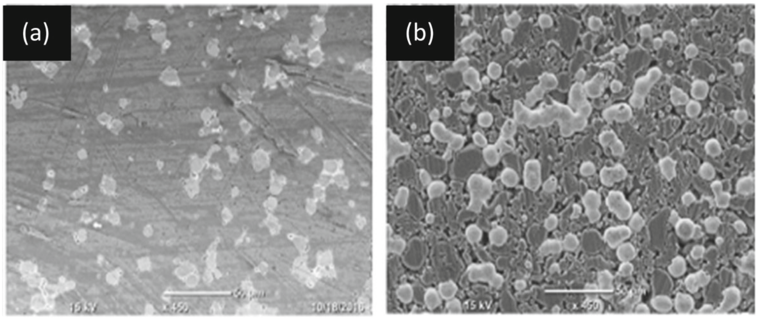

Fig. 4 **a** Microwave sintered and **c** vacuum sintered Al-Cu composite [40]

2.2.1 Infiltration Method

In order to produce Al-Si graphite MMCs, Narciso et al. [42] used the pressure infiltration process, taking into account that the material will be used as an engine piston. Figure 5a displays a schematic illustration of pressure infiltration. Yang et al.'s investigation [43] into graphene-reinforced Al MMCs revealed a 93% improvement in the composite specimen's tensile strength following extrusion. The pressure infiltration technique yielded the composite with the best possible quality without requiring the matrix and reinforcement to be wet. Metal infiltration of Ni-doped freeze-cast TiC preforms with a Cu melt was effectively used to create nacre-mimetic laminated Cu/TiC composites [44]. The pore flaws within the TiC lamellae were completely removed by Ni doping through the carbothermal reduction of NiO, which also improved the Cu/TiC interfacial bonding. This led to a considerable improvement in mechanical characteristics and electrical conductivity.

TiC, Fe, and Al were used to create a lightweight composite with a high reinforcing content [45]. After gently pressing the TiC and Fe preforms, molten Al was poured into them, creating a primarily two-phase matrix known as FeAl and Fe. The

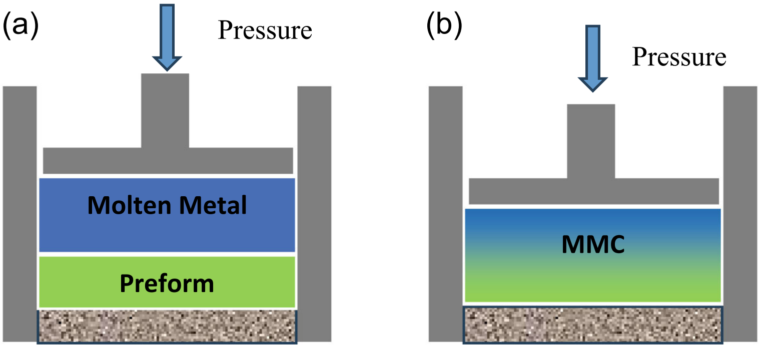

Fig. 5 Schematics for pressure infiltration **a** before, and **b** after

composite may find utility in armour and lightweight aerospace applications due to its enhanced microstructure and toughness. Using prefabricated silicon carbide fibres reinforced with SiC matrix, Tao and Wang investigated the vapour infiltration approach and discovered exceptional thermal conductivity [46]. Using reactive gases at high temperatures, molten metal infiltrates prepared reinforcement during the vapour infiltration process. In a new tungsten fiber-reinforced tungsten composite made by chemical vapour infiltration, Riesch et al. showed improved toughness and steady crack propagation [47].

2.2.2 Casting Method

The most fundamental and well-known method for producing metallic materials is casting. To obtain the appropriate casting for MMCs, the reinforcement, and molten metal are combined, then the mixture is put into a mould cavity and allowed to harden. Numerous auto parts, including the engine block, brake rotors, piston, connecting rods, and so on, are subject to this procedure. Soltani et al. [48] used the stir-casting process to create Al-SiC composites and found that SiC particles may be successfully incorporated when the stirring time and temperature are increased. At 850 °C stirring temperature, there was a 20% rise in modulus while the microhardness was enhanced nearly double. It was discovered that the parameters namely, temperature, stirring and holding times, and the kinds and sizes of reinforcement were critical to the creation and characteristics of MMCs [49].

The feasibility of fabricating magnesium metal matrix nano composites (MMNCs) by the stir casting technique was investigated and assessed by Sathishkumar et al. [50]. The magnesium metal matrix nanocomposite demonstrated a more homogeneous dispersion of particles, leading to remarkably enhanced characteristics like tensile and compression strength at both ambient and high temperatures. The most straightforward and affordable liquid-state production method is stir casting. The non-uniform distribution of the particles resulting from inadequate wettability and gravity-regulated segregation is the sole issue with this technique. By adding degasser tablet to the molten material, this issue is resolved. In the case of the composite material casting, the porosity level is lower.

Melted metal is poured into a die in squeeze casting, and then a hydraulic press is used to forge the metal at high pressure. Squeeze casting was used by Lu et al. [51] to create Al/TiN composites, which demonstrated increased toughness due to ductile rupture and fracture deflection. Additionally, it was noted that as the Al content increased, the flexural strength and hardness decreased. A study was conducted [52] to examine the impact of particular pressure on the mechanical properties and microstructure of ZA27 compressed castings that have a high ratio of thickness to height. Zn-Al alloy ingots were made using 99.99% (mass fraction) pure aluminum, zinc, and magnesium as well as Al-50%Cu master alloys. The sample's makeup is as follows: Mass fractions: Al, 27.1%; Cu, 1.61%; Mg, 0.02%; Zn balance. Squeeze casting Zn-based (ZA27) alloy solidified under high pressure stimulates the main reaction, and as pressure increases, the fine microstructure is formed. The ZA27 alloy, which is a squeeze-cast alloy, has homogeneously dispersed Al and Cu components. By efficiently preventing dislocation motion, the uniformly dispersed high-density fine phase enhances the strength and flexibility of the squeeze-cast ZA27 alloy.

The process of centrifugal casting, which involves putting molten metal into a revolving mould and using centrifugal force to propel the metal outward and onto the mould surface, is widely employed to produce composites. The aluminum SiC MMCs piston was made by Huang et al. [53] using a centrifugal method. The SiC particles are concentrated near the piston head, which helps the piston's wear resistance and thermal expansion. The impact of centrifugal casting modification on the microstructure and mechanical properties of silicon bronzes was investigated by Garbacz-Klempka et al. [54]. By applying zirconium modification at the ideal alloy preparation and mould centrifugal velocity, it is possible to produce casts with a defined shape and reduce the amount of machining allowance. High densification, equiaxial grain orientation, and tiny grain size all contribute to the high strength qualities of these castings.

2.3 *Other Processes*

The method of creating a dispersed phase by an exothermic reaction between molten metal and reinforcing components is known as in-situ reaction synthesis. Their chemical reaction produced a strong interfacial connection with a homogenous microstructure. The mechanical and microstructural properties of Al6061/TiB_2 MMCs made by in-situ synthesis were examined by Ramesh et al. [55]. The homogeneous distribution of TiB_2 particles throughout the aluminum matrix was accompanied by a reduction in grain size due to grain refining. Its ductility was preserved but a greater tensile strength was noted (Fig. 6a).

In order to examine the microstructures and compressive strengths, Zn25Al3Cu/ZrO_2 particulate composites were later created by the compo casting technique, which involved introducing 1 and 3 weight percent of ZrO_2 particles of various sizes into the semi-solid melt of the base alloy [57]. The base alloy's main particles changed from being dendritic to non-dendritic throughout the compo casting process, giving them an elliptic shape. When compared to the parent alloy, the resulting ZA25/ZrO_2 composites showed a notable improvement in mechanical characteristics. Compo casting is an efficient method for creating MMCs because it combines a long production duration with a reduced processing temperature.

The semi-solid slurry is prepared for rheo casting, which involves transferring it to die casting for solidification. Using the RheoMetal™ technique to prepare slurry, four Al–Si–Mg–Fe alloys with Si contents ranging from 1.6 to 4.5 weight percent were rheo cast in a vertical high-pressure die casting machine [58]. Using this method, the globular α1-Al particles in the slurry had a homogeneous distribution of Si. As the amount of Al-Si eutectic phase rose, the phenomenon of dendritic development of globular α1-Al particles during secondary solidification increased concurrently with the final eutectic reaction. By using the accumulative roll bonding method, Rezayat

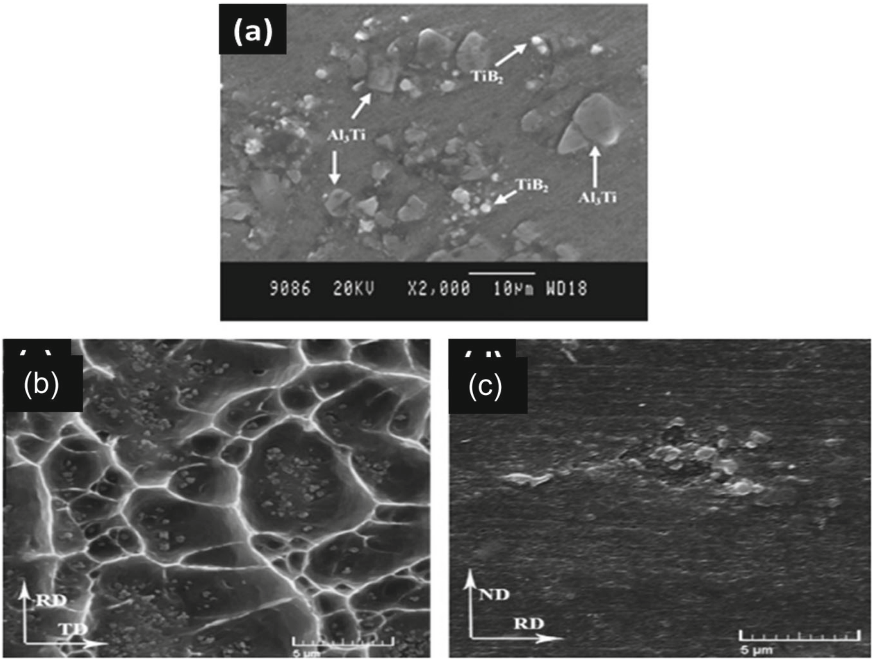

Fig. 6 **a** SEM image of Al6061/TiB$_2$ in-situ composite fabricated using liquid metallurgy route, **b** peeling surface and **c** side section of the Al/Al$_2$O$_3$ composite after six accumulative roll bonding cycles [55, 56]

et al. [56] created Al/Al$_2$O$_3$ composites (Fig. 6c and d). The composites' tensile strength was five times higher than that of the annealed aluminum, demonstrating a strong interfacial bonding between the matrix and reinforcement. The micrographs showed that the particle distribution throughout the matrix was uniform.

While most of the researchers had employed stir, squeeze casting, and powder metallurgy approaches among the previously stated methods, friction stir FSP is a newly developed technique to address a variety of casting-related issues, including porosity and subpar interfaces, among others. Table 1 lists the various MMC manufacturing processes along with their benefits, drawbacks, and appropriate use cases.

3 Physical and Mechanical Properties of Metallic Materials

The focus of research over the past few decades has switched from traditional metals and alloys to Metal Matrix Composites (MMCs), which have better characteristics and can be made lighter and more efficient for the needed applications. Particulates

Table 1 Manufacturing process for metallic materials and their application [17]

Process	Advantages	Limitations	Application
Friction stir processing	Superplasticity, high strength, reduced porosity, and good wear resistance characterize the fine-grain microstructure	The mechanics of the procedure are still unknown	Railways and aerospace application
Spark plasma sintering	The compaction stage is integrated with homogeneous sintering	Preferable for an uncomplicated symmetrical shape, costly procedure	Nozzle, arsenal, transmission conductor
Vacuum sintering	High productivity and uniform microstructure	Costly procedure because a vacuum chamber is required	Micro drills, cutting tools
Microwave sintering	Minimal sintering temperature, quick heating rate, and minimal energy usage	Beneficial only for materials with dielectric characteristics	Biomedical application
High energy ball milling & sintering	Even mixing, good flowability	Ball mills of superior quality are needed	Structural application
Pressure infiltration	Enhancement of wear characteristics, cost-effective for large-scale	Large casting is not recommended because of the high porosity	Motor housing, wheel, piston
Melt infiltration	Economical, able to produce complicated shapes, and capable of extremely high temperatures	Infiltration channel obstruction is caused by large pores and low temperature	Space and industrial application
Vapour infiltration	Reduced fibre damage, reduced residual stress, and increased mechanical strength	High porosity, slow process rate, expensive production	Heat exchangers, burner tubes
Stir casting	Easy to use and appropriate for large-scale manufacturing	To induce improved characteristics, a secondary procedure and appropriate stir parameter control are needed	Cylinder heads, pump housing
In-situ reaction synthesis	High temperature applications and outstanding mechanical strength are the outcomes of strong interfacial bonding	Decreased ductility	Automobile application

(continued)

Table 1 (continued)

Process	Advantages	Limitations	Application
Squeeze casting	Reduced porosity and casting flaws, enhancing homogeneity	Higher production costs as a result of more setup and difficult shape restrictions	Piston, connecting rod, engine block, pump case, fuel pipe
Centrifugal casting	Greater mechanical strength, less porosity, and a denser grain structure than stir-casting	Internal components could have certain flaws	Piston, brake rotors, nozzles
Compo casting	Enhanced wettability and even dispersion	Porosity, parameter control is required	Manufacturing of gear
Rheo casting	Porosity-free, complicated casting, well-finished surface, and strong wear resistance	Expensive	Tribological application
Accumulative roll bonding	Superior tensile strength and resistance to corrosion	Low production rate and high cost as a result of applying a hefty load	Structural applications, especially in construction and marine, etc.

in the micro- and nanoscale form reinforced MMCs are the subject of a comprehensive investigation for the evaluation. The mechanical and physical characteristics of several particle-reinforced composites are disclosed. A thorough discussion is held regarding many metals and their alloys, including but not limited to Al, Cu, Mg, Zn, and Ti.

3.1 Properties of Aluminum Matrix Composites (AMCs)

To make sure the manufactured composite's qualities are appropriate for the intended uses, it is crucial to assess them. Numerous studies have tried to evaluate the mechanical, physical, and tribological behaviour of different composites and have documented their findings. Aluminium and its alloys are essential to the manufacturing of MMC. AMC materials' high specific strength, stiffness, wear resistance, and dimensional stability give them additional advantages in a variety of specific applications. SiC and TiC are the main reinforcing particles that are taken into account. The specifics of the mechanical and physical characteristics of Al-based composites made with SiC and TiC reinforcing particles are displayed in Table 2.

Table 2 Comparison of properties of various Aluminum matrix composites

Reinforcement (% composition)	Density (g/cm^3)	Tensile strength	Hardness	References
SiC (5–20%)	–	80.84–94.21 N/mm^2	–	[59]
SiC (0–12%)	2.64–2.72	100–155 MPa	50–150 VHN	[60]
SiC (0.5–1.5%) B_4C (0.5%)	–	190–240 MPa	80–120 BHN	[61]
SiC (5–10%)	2.06–2.6	248–265 N/mm^2	85.3–87.2 BHN	[62]
SiC (0–20%)	–	28.45–77.56 MPa	24.5–45.4 HV	[63]
SiC (2.02–8.6%) Cu (1.67–5.82%)	–	95.98–138.8 MPa	48–95 BHN	[64]
SiC (0–10%)	–	–	28.5–60.3 BHN	[65]
SiC (0–15%)		54.3–65.1 MPa		[66]
TiC (3–7%)		175–232 MPa		[67]
TiC (5–15%)	2.81–2.93	127–144 MPa	59.6–99.6 HV	[68]
TiC (4%)	–	–	62.7 HV	[69]

3.2 Properties of Copper Matrix Composite (CMCs)

The development of the electrical and electronic sectors has increased demand for connector materials with high conductivity, high strength, and high wear resistance. Because of its great electrical and thermal conductivity, formability, and corrosion resistance, pure copper is widely utilised in those sectors. Although pure copper has certain benefits, its low wear resistance prevents it from being used in other applications, such as sliding. To address the issue, CMCs made by reinforcing different ceramic particles are being explored [26]. The physical behaviour of copper matrix reinforced composites with different particle and fraction compositions is displayed in Table 3.

3.3 Properties of Magnesium Matrix Composite

Researchers have turned their attention to magnesium-based composite materials as a result of the industry's growing requirement for a lightweight, high-performance material [72]. Superior qualities are retained by lightweight magnesium, including enhanced structural qualities and higher machinability with extremely low density. This satisfies the requirements of energy-saving and pollution reduction, making it appropriate for the transportation industry and other automotive applications [73, 74]. Table 4 lists the characteristics of magnesium alloys and composite materials containing magnesium.

Table 3 Comparison of properties of various copper matrix composites

Reinforcement (% composition)	Density (g/cm^3)	UTS (MPa)	Elongation (%)	Tensile toughness (J/m^3)	Hardness	Wear rate (mm^3/min)	References
Unreinforced Cu	8.84	150 ± 4	30 ± 1.2	10 ± 0.5	20 HRC	–	[70]
5% steel chips	8.805	235 ± 5.5	27 ± 0.8	29 ± 0.4	25 HRC	–	[70]
7.5% steel chips	8.775	–			30 HRC	–	[70]
10% steel chips	8.655	–			31.5 HRC	–	[70]
10% Al_2O_3	8.139	200 ± 6	10 ± 1.0	8 ± 0.6	24 HRC	–	[70]
12% SiC	–	–	–	–	116 VHN	245	[71]
12% TiC	–	–	–	–	126 VHN	225	[71]
12% B_4C	–	–	–	–	135 VHN	213	[71]

Table 4 Comparison of properties of Mg-based materials

Reinforcement (% composition)	UTS (MPa)	Ductility (%)	References
Unreinforced Mg	258	7.7	[75, 76]
2% Cu	335	2.5	[72]
4% Cu	386	1.5	[72]
7% Cu	433	1.0	[72]
2% Ni	370	4.8	[72]
3% Ni	463	1.4	[72]
6% Ni	313	0.7	[72]
2% Ti	248	11.1	[72]
4% Ti	239	9.5	[72]
AZ91	358	7.2	[72]
AZ91/4%Cu	382	6.2	[72]
AZ91/10%SiC	152	0.8	[75, 76]
AZ91/15%SiC	289	0.7	[75, 76]

3.4 Properties of Zinc Matrix Composite

The major reason zinc-aluminum (ZA) alloy is utilised is because of its special properties. When compared to SAE 660, phosphor-bronze, and cast iron, ZA alloy is a viable bearing alloy that improves mechanical and tribological properties. When

Table 5 Physical and mechanical properties of Zn alloy and composites [78]

Materials	Density (g/cm^3)	Micro-hardness (HV)
ZA-27 alloy	4.82	119.8
ZA-27 alloy/1% Al_2O_3	4.59	124.5
ZA-27 alloy/3% Al_2O_3	4.32	127.3
ZA-27 alloy/5% Al_2O_3	4.12	132.7

compared to ZA alloy, the latter has a larger density [77]. Shivakumar et al. used stir casting and squeeze casting techniques to create the composite, which is made of ZA alloy reinforced with Al_2O_3 in different fractions [78]. As shown in Table 5, they have ascertained the density and microhardness of the alloys and composites.

3.5 Properties of Titanium Matrix Composite

Titanium and its alloys are rapidly gaining attention in research for a variety of uses, including the aerospace and automotive industries. In addition to being lightweight, these materials typically have desirable qualities including high specific strength, superior chemical resistance, and exceptional biocompatibility. They are the perfect choice for structural, chemical, petrochemical, maritime, and biological applications due to their mix of qualities [79, 80]. However, steel and Ni-based alloys have higher Young's modulus, wear resistance, and heat resistance than titanium materials [81]. Titanium metal matrix composites (TMCs) offer a substitute to get over these drawbacks. The characteristics of Ti alloy and composite materials based on Ti are displayed in Table 6.

4 Concluding Remarks and Future Trends

Processing metallic materials, particularly MMCs, presents several difficulties due to their highly variable characteristics. Thus, selecting an appropriate procedure for precise usage is always crucial. No specific parameters or situations have been found that can produce optimal outcomes. There is a dearth of literature available for the assessment and characterization of metal matrix nanocomposites. Furthermore, there are sufficient study voids concerning the dispersion phase utilisation of CNT and graphene. When processing the composites, material scientists will always be considering how to remove porosity. Metal matrix composites will always be linked to an increase in wettability that affects the mechanical properties of the bonding between the reinforcement and matrix. The alteration of the traditional procedure by altering its parameters necessitates extensive investigation.

Table 6 Physical and mechanical properties of Ti-based materials

Matrix material	Reinforcement (% composition)	Density (%)	Tensile strength (MPa)	Ductility (%)	Hardness	References
Ti	TiB (40–80%)	94.3–99.4	140–280	–	82.7–87.8 HRA	[82]
Ti-6Al-4 V	20% TiB	–	1215	0.5	–	[83]
Ti-4Fe-7.3Mo	10% TiB	99.6	–	–	–	[84]
Ti-22Al-27Nb	6.5%TiB	–	1260	2.3	–	[85]
Ti	5%TiB + (1.17–8.64%)Y_2O_3	–	–	–	38–52.5 HRC	[86]
Ti	Carbon fibres (8–10%)	99	674	–	214 HV	[86]
Ti	35% SiC fibre	–	1163	–	–	[87]
Ti	CNTs (0.18–0.35%)	–	682–754	34.2–38.1	275–285 HV	[88]
Ti-6Al-2Zr-1Mo-1 V	TiC (5–15%)	–	806.4–925.9	1.23–4.32	–	[89]
Ti	MLGs (0.5–1.5)	–	–	–	15.4–14.54 GPa	[90]
Ti	B+ (1–6vol%) CNTs	96–99.3	–	–	25–33 GPa	[91]
Ti	0.5vol% B_4C	–	916	2.6	–	[92]

The stir casting method is the most straightforward, least expensive, and versatile manufacturing technique that may be applied to the mass production of metallic materials. Stir-cast MMCs can be extruded to improve reinforcement distribution and interfacial bonding. The wettability problems of the reinforcement particles with the molten matrix can be solved by preheating the particles before dispersion and by using flux. Due to density differences, agglomeration happens when particles float over the molten metal. This can be prevented by adding reinforcing particles in two stages. Particle distribution and wettability problems are more difficult to solve due to the larger surface area of nano-sized reinforcing particles. When dispersing particles with strong matrix-reinforcement bonding, ultrasonic treatment is beneficial. Better wettability in the reinforcement and matrix, as well as good particle dispersion and inhibition of chemical reactions between the molten matrix and reinforcements, are all achieved through the compo casting process. Squeeze-cast mono composites have better qualities than stir-cast hybrid composites and even squeeze-cast MMCs have superior properties than stir-cast hybrid composites. Segregation is hampered by the thermal spray process's quick solidification. Good wettability and a restriction on excessive interfacial reactions can be achieved by the infiltration technique.

Further consideration should be given to the sustainability of using mineral waste, bio-waste, and scrap as prospective materials for metallic material reinforcement while keeping environmental concerns in mind. Future research should focus on the grey area of using aluminium MMCs in biological applications that require them to be ultra-lightweight and biocompatible. Research on hybrid MMCs using ceramic, biofiber, and industrial waste is necessary to enhance the material's strengthening. By using mathematical modelling tools, there is also a large scope for the prediction of mechanical and wear parameters.

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Textile Materials

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Abstract Textile products are essential to a wide range of sectors and support modern living in many ways. Their adaptability makes them suitable for use in filtration systems, insulation, apparel, aerospace, naval, and composite reinforcement applications. With millions of jobs and a large GDP contribution from the worldwide textile sector, it is a vital economic engine for many nations. Because of their special qualities, textile materials are essential to daily life and a wide range of industrial uses. Textiles in clothes offer protection, comfort, and a way to express one's individual style. Advanced textile composites improve performance in the aviation and naval industries by providing strong, long-lasting, and heat-resistant solutions. By efficiently capturing impurities, textiles used in filtration systems enhance the quality of the air and water. Insulating fabrics support the preservation of energy efficiency in automobiles and buildings. Furthermore, textiles provide more adaptable, strong, and environmentally friendly packaging options than conventional materials. Innovations like smart textiles that can monitor health issues or adjust to environmental changes are the result of continuous research and development in the field of textile science. This invention emphasizes how crucial textile materials are to advancing technology and raising standards of living.

1 Introduction

Textile products are essential to a wide range of sectors and support modern living in many ways. Their adaptability makes them suitable for use in filtration systems, insulation, apparel, aerospace, naval, and composite reinforcement applications. With millions of jobs and a large GDP contribution from the worldwide textile sector, it is a vital economic engine for many nations.

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The earliest humans dressed themselves in natural fibers like flax and wool, which is when the textile history began. The ancient Egyptian, Greek, and Roman civilizations were among the first to grasp the art of producing textiles, and the discovery of spinning and weaving techniques represented a major breakthrough in this regard. The introduction of automated looms and spinning machines during the Industrial Revolution in the 18th century brought about a seismic shift in production capacity and efficiency. The 20th century also witnessed the emergence of synthetic fibers like polyester and nylon, which transformed the textile sector by providing new features and uses [1].

The worldwide textile business has grown significantly in the last ten years. The size of the global textile market was estimated by Statista to be at USD 1 trillion in 2023, and by 2025, it is expected to grow to USD 1.23 trillion. Both production and trade volumes have steadily increased in the business. For example, the total value of textile exports worldwide in 2023 was approximately USD 870 billion. The European Union, China, and India are important exporters; China leads the pack, making up around 40% of all textile exports worldwide. With an increasing demand for recyclable and environmentally friendly textile items, changes in production techniques toward sustainable and ethical standards have also had an impact on trade dynamics.

Because of their special qualities, textile materials are essential to daily life and a wide range of industrial uses. Textiles in clothes offer protection, comfort, and a way to express one's individual style [2]. Advanced textile composites improve performance in the aviation and naval industries by providing strong, long-lasting, and heat-resistant solutions. By efficiently capturing impurities, textiles used in filtration systems enhance the quality of the air and water. Insulating fabrics support the preservation of energy efficiency in automobiles and buildings. Furthermore, textiles provide more adaptable, strong, and environmentally friendly packaging options than conventional materials.

Innovations like smart textiles that can monitor health issues or adjust to environmental changes are the result of continuous research and development in the field of textile science. This invention emphasizes how crucial textile materials are to advancing technology and raising standards of living.

2 Categories of Textile Materials

Textiles are made of fiber-based materials. These fiber materials can be derived from minerals, cellulose, or proteins in a natural way. Below is a quick rundown of a few frequently used textile materials [3]. A summary of fibrous materials used in textiles is also provided in the Table 1.

2.1 *Cellulose Based Natural Fibers*

Most of these fibers are utilized in apparel applications [4]. Some of the commonly used cellulosic fibers include cotton, linen and hemp.

2.1.1 Cotton

The main constituent of cotton, which is made from the seed fibers of the Gossypium plant, is cellulose, a naturally occurring polymer that makes up 90–95% of the cotton fiber. Pectin, waxes, and other compounds are present in smaller amounts. Cotton is well-known for being breathable and soft, which promotes good air circulation and moisture absorption. As a result, cotton is incredibly comfortable for daily use in warm temperatures. It can store 24–27 times its own weight in water due to its great absorbency. Cotton is very robust and long-lasting; it keeps its integrity even after several washings. Being biodegradable makes it more aesthetically pleasing because it breaks down organically without disrupting the ecosystem. Cotton is a versatile material that can be used for many different things. Some of these products include undergarments, jeans, and t-shirts; household textiles like towels and bed linens; and industrial goods like filtration fabrics and medical supplies.

Table 1 Summary of fibrous materials used in textiles

Fibers	Summary
Natural fibers	
Cotton	Made from the seed fibers of the cotton plant, composed mainly of cellulose. It is soft, breathable, absorbent, durable, and biodegradable. Used in clothing and home textiles
Wool	Derived from the fleece of sheep and other animals, primarily composed of keratin. Known for insulation, moisture wicking, elasticity, and fire resistance. Used in cold weather clothing and home textiles
Silk	Produced by silkworms, mainly composed of fibroin. Known for its sheen, high tensile strength, smooth texture, and thermoregulatory properties. Used in luxury clothing and medical sutures
Linen	Made from the flax plant, composed of cellulose. It is strong, absorbent, quick drying, and durable. Used in summer clothing, suits, and home textiles
Hemp	Made from the Cannabis sativa plant, composed of cellulose, hemicellulose, and lignin. It is strong, breathable, moisture-wicking, and durable. Used in clothing, accessories, home textiles, and eco-friendly products

(continued)

Table 1 (continued)

Fibers	Summary
Synthetic fibers	
Polyester	Made from polyethylene terephthalate (PET). It is strong, durable, quick drying, and resistant to wrinkles. Used in clothing, home furnishings, and industrial fabrics
Nylon	Made from polyamides. Known for its strength, elasticity, abrasion resistance, and low moisture absorbency. Used in clothing, industrial products, and automotive components
Acrylic	Made from polyacrylonitrile. It is lightweight, soft, warm, and resistant to moths, chemicals, and sunlight. Used in sweaters, blankets, and outdoor textiles
Spandex	Made from polyurethane. Noted for its elasticity, strength, and resistance to perspiration. Used in sportswear, swimwear, and compression garments
PLA Fibers	Made from renewable resources like corn starch or sugarcane, composed of polylactic acid. It is strong, biodegradable, moisture-wicking, and breathable. Used in sustainable clothing, sportswear, packaging, and medical products
Regenerated fibers	
Rayon	Made from wood pulp or cotton linters. It mimics natural fibers, offering absorbency, softness, and drapability. Used in clothing, home textiles, and industrial products
Lyocell	Made from wood pulp using an ecofriendly process. It is strong, soft, absorbent, and biodegradable. Used in clothing, home textiles, and hygiene products
Modal	Made from beech tree pulp. It is absorbent, soft, and resistant to shrinkage and fading. Used in intimate apparel and loungewear
Advanced and technical textiles	
Carbon Fibers	Composed of carbon atoms in a crystalline structure. They are strong, lightweight, and heat resistant. Used in aerospace, automotive, sports equipment, and construction
Aramid Fibers	Made from aromatic polyamides. Known for high strength, heat resistance, and flame retardance. Used in bulletproof vests, protective clothing, and high-performance applications
Glass fibers	Made from silica-based materials. Strong, lightweight, and chemical resistant. Used in insulation, composites, filtration, and reinforcement materials

2.1.2 Linen

The main component of linen, which is derived from the flax plant (Linum usitatissimum), is cellulose, much like cotton, but with a higher degree of polymerization and crystallinity. Because of this composition, linen is more durable than cotton, particularly when damp. Summer apparel and hot temperatures benefit from the cool, crisp feel that linen provides due to its high absorbency and rapid drying time. Because it wears well over time and is abrasion-resistant, it is also renowned for its durability. Linen is a popular fabric for dresses and suits and other warm-weather clothing because of its breathability and coolness. Furthermore, linen decomposes naturally, promoting environmental sustainability. In addition to being used in apparel, linen is also utilized in industrial products like insulating materials and canvas, as well as domestic textiles like tablecloths and bed linens.

2.1.3 Hemp

The stalks of the Cannabis sativa plant are used to make hemp fiber, which is prized for its remarkable strength, resilience, and environmental benefits. Hemp fibers are tough because of their high degree of polymerization and crystallinity, which are mostly derived from cellulose, hemicellulose, and lignin. Hemp is extremely resilient because, in contrast to many other natural fibers, its strength improves as it gets wet. It is renowned for its capacity to wick away moisture and breathe, which guarantees comfort in hot and cold weather. Because of its adaptability, hemp is a popular material for a variety of items, including household textiles like carpets and upholstery as well as apparel and accessories. Hemp is also a very sustainable crop due to its quick growing cycle and little requirement for pesticides and herbicides. Hemp's capacity to decompose naturally amplifies its ecological advantages, establishing it as a vital component in the transition to more environmentally friendly textile manufacturing practices.

2.2 Protein Based Natural Fibers

2.2.1 Wool

Wool is mostly made of the fibrous protein keratin, which is derived from the fleece of sheep and other animals such as goats (cashmere), alpacas, and rabbits (angora). Wool is highly regarded for its outstanding insulating qualities, which make it perfect for cold areas since it maintains heat effectively. Because of its inherent ability to wick away moisture, it keeps the wearer dry and comfortable by absorbing moisture vapor. Wool fibers may stretch and revert to their original shape without causing any harm because of their elasticity. In applications where flame retardance is essential, wool's self-extinguishing properties and fire resistance give an extra degree of safety. Wool naturally breaks down and contributes to the sustainability of the environment because it is biodegradable. Applications of wool include home textiles like carpets and blankets, technical textiles like clothes resistant to fire, and apparel like coats, sweaters, and jackets.

2.2.2 Silk

The majority of the protein called fibroin, which makes up over 75% of the structure of silk produced by silkworms (mostly Bombyx mori), is sericin [5]. The characteristic sheen and shine of silk stems from its structure, which resembles a triangle prism and refracts light. This fiber is prized for its very smooth and soft texture as well as its great tensile strength, which diminishes when wet. Silk is suitable for people with allergies because of its hypoallergenic qualities, which also make it resistant to mold and dust mites. Moreover, silk has outstanding thermoregulatory qualities that help the body stay warm in the winter and cool in the summer. Due to these characteristics, silk is a favored fabric for high-end apparel, such as gowns, ties, and scarves, as well as for textiles used in homes and offices, such as draperies and bedding, and even for sutures.

2.3 Synthetic Fibers

2.3.1 Polypropylene

Synthetic fibers, notably polyethylene terephthalate (PET), are used to make polyester. It is well known for having great strength, resilience to deterioration, and resistance to stretching and shrinking. Polyester's durability and ease of maintenance are increased by its short drying time and resistance to abrasions and wrinkles. This fiber is perfect for outdoor and sporting applications since it is low absorbent and hydrophobic, which means it repels water. Polyester is widely used in apparel, home furnishings, industrial fabrics, and packaging materials, demonstrating its flexibility. It is an essential component of the textile industry since it can be used with natural fibers to provide strength and comfort.

2.3.2 Nylon

One of the first completely synthetic fibers to be introduced to the textile market was Nylon, a synthetic polymer derived from polyamides. Nylon fibers are robust and, despite stretching, return to their original shape. They are well-known for their remarkable strength and elasticity. Nylon is appropriate for many demanding applications due to its great abrasion resistance and minimal moisture absorbency. It is widely utilized in carpets, industrial goods, automotive components, and apparel, including undergarments, sportswear, and swimwear. Because of its strength and low weight, nylon is an excellent material for a wide range of applications.

2.3.3 Acrylic

The material used to make acrylic fibers, polyacrylonitrile (PAN), is renowned for being warm, soft, and lightweight, much like wool. Acrylic is a robust choice for a variety of applications since it is resistant to insects, oils, chemicals, and solar deterioration. It is extensively utilized in the production of outdoor textiles, carpets, blankets, and sweaters. Bright colors that don't fade quickly can be applied to acrylic fibers, and they keep their shape well even after washing. Because of these qualities, acrylic is a common material for textiles used in both home and fashion, providing a practical and affordable substitute for natural fibers.

2.3.4 Spandex

Spandex, sometimes referred to as elastane, is a polyurethane-based synthetic fiber. It is known for having extraordinary elasticity, which allows it to stretch up to five times its original length before regaining its original shape. Spandex fibers are robust, lightweight, and impervious to body oils, detergents, and sweat. Because of these qualities, spandex is the perfect material for items that need to be flexible and comfortable, like compression clothes, sportswear, swimsuits, and undergarments. The fiber is frequently used with other fibers to add stretch and enhance the comfort and fit of different clothes.

2.3.5 Polylactic Acid (PLA)

Biodegradable synthetic fibers called PLA (polylactic acid) are made from renewable materials like sugarcane or maize starch. PLA fibers are known for their eco-friendly qualities and are made to be strong, breathable, and moisture-wicking. Because of these qualities, PLA fibers are a great option for many uses, such as eco-friendly apparel, athletic wear, and biodegradable packaging materials. Because PLA fibers are biocompatible and break down into non-toxic metabolites, they are also utilized in agricultural products and medical sutures. The transition to more environmentally friendly and sustainable materials depends heavily on PLA fibers because of their performance and biodegradability.

2.4 Regenerated Fibers

2.4.1 Rayon

Rayon is a semi-synthetic fabric composed of cellulose that is obtained from cotton linters or wood pulp. The cellulose is dissolved during the production process and subsequently recycled into fibers. Rayon is well renowned for its capacity to replicate the qualities of organic fibers like silk and cotton, providing exceptional drapability, softness, and absorbency. It is appropriate for apparel, household textiles, and industrial products because it is smooth and cool to the touch. It is also comfortable to wear. Because of its adaptability, rayon can be utilized for a wide range of products, including medical supplies and everyday clothing.

2.4.2 Lyocell

One type of rayon called lyocell is created from wood pulp, specifically from eucalyptus trees, which grow quickly. Because the production method uses a closed-loop system to recycle the solvent used, it is environmentally benign. Cellulose makes up lyocell, which is renowned for its strength, suppleness, and excellent absorption of moisture. It is an environmentally beneficial choice since it is also biodegradable. Clothing, household textiles, and hygiene items are just a few of the products that can benefit from lyocell's smooth texture and long-lasting nature. Its comfort and adaptability are enhanced by its capacity to both absorb and release moisture.

2.4.3 Modal

One kind of rayon derived from beech tree pulp is called modal. Although the manufacturing process is similar to that of rayon, the fibers produced are more robust and long-lasting. Modal is a great material for loungewear and intimate clothing since it is soft, absorbent, and resistant to fading. It drapes nicely and holds its color and form well after several washings. Because beech trees are harvested sustainably, modal has a smooth texture and breathability that contribute to its comfort and environmental benefits.

2.5 Advanced and Technical Textiles

2.5.1 Carbon-Based Fibers

Carbon atoms together in a crystalline form make up carbon fibers. These fibers are incredibly lightweight, robust, and resistant to exposure to chemicals and high temperatures. Because of its excellent strength-to-weight ratio and longevity, carbon fibers are utilized in construction materials, automobiles, sports equipment, and aerospace. They are indispensable in high-performance and crucial applications since they are frequently utilized in composite materials to minimize weight and give structural support.

2.5.2 Aramid Fibers

Aromatic polyamides are the building blocks of aromatic fibers, such Kevlar. They have a reputation for being extremely strong, heat resistant, and flame retardant. Due to its five times greater strength than steel when compared to equal weight, Kevlar is the material of choice for helmets, protective gear, and bulletproof vests [6]. Where durability and safety are crucial, aramid fibers are also utilized in aerospace, automotive components, and high-performance sporting products.

Comparably, Nomex is a top-performing aramid fiber renowned for its remarkable resistance to heat and flame. For people who are exposed to hazardous situations, such as firefighters, industrial workers, and military personnel, Nomex is the perfect material for protective gear and equipment. Nomex is utilized for insulation and other high-temperature applications in the aerospace and automotive industries in addition to its protective uses. Because of its resilience and capacity to keep its structural integrity in high temperatures, Nomex is an essential part of many contexts where performance and safety are paramount.

2.5.3 Glass Fibers

Glass fibers are renowned for their great strength, low weight, and resilience to heat and chemicals. They are produced from materials based on silica. Applications for them include reinforcing materials, composites, filtration systems, and insulation. Glass fibers are corrosion-resistant, non-conductive, and offer structural integrity and durability. These characteristics render them appropriate for application in the automotive, aerospace, and construction sectors.

2.5.4 Conductive Fibers

Specialized materials called "conductive fibers" are designed to efficiently transfer electrical impulses or currents. These fibers, which can be made of metals, carbon-based materials, or conductive polymers, have special electrical conductivity qualities that make them indispensable in a variety of applications. Conductive fibers are essential to smart textiles because they make it possible to incorporate flexible circuitry, antennae, and sensors into textiles. This invention encourages the creation of cutting-edge wearable technology, including interactive clothes and health monitoring gear. Beyond wearables, conductive fibers are utilized to improve functionality and performance in fabrics for touch-sensitive interfaces, heated clothing, and electromagnetic shielding [7]. Their remarkable adaptability and conductivity are essential in sectors demanding superior electrical performance and pliability, propelling progress in consumer electronics and industrial uses alike.

3 Development and Production

3.1 Raw Materials Sourcing

The procurement of raw materials for textiles has witnessed a growing emphasis on sustainable and ethical methodologies. Fair labor practices, humane working conditions, and equal compensation for individuals engaged in the manufacturing of textile raw materials are all part of ethical sourcing. Sustainable methods place a high priority on the effects that textile production has on the environment, with a focus on lowering carbon footprints, water use, and chemical contamination.

Organic agricultural practices are becoming more and more popular for natural fibers like cotton and wool. By avoiding synthetic fertilizers and pesticides, organic cotton cultivation improves soil health and lowers environmental contamination. Using recycled resources for synthetic fibers—such as polyester made from PET bottles and post-consumer textile waste—is a significant sustainable project that lowers energy usage and waste [8].

3.2 Yarn Production

A crucial stage in the creation of textiles is yarn formation, which turns unprocessed fibers into continuous strands fit for knitting or weaving. One of the traditional methods of spinning yarn is ring spinning, which yields yarns of excellent quality, strength, and consistency. Technology has led to the introduction of rotor spinning, which creates yarns with slightly lesser quality but is faster and more affordable.

Modern spinning techniques like vortex and air-jet spinning provide better yarn qualities and productivity. A high-speed air jet is used in air-jet spinning to twist fibers into yarn, producing a smooth and uniform end product. In contrast, vortex spinning uses an air vortex to twist the fibers, producing yarns that are minimally hairy and have a high tensile strength. These developments in spinning technology boost the efficiency and quality of yarn production, catering to varied textile applications [9].

3.3 Fabric Manufacturing

The qualities and uses of textiles are greatly influenced by the processes used in fabric manufacturing. The most common and ancient method is weaving, which is the interlacing of warp and weft threads. Common weave patterns include plain weave, twill weave, and satin weave, each giving various properties in terms of texture, strength, and appearance.

Yarns are looped together during knitting, giving the cloth flexibility and comfort. Weft knitting and warp knitting are the two main categories of knitting. Weft knitting, utilized in items like T-shirts and sweaters, generates materials that are elastic and comfy. Structures made with warp knitting, which is used to make lace and tricot fabrics, are less elastic and more stable [10].

Three or more yarns or strands are interlaced in braiding techniques to form strong, flexible structures that are frequently tubular in shape. utilized for things like medical sutures, shoelaces, ropes, and cables.

Non-woven methods including needle punching, spun bonding, and felting are used to make fabrics without the use of conventional yarns. These techniques yield materials with distinctive qualities appropriate for use in geotextiles, filtration, and medical textiles. For example, spun bond and melt blown techniques are crucial in the production of non-woven materials used in hygiene products and personal protective equipment.

3.4 Textile Processing

Textile processing is the term used to describe a variety of procedures intended to improve the look, feel, and use of textiles. The two main finishing methods used to add color and design are dying and printing. Using methods like batch dyeing and continuous dyeing, uniform coloration is achieved by immersing materials in dye solutions during the dyeing process. On the other hand, printing allows for complex patterns and designs by applying colorants to particular places. Chemical processes improve the qualities of textiles even more. Waterproofing, flame retardancy, antimicrobial, stain repellency, and mechanical finishing are examples of common treatments.

Waterproofing fabrics includes applying hydrophobic chemicals, which produce a protective barrier on the fabric surface, preventing water penetration but allowing breathability. By treating textiles with flame-retardant chemicals [11], which can be applied in a variety of ways, such as coating, back-coating, or embedding them into the fiber during the production process, flame retardancy in textiles is produced. As a result, industrial personnel, firefighters, and home textiles (curtains, upholstery, etc.) can wear protective apparel with greater safety [12]. Antimicrobial treatments stop bacteria, fungus, and other microorganisms from growing. Silver and zinc oxide nanoparticles are essential for applications where hygiene is critical, such as hospital bedding, surgical gowns, sportswear, and everyday apparel. They are frequently used in medical textiles and activewear to preserve hygiene and prevent odor [13].

Calendaring and brushing are examples of mechanical finishing techniques that improve the texture and appearance of fabric without changing its chemical makeup. Calendaring is the process of smoothing, compacting, and polishing the fabric surface to produce a glossy, smooth finish by running it over heated rollers made of steel or paper. This procedure makes fabric appropriate for use in fine clothing and household textiles by enhancing its shine and decreasing its porosity. On the other side, brushing adds a delicate, fuzzy texture that accentuates warmth and tenderness by raising the nap of the fabric with fine wire brushes. This method is frequently used to enhance the insulating qualities and tactile appeal of fleece materials meant for winter apparel, blankets, and upholstery.

4 Properties

4.1 Mechanical Properties

When evaluating whether textile materials are suitable for a certain application, mechanical qualities play a critical role [14].

4.1.1 Tensile Strength

The resistance of a fiber to breaking under tension is measured by its tensile strength. Durability and performance are highly dependent on high tensile strength, particularly in protective and industrial textiles [15]. For instance, Kevlar's extraordinarily high tensile strength qualifies it for use in reinforced composites and bulletproof vests.

4.1.2 Elasticity

The ability of a cloth to regain its previous shape after being stretched or squeezed is referred to as elasticity. Because spandex is so elastic, it can provide the necessary stretch and recovery for sportswear and compression clothes. Elasticity in clothing helps with fit, comfort, and provides flexibility of movement.

4.1.3 Abrasion Resistance

This characteristic shows how resistant a cloth is to friction-induced surface wear. Textiles used in sports equipment, workwear, and upholstery must be able to withstand abrasions. For example, nylon has good abrasion resistance, which makes it perfect for applications that need long-lasting, robust materials.

4.2 Thermal Properties

The ability of a textile to function under different temperature situations is largely dependent on their thermal characteristics.

By holding onto body heat, insulating materials trap air inside their structure to provide thermal comfort. Since wool is a natural insulator, it is frequently used in blankets and winter apparel. Air pockets are created by their crimped fibers, which improve insulation [16].

4.2.1 Thermal Conductivity

A material's ability to conduct heat is measured by its thermal conductivity. In technical applications, high thermal conductivity is advantageous for heat dissipation, whereas low thermal conductivity is preferred for insulating materials. For instance, low thermal conductivity textile fabrics are frequently utilized in aerospace to protect against extremely high temperatures.

4.2.2 Heat Resistance

The capacity of a cloth to tolerate high temperatures without deteriorating is known as heat resistance. Because of their exceptional heat resistance, aramid fibers, such as Nomex, are a good choice for industrial safety gear and firefighting clothes. Even at high temperatures, these fibers keep their protective properties and structural integrity.

4.3 Chemical Properties

The way textiles react to different chemicals is determined by their chemical properties, which also affect how long-lasting and environment-specific they are. Selecting the appropriate textile materials for various industrial and consumer uses requires an understanding of these qualities.

4.3.1 Resistance to Acids

Acid-resistant textiles are essential in a variety of industrial applications where workers frequently come into contact with acidic materials. Because of their superior acid resistance, polyester fibers are a great option in these situations. The long-chain synthetic polymers that make up polyester's molecular structure give it a great level of chemical stability. Because of this, it can be used in businesses, laboratories, and chemical processing facilities where materials are regularly exposed to acids. Furthermore, the acid resistance of polyester contributes to the fabric's integrity and lifespan, making sure that it is strong and useful for lengthy periods of time. Other materials, such as aramids and polypropylene, are utilized in comparable applications where chemical exposure is a concern and also show strong acid resistance.

4.3.2 Resistance to Bases

In areas where cleaning agents and industrial chemicals are present, textiles must be similarly resistant to bases, or alkaline substances, in order to maintain their structural integrity. Fibers made of polyester and nylon are renowned for having strong bases resistance. Strong covalent links in the polymer chain of nylon, a polyamide, provide it resilience against alkaline hydrolysis. Because of this, nylon is a great material for use in the textile sector, where regular washing and detergent exposure are commonplace. Because of its ester connections, polyester is resistant to deterioration in basic conditions, which makes it useful for a variety of industrial applications. These fibers are utilized in industrial gear, uniforms, and other applications where resistance to chemical exposure is required.

4.3.3 Resistance to Solvents

For textiles used in settings where organic solvent contact occurs often, solvent resistance is an essential feature. For example, acrylic fibers show notable resilience to a wide range of solvents. This is because of their distinct polymer structure, which has potent intermolecular interactions that keep the fiber from disintegrating in solvents. Because solvent contact is unavoidable in coatings, filtration systems, and other applications, acrylic fabrics are often employed in these settings. Their ability to withstand solvents such as acetone, benzene, and different types of alcohols guarantees that the fabric will continue to function and won't break down. Other fibers with superior solvent resistance, such as polypropylene and several high-performance aramids, have a wider range of applications in technical and industrial textiles.

4.4 Functional Properties

Beyond their basic physical attributes, textiles with functional properties perform better in particular applications. These characteristics increase fabrics' usefulness and adaptability, making them appropriate for a variety of specific applications. As was previously mentioned, textile processing is typically used to obtain these qualities. Water repellency, antibacterial, UV protection, stain resistance, and antistatic qualities are a few of the crucial functional qualities needed for the fabrics.

4.4.1 Water Repellency

Textiles that are water-repellent keep out moisture, keeping you comfortable and functional in damp weather. Hydrophobic surfaces are produced chemically to give surfaces this characteristic. Fluoropolymers, silicone-based compounds, and durable water repellent (DWR) coatings are often utilized materials. Outdoor gear benefits greatly from silicone treatments, which offer flexibility and durability. Fluoropolymers are frequently utilized in high-performance rainwear due to their exceptional water and oil repellency. Water can bead up and roll off the surface with the aid of DWR coatings, which are applied as a finish to a variety of materials, avoiding saturation. For outdoor clothing, tents, and backpacks to keep their users dry in rainy weather, these treatments are necessary.

4.4.2 Antibacterial

Antimicrobial textiles improve cleanliness and lessen odors by preventing the growth of bacteria, fungus, and other microorganisms. Activewear, home furnishings, and medical textiles are three areas where these qualities are very useful. Natural agents including chitosan, triclosan, and silver ions are materials that are frequently utilized for antimicrobial treatments. Because of their long-lasting protection and broad-spectrum antibacterial qualities, silver ions are quite effective. Despite its effectiveness, triclosan is being replaced by safer alternatives like chitosan because of possible health hazards. These treatments, which provide long-lasting antimicrobial activity and preserve fabric freshness and hygiene, are applied to fabrics using a variety of techniques, including coatings, impregnations, and fiber inclusion.

4.4.3 UV Protection

UV-protective textiles shield the skin from sun damage by blocking or absorbing harmful UV rays. This is accomplished either by employing naturally UV-resistant fabrics like polyester and some types of treated cotton, or by including UV-absorbing chemicals like zinc oxide, titanium dioxide, and different organic compounds [17]. Due to its efficiency in both dispersing and absorbing UV rays, titanium dioxide and zinc oxide are frequently found as additions in sun-protective apparel. To improve their protective qualities, textiles can also be treated with UV-absorbing coatings or woven more tightly. To help avoid skin cancer and other sun-related health issues, UV-protective clothing is needed for outdoor activities, beachwear, and work locations with excessive sun exposure.

4.4.4 Stain Resistance

Textiles that are stain-resistant are made to repel or resist stains from penetrating them, making cleaning and upkeep simpler. Stain-repellent treatments, such Teflon or silicone-based coatings, are commonly used to achieve this feature. These treatments form a barrier that keeps liquids and dirt from sticking to the fabric. These treatments work particularly well on clothing, rugs, and upholstery—especially in areas where spills and stains are common. By keeping stains from setting in, the coatings, which are applied during the finishing process, help preserve the fabric's beauty and longevity.

4.4.5 Anti-Static

Textiles with anti-static properties lessen the accumulation of static electricity, which can be uncomfortable and draw dust and lint. This is accomplished by using anti-static coatings that promote the dissipation of electrical charges or by introducing conductive fibers like carbon or stainless steel. These fabrics are especially helpful in industries like explosive handling or electronic manufacturing where static electricity can be dangerous. Moreover, anti-static qualities improve the general performance of fabrics and lessen static cling, making home textiles and everyday apparel more comfortable and useful.

5 Applications

5.1 Clothing

Textile materials are essential to the apparel business since they may be used for everything from protective gear to high-end fashion and daily wear [18].

5.1.1 Everyday Wear

Everyday textiles are designed with comfort, longevity, and carefree maintenance in mind. Natural fibers are favored for their comfort and breathability, such as cotton and wool. Because of their longevity and resistance to wrinkling, synthetic fabrics like polyester and mixes are preferred. These materials are used to make everything from casual dresses and active wear to T-shirts and trousers.

5.1.2 Fashion

Many textiles are used by the fashion industry to make visually appealing clothing. Because of its smooth texture and inherent sheen, silk is frequently used in luxury fashion. Innovative materials like metallic fibers and smart fabrics that alter color or shape in reaction to external cues are also being experimented with by designers. Textiles are essential in high fashion because of their adaptability and vast array of textures, patterns, and finishes [19].

5.1.3 Protective Clothing

Textiles designed to provide protection against environmental risks are called protective textiles. Because of their high tensile strength and thermal stability, materials like

Kevlar and Nomex are utilized in bulletproof vests and fire-resistant clothing, respectively. Outdoor and sportswear also incorporates fabrics coated with UV-protective, antibacterial, and water-repellent treatments to offer extra protection.

5.2 Industrial Uses

In industrial applications, textiles are appreciated for their strength, durability, and practical characteristics.

5.2.1 Aerospace

The aircraft industry uses advanced composite fabrics, such as those made of carbon and aramid fibers, to create components that are both strong and lightweight [20]. By lowering the weight of the airplane, these materials enhance performance and fuel efficiency. Textile composites find application in thermal insulation, structural components, and aircraft interiors. Natural fiber composites are becoming more and more popular for usage in non-load bearing aircraft parts [21].

5.2.2 Automotive

In the car business, textiles are utilized for both external and interior parts. A range of materials with comfort, durability, and safety in mind are used to make airbags, headliners, carpets, and seat fabrics. Because of their exceptional strength and resilience to heat, reinforced textiles are also utilized in tires and under-the-hood components.

5.2.3 Construction

Textiles are used in buildings because of their protecting and reinforcing properties [22]. In civil engineering projects, geotextiles—made of synthetic fibers—are used to improve drainage, stabilize soil, and manage erosion. In order to improve building performance and safety, textiles are also utilized in insulation, roofing materials, and scaffolding nets.

5.3 Medical Applications

Medical textiles serve vital roles in healthcare and are specifically made to adhere to strict health and safety regulations.

5.3.1 Sutures

Because biodegradable fibers, such as polyglycolic acid, are used to make surgical sutures, fewer surgeries are required to remove them from the body. For longer-term wound support, non-biodegradable sutures composed of materials like polyester are utilized.

5.3.2 Implants

Hernia meshes and vascular grafts are two examples of medical implants that require textile materials that are both long-lasting and biocompatible. The long-term stability and compatibility of polyester and expanded polytetrafluoroethylene (ePTFE) with human tissue make them widely used materials.

Absorbent, non-adherent fabrics are used to make wound care items like bandages and dressings, which aid in healing and stave off infection. Antimicrobial drugs are added to advanced dressings to increase their efficacy even further.

5.4 Environmental Applications

Textiles are used in environmental applications to solve a range of ecological issues by utilizing their functional qualities. By finding creative solutions, these applications promote sustainability and enhance human well-being.

5.4.1 Filtration

Because of their structural characteristics, textile materials are essential to water and air filtration systems because they allow for efficient particle capture. The high surface area, porosity, and mechanical strength of non-woven fabrics, which are manufactured from synthetic fibers like polyester and polypropylene, are especially appreciated. These characteristics enable them to effectively capture pollutants and particle matter. Non-woven filters in HVAC systems eliminate dust, pollen, and other airborne particles to enhance air quality. Textile filters are used in industrial settings to purify gases and liquids in order to comply with environmental requirements. Textile-based filters are also used in water purification procedures to eliminate germs, pollutants, and other dangerous materials, helping to provide clean drinking water. Facemasks made of multilayered nonwoven filters are also utilized [23].

5.4.2 Insulation

Effective thermal and acoustic insulation is provided by textiles, which greatly improves comfort and energy efficiency in a variety of environments. Because of their exceptional heat resistance and sound absorption qualities, fiberglass and mineral wool are often used materials in textile insulation products. By preserving constant interior temperatures, these materials contribute to a reduction in building energy consumption and associated heating and cooling expenses. In cars, cloth insulation is also used to reduce noise and heat transfer, which enhances passenger comfort. Insulating textiles in appliances help in heat and sound management, making their operation quieter and more effective. In soundproofing applications, textile insulation materials play a crucial role in reducing noise pollution in both residential and business settings.

5.4.3 Geotextiles

In environmental engineering, geotextiles are essential because they improve soil stability, stop erosion, and make drainage easier [24]. Geotextiles are made of resilient synthetic fibers like polyester, polypropylene, and polyethylene that are resistant to both chemical and biological deterioration and severe environmental conditions. They strengthen the soil during the construction of roads, increasing their capacity to support loads and prolonging their life. Additionally, geotextiles are utilized in landfill projects to keep groundwater clean and separate garbage strata. By stabilizing soil and encouraging vegetation development, these textiles aid in the preservation of natural landscapes by mitigating erosion along the shoreline. Geotextiles are crucial to the construction of sustainable infrastructure because of their adaptability and durability.

5.5 Smart Textiles

Smart textiles offer cutting-edge functions that go well beyond those of conventional materials, marking a groundbreaking merging of textile technology and electronics. Smart textiles may sense, respond, and adapt to environmental factors or the wearer's demands by integrating sensors, actuators, and other electronic components into the textile fibers. This allows for a wide range of creative applications across multiple industries.

5.5.1 Wearable Health Monitoring

Wearable health monitoring is one of the biggest fields in which smart textiles are being used. Sensors that are built into these textiles allow for the continuous monitoring of vital signs like blood pressure, respiration rate, body temperature, and heart rate. Real-time health data is gathered using conductive fibers and flexible sensors inserted in the fabric, and it can be sent to healthcare practitioners for remote monitoring [25]. With the help of this technology, chronic illness management, early health issue diagnosis, individualized healthcare solutions, improved patient outcomes, and lower healthcare costs may all be effectively managed.

5.5.2 Sports and Fitness

By giving athletes access to comprehensive performance information, smart textiles are revolutionizing the sports and fitness industries. Motion, pressure, and conductive threads inserted in fabrics allow them to track biomechanical motions, assess exertion levels, and monitor physical activity. Athletes can improve overall performance, avoid injuries, and optimize their training routines with the use of this data. In order to ensure comfort and enhance athletic performance, smart fabrics in sportswear can also contain capabilities like moisture management and temperature regulation.

5.5.3 Fashion and Interactive Clothing

Smart fabrics are making it possible to design interactive and adaptable clothing in the fashion business. Textiles incorporating LEDs, color-changing fibers, and touch-sensitive screens enable users to customize the look of their clothes and communicate with digital devices through them. Smart fabrics are being used by designers to produce futuristic clothing that reacts to user input or the surroundings, providing new avenues for individual style expression. Furthermore, intelligent fabrics have the ability to incorporate cooling systems for comfort in hot weather or heating components for warmth in cold climes.

5.5.4 Environmental Monitoring

Thanks to the integration of sensors that measure changes in temperature, humidity, pollutant levels, and air quality, smart textiles are essential for environmental monitoring. These textiles can be utilized to offer real-time environmental data in industrial settings, metropolitan areas, or nature settings. In order to manage natural resources, combat pollution, and guarantee that environmental laws are followed, this knowledge is essential. As an adaptable and discrete monitoring tool, smart textiles support environmentally conscious practices.

5.5.5 Energy Harvesting

Intelligent textiles including energy-harvesting technologies have the ability to produce electricity from surrounding sources such temperature gradients, kinetic energy, and solar radiation. Piezoelectric fibers are used to capture mechanical energy from motion, whereas photovoltaic fibers are woven into fabrics to turn sunshine into electricity [26]. Wearable technology, sensors, and tiny electrical devices can be powered by these fabrics, which helps to reduce the need for batteries and promote sustainable energy sources.

5.5.6 Protective Clothing

Smart fabrics improve the usability and safety of protective gear in dangerous conditions. These textiles may have sensors incorporated into them that may identify harmful gasses, extremely high or low temperatures, or physical impacts and notify the wearer in real time [27]. Furthermore, materials that alter their characteristics in reaction to external cues—like hardening upon impact to offer more protection—can be incorporated into smart textiles. Smart fabrics are used in industrial safety gear, military uniforms, and firefighter suits, among other applications, to provide enhanced protection and situational awareness.

6 Conclusion

The chapter on textile materials has covered the various classifications, production methods, characteristics, and wide range of applications for these materials. Textile materials—from high-performance specialized fibers like Kevlar and Nomex to natural fibers like cotton and wool—have proven their adaptability and crucial role in a variety of industries. In the future, there will be a great deal of room for innovation in textile materials due to the development of new technologies and growing awareness of environmental effect and sustainability.

With advancements in material science, nanotechnology, and smart textiles, the field of textile materials is set for major innovation. In order to produce textiles with improved utility and performance, researchers are constantly experimenting with new fiber compositions and production processes. For example, adding nanoparticles to fabrics can give them better strength, thermal conductivity, and self-cleaning capabilities. Another field experiencing significant development is smart fabrics, which are incorporated with sensors and electronic components. These fabrics have the ability to track health metrics, modify their characteristics in reaction to changes in the surrounding environment, and even produce energy through movement. Smart textile applications promise to transform our everyday interactions with fabrics and span from sports and healthcare to space exploration and the military.

Given the substantial environmental impact of traditional textile production, sustainability is quickly rising to the top of the textile industry's priority list. The industry is mostly at blame for waste production, chemical pollution, and excessive water use. There is an increasing focus on creating sustainable materials and procedures to address these issues. Using more organic and recycled fibers is one strategy. Grown without synthetic fertilizers and pesticides, organic cotton improves soil health and lessens its negative impact on the environment. Recycled fibers contribute to waste reduction and a reduction in the carbon footprint of textile production, especially recycled polyester manufactured from PET bottles. Innovations in finishing and dying techniques for textiles also support sustainability. The use of new methods like digital printing and supercritical CO_2 dyeing, which use less water and energy, is helping to lessen the environmental effect of the textile manufacturing industry. In addition, the textile industry's adoption of a circular economy model seeks to increase product life cycles through upcycling and recycling. This method encourages the sustainable use of materials while reducing waste and conserving resources.

In conclusion, there will likely be major breakthroughs and developments in the field of textile materials as they continue to develop. Meet the growing demand for high-performance, eco-friendly products in the textile sector by adopting sustainable practices and creating new technologies. The future of textiles will be shaped by the combination of technological innovation and sustainability, which will ensure their continued use in our lives while reducing their negative effects on the environment.

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Composite Materials

Khubab Shaker and Abdelghani Saouab

1 What is Composite Material?

A composite is a macroscopically homogeneous material produced by the dispersion of a reinforcing phase in a relatively weaker material, i.e., a matrix [1]. The matrix keeps the geometric arrangement of reinforcement and transfers the load acting on the composite to the reinforcement. The resulting composite material has intermediate mechanical performance, which is superior to that of the matrix but lower than that of the reinforcement. In addition to mechanical performance, composite materials are also preferred for certain functional properties.

Composite materials are not new and have been used since ancient times. Wood, straw, and mud bricks used for construction have been everyday composites. Roman invented a special type of long-lasting concrete in 200 B.C., which was an advanced form of composite material developed by a combination of a white powder known as slaked lime, small particles, and rock fragments called tephra ejected by volcanic eruptions, and water [2].

Composite Bows were used by ancient civilizations such as the Mongols, Persians, and Greeks, and were crafted by combining different materials like wood, animal horn, and sinew (tendons) to create a powerful and flexible weapon. The ancient Chinese developed composite armor known as “lamellar armor.” This armor consisted of small overlapping plates made from materials like iron, leather, and bone, providing a lightweight yet protective defense.

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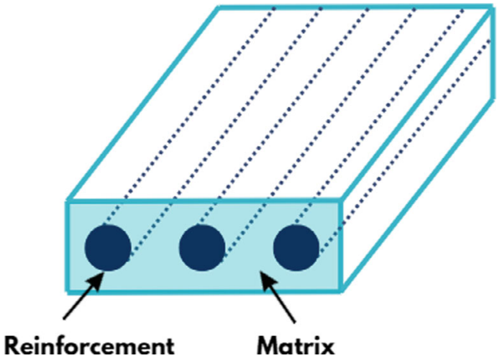
No longer limited to specialized applications, composite materials are now commonly used in a number of industries. The massive wind turbine blades to capture energy, and sleek hulls of racing yachts cutting through the water, are prime examples of composites revolutionizing various fields. The high strength to weight ratio of composites makes them ideal for airplane fuselages. Construction sites utilize composites in long-lasting beams and bridges. Other applications range from athletic equipment that helps us push our limits to the electronic devices in our pockets, composites are silently woven into the fabric of our daily lives. The versatility and exceptional performance of these materials position them as a key driver of innovation across a wide range of industries.

1.1 Constituents of Composite Materials

The constituents of a composite material are the reinforcement and the matrix, as discussed earlier. The reinforcement is regarded as the load-bearing component, while the matrix surrounds the reinforcement, binds, and protects it from external factors [3]. It also helps to transfer the applied load towards the reinforcement phase. The schematic of a composite material showing reinforcement and matrix is shown in Fig. 1.

The reinforcement is generally in the form of fibers due to their high tensile modulus and strength, thus enabling the composite material to withstand higher loads. The fiber-reinforced composite materials are therefore preferred for structural applications. However, the fiber/matrix interface is another constituent that exists in the composite material and controls the load-bearing properties of the composite material. Interface is the transition area and the effectiveness of fiber/matrix bonding in this area determines the failure behavior of composite material. When the interfacial adhesion is strong, fiber breakage is the dominant failure behavior. In the case of weak interfacial adhesion, debonding between fiber and matrix is observed under applied load. The interfacial adhesion may be enhanced by a number of surface

Fig. 1 Schematic of a composite material unit cell



treatments including fiber sizing, chemical surface modification, plasma treatment, etc.

1.2 Advantages of Composite Materials

Composite materials offer numerous advantages over conventional materials, making them increasingly popular in various industries. The foremost advantage of composite materials is their exceptional strength-to-weight ratio. These are lightweight materials, exhibiting high strength and stiffness and are especially useful in applications where weight reduction is critical, such as aerospace, automotive, and sports equipment. The lightweight nature of composites not only improves fuel efficiency but also enables faster acceleration, better maneuverability, and reduced structural fatigue.

Secondly, composites offer superior corrosion resistance. Unlike metals, which are prone to rust and degradation when exposed to moisture, chemicals, or harsh environments, composite materials exhibit excellent corrosion resistance. This property makes composites ideal for applications in marine, chemical processing, and infrastructure, where durability and long-term performance are essential. By using composites, industries can reduce maintenance costs, extend the lifespan of structures and equipment, and ensure consistent performance even in challenging conditions.

Additionally, composites provide design flexibility and versatility. They can be tailored to meet specific requirements by varying the types, orientations, and volume fractions of the reinforcing fibers, as well as the choice of resins and additives. This customization allows engineers and designers to optimize the mechanical, thermal, electrical, and acoustic properties of the materials, resulting in tailored solutions for diverse applications.

The ability to create complex shapes, intricate geometry, and integrated functionalities further expands the design possibilities and opens up new opportunities in industries such as architecture, consumer goods, and renewable energy. These properties make composites highly desirable for various applications, offering improved performance, durability, and efficiency compared to traditional materials. As technological advancements continue to enhance composite manufacturing processes, we can expect to see even more innovative uses of composites in the future.

1.3 Classification of Composite Materials

As discussed in the previous section, fibers are one of the most used types of reinforcements. However, the other reinforcement forms include particles, flakes, whiskers, short fibers, continuous fiber, fabric sheets (2D and 3D), shaped fabrics, honeycomb sandwich structures, etc. Similarly, the matrices are also of three different forms,

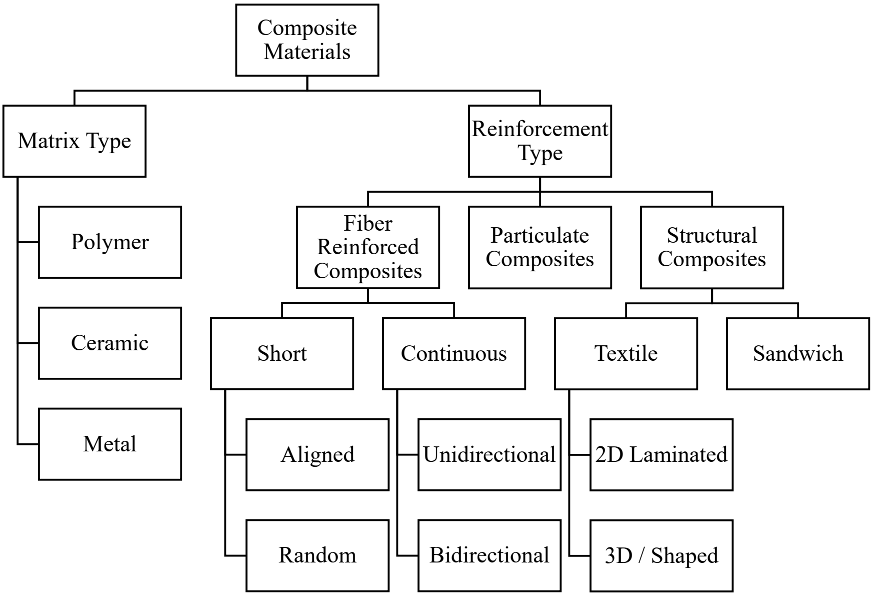


Fig. 2 Reinforcement and matrix-based classification of composite materials [4]

namely polymer, ceramic, and metal matrices. The composite materials are classified based on reinforcements (w.r.t. geometry) and matrix materials, as shown in Fig. 2.

Fibrous reinforcements are also classified on the basis of raw material, i.e. glass, carbon, aramid (Kevlar), and natural fibers (flax, hemp, etc.). Fibers usually exhibit higher strengths and stiffness as compared to the same material in bulk form owing to the alignment polymeric chains in their structure. High-performance fibers (Carbon, aramids, etc.) are distinguished from other fibers by their remarkably high specific modulus. This property enables these fibers to be used for advanced engineering and load bearing applications, e.g. aerospace, ballistics, etc. The details of these fibrous materials have been discussed earlier in Chap. 4.

Most commonly used particulate reinforcements, such as silicon carbide or aluminum oxide, help to improve wear resistance or provide specific functionalities. Continuous textile fabric sheets, known as laminates, are also used in applications where high strength and impact resistance are required, such as in aerospace or automotive industries. The selection of reinforcement materials depends on the desired properties of the composite, including strength, weight, thermal stability, electrical conductivity, and cost-effectiveness. The combination of the matrix material and the reinforcement materials determines the final properties and performance of the composite.

2 Constituents of Composite Materials

This section focuses on three aspects of composite materials, including reinforcement material, matrix material, and composite material fabrication. The reinforcement geometries discussed in Fig. 2 are produced using different techniques. The matrix material, reinforcement material, and reinforcement geometries are highly specific in their end applications.

2.1 Reinforcement Material

2.1.1 Fibrous and Particulate Reinforcement

The commonly used reinforcement processing techniques include weaving, knitting, braiding, web formation and web bonding, stitching, multiaxial warp knitting, multilayer weaving, shaped structures, honeycomb structures, etc. in addition to these, particulate reinforcements including microparticles, nanoparticles, graphene, CNT, etc. are also used for composite materials. The structure of reinforcements produced using these techniques varies greatly, as shown in Fig. 3.

The randomly oriented chopped fibers represent the category of reinforcement providing approximately similar mechanical properties in different directions. It is also commonly called as Chopped Strand Matt (CSM) and has a wide range of engineering applications. However, due to short length fibers, its mechanical properties are quite low as compared to continuous fiber composites. In unidirectional composites, continuous fibers are aligned in a single direction, providing maximum strength along that direction. This configuration is ideal for applications where load is predominantly applied in one direction. However, the mechanical performance is very poor in the cross direction (perpendicular to fiber orientation).

Contrary to these, woven fabrics are produced by the interlacement of two sets of yarns called warp and weft. Woven fabric composites offer enhanced strength and stiffness in multiple directions, as compared to unidirectional composites. It makes woven fabric composites suitable for applications where load is applied from different directions. Also, these structures have high dimensional stability and are easy to handle during composite fabrication. Different weave structures (plain, twill, satin) in woven fabrics allow for the customization of their drape and mechanical performance.

The knitted reinforcement is either produced by weft knitting or warp knitting. Both of these knitted reinforcements are not a preferred choice for composite materials due to their open structure and low dimensional stability and lack of straight yarns. However, this feature of knitted structures can be employed to produce flexible composites, using elastomeric matrix and knitted reinforcement [5]. These flexible composites offer high energy absorption properties and forming capabilities as compared to traditional composites. Verpoest et al. [6] reported that the in-plane

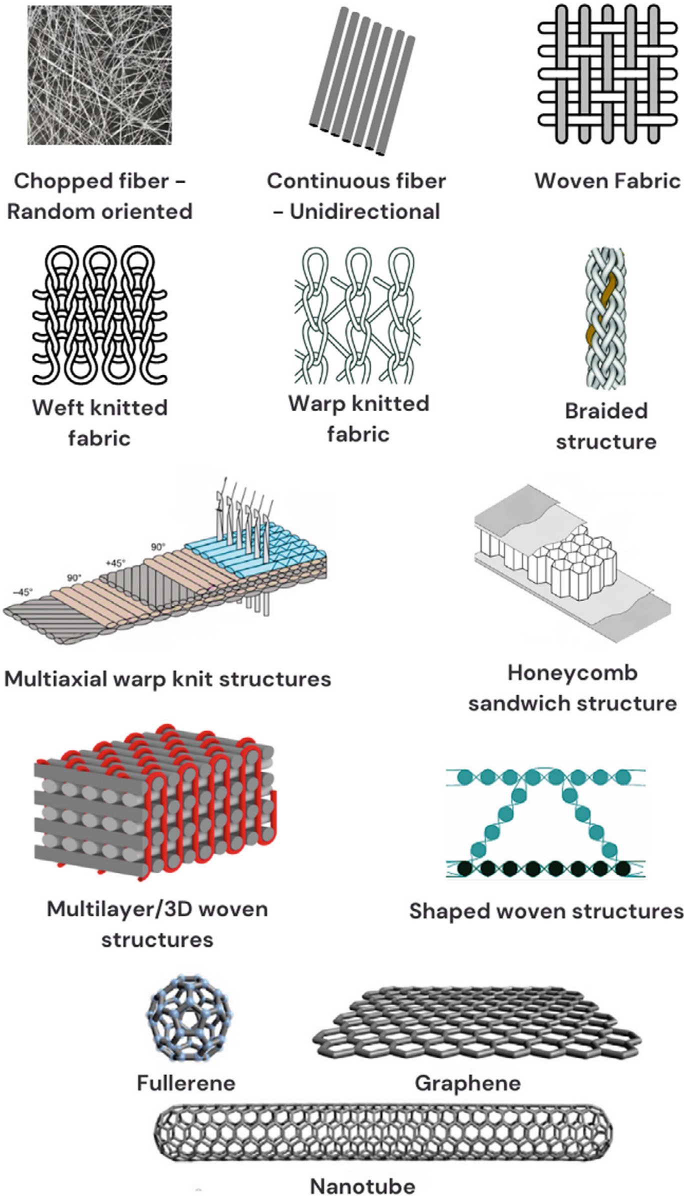


Fig. 3 Different reinforcements used for composite materials

mechanical properties of knitted composites are comparable with those of woven composites, while their out of-plane properties are superior. Loops in a knitted structure allow for a higher elastic deformation of the preform; thus, allowing for shaping into complex composite parts. Hybrid reinforcements are also used sometimes to get tailorable properties [7].

Braids are textile structures, produced using at least three yarns and interlaced in two directions. Unlike warp and weft in woven fabrics, yarns run at an angle from one edge of the braided structure to the other or like a helix around a tubular support [8]. The angle of yarn with longitudinal axis is termed as braid angle. This angle depends on the difference between braid take-up speed and the speed of bobbins. Technically, braids can be produced with a braid angle ranging between 10° and 89° [9]. However, achieving a fully closed braid with 100% fiber coverage is crucial to prevent resin-rich areas within the composite structure. The coverage is determined by four factors including mandrel diameter, braid angle, number of yarns and width of the yarns. Braiding can be either circular, flat or 3 dimensional, depending on the product shape/requirements. However, there is still a lack of acceptance for this technique due to its complex architecture and dependency on a huge number of parameters.

2.1.2 3D Reinforcements

Three-dimensional reinforcements contain planar as well as through-thickness reinforcing yarns, addressing limitations of conventional laminates. The delamination resistance and impact damage tolerance of these reinforcements is increased due to the presence of yarns in out of the plane (through thickness) direction [10]. Several techniques are used to produce the 3D fiber reinforcement, including weaving, stitching, braiding, z-pinning, tufting, and z-anchoring. However, the basic structure of all 3D reinforcements is quite similar, featuring a high percentage of continuous in-plane fibers (like traditional laminates) for excellent in-plane strength, a relatively small fraction of high-strength z-binders, oriented through the thickness (z-direction). The pros and cons of all these techniques have been summarized in Table 1 [11].

The z-binders present in the thickness direction offer a number of advantages in the 3D reinforcement. The z-binders, although in low volume fractions (under 5–10%), significantly enhance the resistance to delamination and impact damage of composite as compared to laminates. An additional advantage of z-binders is the potential improvement in composite joint properties, resulting in higher failure strength, fatigue life, and damage tolerance as compared to conventional mechanical/adhesive bonded joints. The use of 3D reinforcements also minimizes the ply slippage during manufacturing, resulting in reduced preform lay-up time, leading to cost savings. A careful selection of appropriate z-binder can also help to achieve through-the-thickness thermal or electrical conductivity [12].

Three-dimensional composites, including woven, stitched, z-pinned, and braided variants, offer a wide range of potential applications across various sectors [11].

Table 1 Pros and cons of different 3D reinforcement fabrication techniques

Fabrication technique	Advantages	Disadvantages
3D weaving	• High structural integrity due to interlacement of yarns • Precise control over 3D shape and properties • Multiple material choices • Through Thickness Properties are good • No delamination of plies	• Complex machinery and process • Limited design complexity compared to additive techniques • High production cost
3D knitting	• Produces soft and flexible fabrics • Good for complex shapes and hollow sections • Can incorporate various yarns and functional materials	• Lower in-plane strength compared to weaving • Can be time-consuming for intricate structures • Limited machine availability
3D stitching	• Fast and versatile production • Good for incorporating pre-formed components • Lower machinery cost than 3D weaving	• Lower structural integrity compared to weaving • Stitching threads can affect aesthetics and comfort • Limited control over fabric thickness
Braiding	• Excellent strength and stability in specific directions • Good for hollow and tubular structures • Can incorporate multiple materials • High crush and impact resistance • High delamination resistance • High fracture toughness	• Limited design flexibility • Requires specialized machinery • May not be suitable for all applications • Poor In-plane properties due to intertwined yarns • Crimping
Non crimp knitting	• High production speed • Suitable for large and seamless fabrics Offers good strength and weight reduction • High tensile properties due to straight yarns • No crimp • Less prone to cracks	• Limited 3D design capabilities • Higher fabric thickness • Requires specialized machinery
Tufting	• Effective for adding pile or loops to existing fabrics • Offers good aesthetics and functionality Lower production cost than some techniques	• Limited 3D shaping capabilities • Can affect fabric breathability • Potential for loop snags

(continued)

Table 1 (continued)

Fabrication technique	Advantages	Disadvantages
Z anchoring	• Strong and durable attachment for reinforcements • Offers low profile and minimal fabric disruption • Good for localized stiffness addition	• Requires precise placement and specialized tools • Limited 3D shaping capabilities • May not be suitable for all materials • Crimping of in plane yarns
Z pinning	• Simple and cost-effective • Easy to use with existing • Fabrics • Suitable for light reinforcement • High delamination resistance • Suitable for pre pregs as compared to other techniques	• Limited thickness and structural integrity • Not ideal for complex shapes • Potential for yarn damage during pinning • More prone to cracking

- **Aerospace**: 3D woven composites are used in missile components (nose cones, engine nozzles), aircraft skins (stiffened panels, leading edges, wing connections), turbine engine parts (inlet blades, rotors), and even H-shaped connections [13].
- **Civil Infrastructure**: I-beams produced by weaving offer new possibilities for the construction sector.
- **Ballistic Protection**: Both 3D woven, and z-pinned composites have the potential to be used in ballistic and armor panels for personal and vehicular protection.
- **Transportation**: Manhole covers, roll-over bars in race cars, and even ship propeller blades can also benefit from 3D composites [14].
- **Medical Applications**: Prosthetics are another exciting area where 3D woven composites can play a role.
- **General Applications**: 3D stitched composites are suitable for various joint connections in structures, while the highly versatile 3D braided composites find applications in beams, trusses, shafts, automotive parts (body panels, chassis, drive shafts), and bridge structures.

Comparison of performance, mouldability and processing cost of different reinforcement geometries is given in Fig. 4. It is evident that chopped fibers, with random orientation, offer versatility and adaptability in reinforcing composite materials. On the other hand, continuous fiber in a unidirectional arrangement provides excellent strength and stiffness, ideal for applications requiring high performance. Woven and braided fabrics bring a different dimension to the mix, offering a balance between strength and moldability. Knitted fabrics, with their unique construction, provide a blend of flexibility and strength, making them suitable for a wide range of applications. Moreover, the production costs associated with each type vary significantly. Chopped fiber and knitted fabrics tend to have lower production costs, making them more accessible for certain projects. Conversely, continuous fiber and certain woven or braided fabrics may incur higher production costs due to their specialized manufacturing processes and materials.

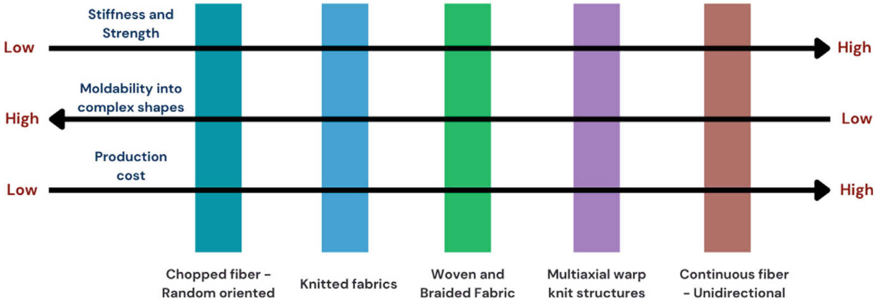


Fig. 4 Comparison of performance, mouldability and processing cost of different reinforcement geometries

The fibrous reinforcement plays a key role in tailoring the mechanical performance of the composite materials. The selection of appropriate reinforcement can significantly improve the load-bearing properties of the composites. The wide range of fibrous reinforcement offers versatility and customization options, allowing for the design of composites with tailored properties to meet specific application requirements. Continuous advancements in materials fibrous materials, in combination with reinforcement geometry can play a vital role in the development of lightweight high-performance composite materials.

2.1.3 Nano-Reinforcements

Graphene and nanotubes belong to a novel class of nanoscale sheets and fibers. The high aspect ratio of nanotubes makes them an ideal candidate as reinforcement for polymeric materials to get enhanced mechanical performance and conductivity [15]. Carbon nanotubes are the most commonly used example of nanotubes and are either single walled or multiwalled. Lengths of CNTs typically vary from hundreds of nanometers to hundreds of microns, but millimeter and centimeter long CNTs have also been reported. The CNT reinforced polymer composite finds potential applications for electromagnetic interference (EMI) shielding, photo-degradation protection, fire retardation, sensing, and solar cells. However, there are only a few examples of CNT reinforced polymeric composite being currently produced commercially, i.e., sports equipment and high-end yachts.

2.2 *Matrix Material*

The classification of composite materials on the basis of matrix materials is shown in Fig. 2. The matrix material can be a polymer, ceramic, metal, or a combination of these. Polymers, such as epoxy, polyester, phenol, etc. are examples of commonly used matrix materials. The polymer matrices offer excellent mechanical performance, have ease of processing, and are cost effective. Ceramic matrices, such as silicon carbide and alumina, offer exceptional temperature resistance and are used in high-temperature applications. Metal matrices, such as aluminum or titanium alloys, provide high strength and stiffness. However, as the role of the matrix is to bind the reinforcement in place and protect from environmental factors, choice of the matrix material depends on the specific requirements and desired application of the composite material.

2.2.1 Polymer Matrix Composites (PMCs)

It is the most used category of composite materials, holding a share of more than 80% of the total composite materials market. A key advantage of PMCs is their lightweight, an inherent characteristic of polymers. These matrices are further categorized into thermosets and thermoplastics. Thermosetting matrices cure irreversibly and form a 3D cross-linked network, and therefore, cannot be remelted. Contrary to this, thermoplastics have the ability to melt and can be reshaped. Polymer matrices offer a broad spectrum of desirable properties, including high strength and modulus (Fig. 5), excellent impact resistance, good performance under compression and fatigue, and outstanding chemical and corrosion resistance.

The performance of PMCs depends on several factors, including the matrix material, reinforcement material and geometry, processing methods, and the interphase between the two. PMCs reinforced with glass fiber occupy the largest market share (approximately 70%), while other reinforcements include carbon, aramid, natural fibers, etc. However, manufacturers have leverage to create cost-effective products with various manufacturing techniques, tailoring the final product to specific

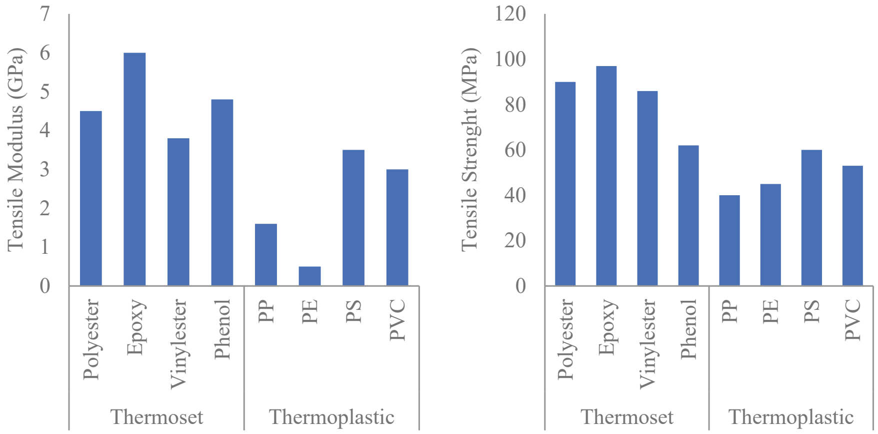


Fig. 5 Tensile strength and tensile modulus of common polymer matrices [16]

needs. These combined benefits make PMCs an excellent choice for applications in demanding environments, such as automotive, sports, aircraft, etc.

2.2.2 Ceramic Matrix Composites (CMCs)

Ceramic matrix composites (CMCs) are a unique class of materials combining ceramic reinforcements like particulates, fibers, or whiskers within a ceramic matrix [17]. These matrices typically exhibit strong ionic or covalent bonds, offering exceptional properties for demanding environments. Ceramic matrices exhibit high melting points, superior compressive strength, and excellent stability at elevated temperatures. This makes CMCs the preferred choice for applications like pistons, blades, and rotors in gas turbine parts, where they can withstand extreme heat and corrosive environments. The addition of reinforcements significantly improves the material toughness as compared to inherently brittle monolithic ceramics [18] (Fig. 6).

However, a key drawback of CMCs is their susceptibility to failure at low strain levels. This limits the stress that can be applied to these materials. Despite their high stiffness, lower ductility of CMCs makes them less adaptable to manage thermal stresses arising from variations in thermal expansion coefficient. CMCs offer a compelling combination of strength, high-temperature performance, and corrosion resistance [19].

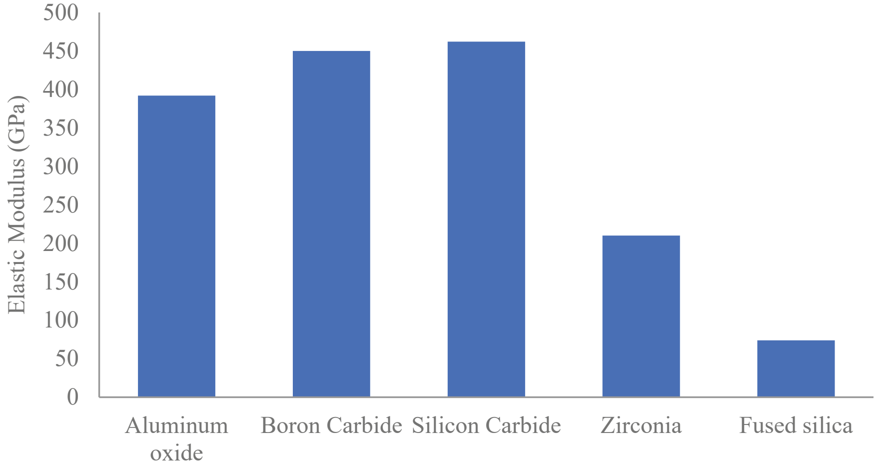


Fig. 6 Elastic modulus of ceramic matrices

2.2.3 Metal Matrix Composites (MMCs)

Metal matrix composites (MMCs) are a class of advanced materials gaining significant interest due to their superior properties as compared to conventional metals. They offer enhanced mechanical and thermal properties, including improved wear resistance and exceptional thermal conductivity. Aluminum, magnesium, copper, nickel, iron, and titanium are the primary metals used as the matrix in MMCs. Aluminum alloys, known for their formability, good joining properties, low density, and excellent strength-to-weight ratio, are popular choices in the automotive and aerospace sectors for structural applications.

Ceramic reinforcements are incorporated into MMCs to enhance the strength of metals like aluminum. These MMCs leverage the metallic properties of the matrix and the ceramic characteristics of the reinforcements. Titanium-based composites are particularly valuable for high-temperature structures due to their exceptional strength and corrosion resistance at elevated temperatures, although their cost remains a drawback. Magnesium, the lightest of these metals, finds applications in electronics equipment and aerospace components due to its weight savings. Copper-based MMCs, known for their excellent wear resistance, are used in electronics. Alumina (Al_2O_3), silicon carbide (SiC), titanium carbide (TiC), boron carbide (B_4C), and titanium nitride (TiN) are commonly used particle reinforcements to improve strength and elastic modulus of MMCs (Fig. 7).

The potential applications of MMCs span various industries. Recent research highlights their promise for producing composites with outstanding mechanical properties, potentially replacing expensive conventional alloys in both structural and functional applications. Aluminum matrix composites are particularly well-suited for advanced structural applications. However, achieving commercially viable MMCs requires more efficient fabrication methods. Research is ongoing to develop cost-effective and production-friendly techniques to meet the needs of different industries. The goal is to create the ideal combination of metallic matrix and reinforcement to achieve the desired properties for a given application.

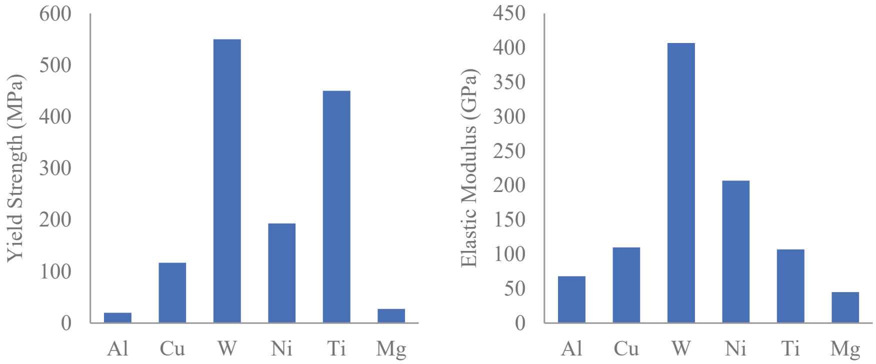


Fig. 7 Yield strength and elastic modulus of metals

2.3 Material Selection Criteria

The growing interest in lightweight and high-performance materials creates opportunities for composite materials, offering opportunities to replace conventional materials across diverse sectors. However, simply replacing a material (e.g., steel with a composite material) is insufficient, and redesigning the product to take full advantage of the composite material properties and processing characteristics is crucial. However, selecting the ideal material for a product is a crucial task for design engineers. This process can be complex due to the vast number of potential composite materials available, and diverse requirements across various industries [20]. For example:

- **Automotive**: Cost and energy efficiency are key drivers.
- **Aerospace**: High performance and lightweight materials are paramount.
- **Consumer Products**: Cost and user-friendliness take precedence over performance.
- **Sports Goods**: Lightweight as well as high performance materials are essential.
- **Marine Industry**: Corrosion-resistant materials, having lightweight are in high demand.

For composite materials, design engineers need to clearly define key characteristics including fiber type (carbon, glass, Kevlar, etc.), ply structure (chopped, unidirectional, woven, etc.), ply thickness and areal weight, matrix type (thermoset, thermoplastic, etc.), and resin content [21]. In addition to this, manufacturing engineers also need specific parameters like drape, cure cycle, processing temperature, gel time, and flow characteristics for the selected material. Material selection is a complex process involving four generic steps to narrow down the list of candidate materials, as shown in Figs. 3 and 8.

2.3.1 Understanding and Prioritizing Requirements

The selection of an ideal material starts with a clear understanding of a product's performance requirements. While materials offer various benefits, some properties are more crucial than others depending on the application. For instance, weight might be a non-issue for a household item, but critical for an airplane component. Similarly, wear resistance might be paramount for one product but irrelevant for another. Therefore, prioritizing these requirements at the outset of the material selection process is

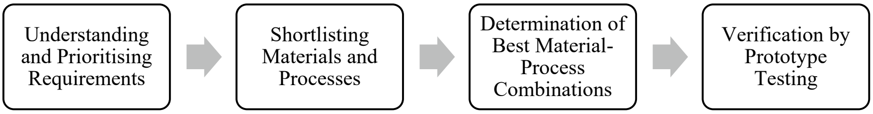


Fig. 8 Steps involved in the material selection process [22]

critical. Some key factors to consider when prioritizing needs for material selection include:

- **Strength**: The ability of the material to withstand applied loads without breaking.
- **Impact resistance**: The ability of material to absorb energy by sudden impacts.
- **Temperature resistance**: Performance of material at extreme hot or cold temperatures.
- **Environmental resistance**: Response of material to factors like humidity, temperature, chemicals, etc.
- **Processing**: The compatibility of the material with desired manufacturing techniques.
- **Production rate**: How efficiently the material can be processed into the finished product.
- **Cost**: The overall economic feasibility of using the material, considering both material price and processing costs.

By prioritizing these requirements and understanding their relevance to the specific application, engineers can make informed decisions and identify the most suitable material for the job.

2.3.2 Shortlisting Materials and Processes

Once application requirements are defined, the next step is to identify potential material-process combinations that meet those needs. This is crucial for composite materials, where material selection often dictates the feasible manufacturing process. To narrow down the possibilities, engineers establish minimum or maximum requirements for both the material and the process. These requirements should be phrased to yield clear “yes” or “no” answers. Material selection charts (also called Ashby charts) are commonly used for this purpose [23]. This screening phase helps eliminate unsuitable options and focuses attention on promising material-process combinations for further consideration. This process involves consulting material databases from suppliers and reference handbooks. This ensures access to the latest information on available materials and their properties.

2.3.3 Determination of Best Material-Process Combinations

After shortlisting potential materials, the next step is to identify the optimal choice for the specific application. During the conceptual design phase, it is beneficial to consider multiple material-process combinations to explore creative and innovative solutions. This keeps design options open. For example, a composite fan blade could be manufactured using RTM, vacuum infusion, or prepreg, using carbon, glass or natural fibers, each offering advantages in weight, cost, and performance compared to conventional steel or aluminum options.

Compare the pros and cons of each material-process combination with the established design requirements. Evaluate the cost, weight, and performance for each design concept. Finite Element Analysis may be performed to determine the stresses, in order to optimize the design. A thorough understanding of the product and its requirements is crucial for selecting the most suitable material and manufacturing process.

2.3.4 Verification by Prototype Testing

Once candidate materials and manufacturing processes are chosen, the next step is to validate the design through prototype testing. The testing considerations include the number of prototypes (depending on the criticality of application), static and dynamic tests under various service conditions (humidity, chemicals, temperature, etc.), and simulation of worst-case scenarios (sequencing tests like thermal cycling, impact, etc.) to reveal potential weaknesses [24].

3 Composite Fabrication Techniques

The composite material fabrication techniques are highly specific to the matrix as well as reinforcement geometry [24]. The most commonly used techniques for thermoplastic and thermoset matrices, along with continuous and discontinuous reinforcements are given in Fig. 9.

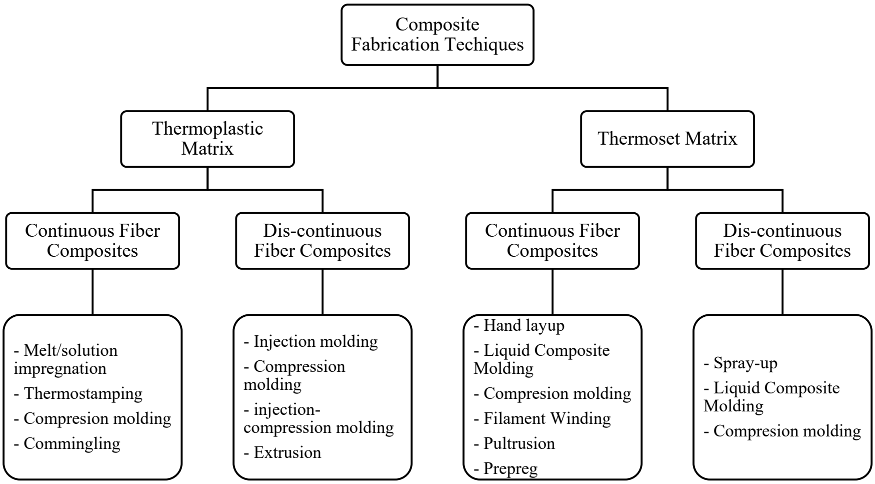


Fig. 9 Composite fabrication techniques w.r.t. matrix and reinforcement geometry [25, 26]

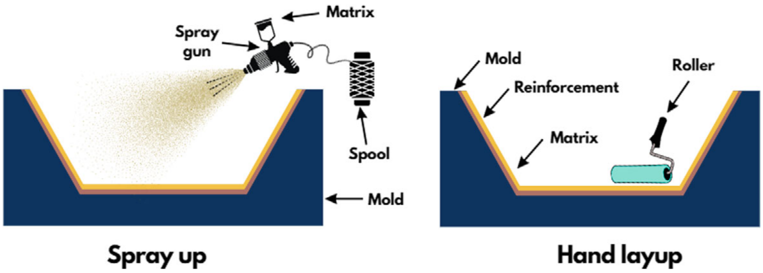


Fig. 10 Schematic of spray up and hand layup process

3.1 Hand Layup

Hand lay-up is the least expensive and most common approach of composite fabrication and is attributed as an open-molding method, requiring no specific equipment. The fibrous reinforcement is placed in the mold by hand and impregnated with resin using a brush [27]. Consolidation and resin distribution is also achieved by the action of this roller. The resulting laminate is then allowed to cure in place without further treatment. The schematic of hand layup process is given in Fig. 10.

3.2 Spray-Up

Spray-up is also an open molding technique, similar to hand layup, but is an automated version. It utilizes a chopper gun to chop reinforcement materials into short fibers, then mixes them with resin. This combined mixture, called "chop," is then sprayed directly onto a mold surface. This automation makes spray-up a faster option than hand lay-up, particularly for producing large parts or high volumes of composite components. The schematic of hand layup process is given in Fig. 10.

3.3 Liquid Composite Molding

There are some variants of liquid composite molding technique, including vacuum bagging, vacuum resin infusion and resin transfer molding, as shown in Fig. 11. In vacuum bag molding process, the fibrous reinforcement is placed by hand in a mold and impregnated with resin using a brush. Subsequently, this mold /laminate is sealed with a vacuum bag. Once the vacuum is created, it forces out the air trapped in the fibrous structure and removes excess resin, thus compacting the laminate and providing uniform distribution of matrix. This technique helps eliminate excess resin that builds up when structures are made using open-molding technique.

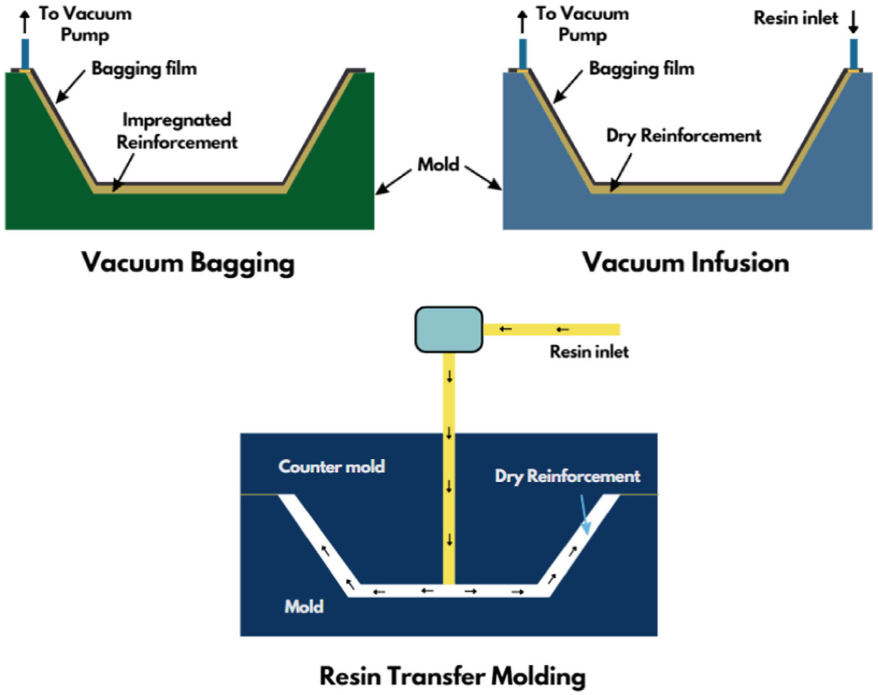


Fig. 11 Schematic of vacuum bagging, vacuum resin infusion and resin transfer molding

Vacuum Resin Infusion (VRI) is a cost-effective technique for creating strong, lightweight composite laminates with minimal emissions. It utilizes a vacuum pump to draw resin into a dry laminate stack sealed within a mold. Similar to the open-molding process, VRI requires minimal equipment (a mold and vacuum pump), and accessories (vacuum bag, peel ply, breather film, sealant tape, etc.) and offers design flexibility. Dry reinforcement along with other accessories is placed in the mold and sealed with a vacuum bag. There are a minimum of two connections made to the bag, one for inlet of resin and other for the vacuum pump (to remove air). Leak tightness of vacuum bag is tested by closing the resin inlet, switching on the vacuum pump, and checking the vacuum level (it should be more than 95%). The resin and hardener are mixed according to given ratios in a supply container and resin supply is opened. The pressure difference between atmospheric pressure and the applied vacuum drives resin into the mold cavity. Once the liquid resin has infused through the whole laminate, it is allowed to cure for a period of time, depending on the resin system and part size. Once fully infused, the resin cures, and the part can be removed from the mold.

Resin Transfer Molding (RTM) is a closed-molding process suitable for complex parts with high-quality surface finishes. Dry reinforcements are placed in the mold, which is then closed with a counter mold and clamped. Resin is injected under pressure through designated ports into the mold cavity, impregnating the reinforcements.

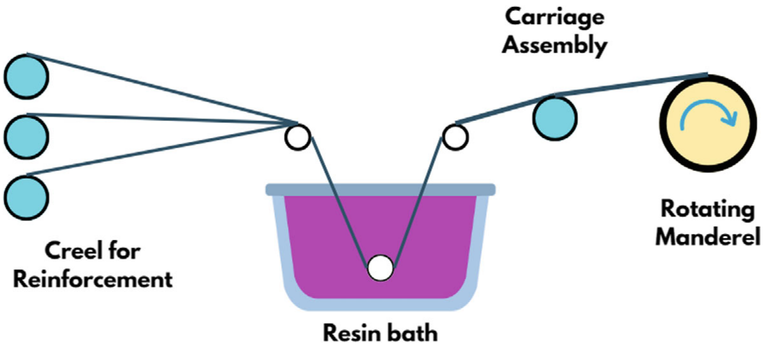


Fig. 12 Schematic of filament winding process

RTM allows for more intricate designs with various fiber combinations and orientations due to the dry placement within the mold. This process can be automated for faster cycle times and is commonly used for low-volume production of parts like boat hulls and car components.

3.4 Filament Winding

This process is used specifically to produce composite parts with cylindrical geometry. Fibers are drawn from the spools placed on a creel and impregnated with resin in a bath (Fig. 12). A carriage assembly then guides these wet fibers on to a rotating mandrel layer by layer, to build up the desired thickness. Once complete, the mandrel is taken off the machine, and resin in allowed to cure. The solid composite part is then taken off the mandrel. The mandrel is either collapsable or dissolvable for easy removal. In some cases, the mandrel serves as a liber and may be left inside the composite part. It is a recommended technique for the production of pressure vessels, due to the circumferential orientation of fibers, which provides high hoop strength for containing pressure. However, this technique is limited to the production of axisymmetric parts only (shapes with a circular cross-section throughout their length). Additionally, achieving low void content (air pockets within the composite) can be challenging without using an autoclave (a pressurized oven for curing). For thick parts, the process might have to be paused to allow partial curing of initial layers before adding more, as the pressure from additional layers can force out resin.

3.5 Pultrusion

In the pultrusion process, fibers/roving are pulled from a set of spools placed on a creel and through a resin bath, as shown in Fig. 13. These impregnated fibers/

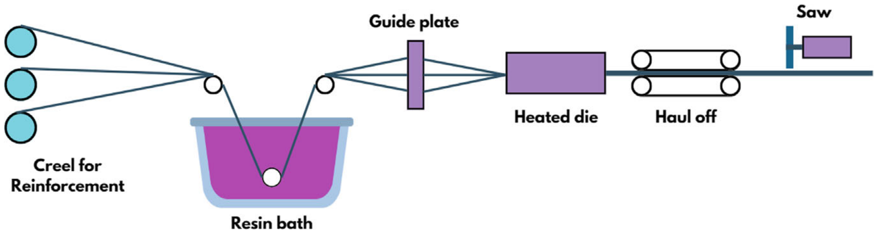


Fig. 13 Schematic of pultrusion process

roving are then passed through a pre-former, which aligns the fibers/roving into the required cross-sectional shape. The subsequent forming and curing dies shape the composite part, remove excess resin and cure the composite. Once cured, the composite part is cut according to the required length. The process of pultrusion is highly recommended for high volume and continuous production of composite parts with high fiber density. However, this process is limited to the production of parts with uniform cross-sectional area.

3.6 Prepreg

Prepreg is a sheet, tape, or tow of fibrous reinforcement pre-impregnated with resin. The most common reinforcement geometries for prepreg are unidirectional fibers or woven fabrics. The resin in prepregs is cured up to certain %age only and is therefore regarded as an intermediate form of composite material. These prepregs can be easily consolidated into the desired product through a simple thermoforming process, enabling quicker production rates and increased efficiency. Other key advantages of using prepregs include excellent control of fiber content %, short manufacturing process, lesser toxicity and reduced energy cost.

3.7 Injection Molding

It is a closed-mold technique, suitable for processing thermoplastic matrices and chopped fibers. There are two variants of this technique, including direct injection molding and extrusion-injection molding. For both variations, it is critical to optimize factors like screw speed, injection pressure, and mold cooling rate to achieve the desired composite part and properties [28].

Direct injection molding feeds both chopped fibers and polymer granules directly into the barrel of machine. Here, heat melts the thermoplastic matrix while a rotating screw ensures even mixing of fibers and polymer. This high-pressure mixture is then forced through a nozzle and into the mold cavity, as shown in Fig. 14a. In some cases,

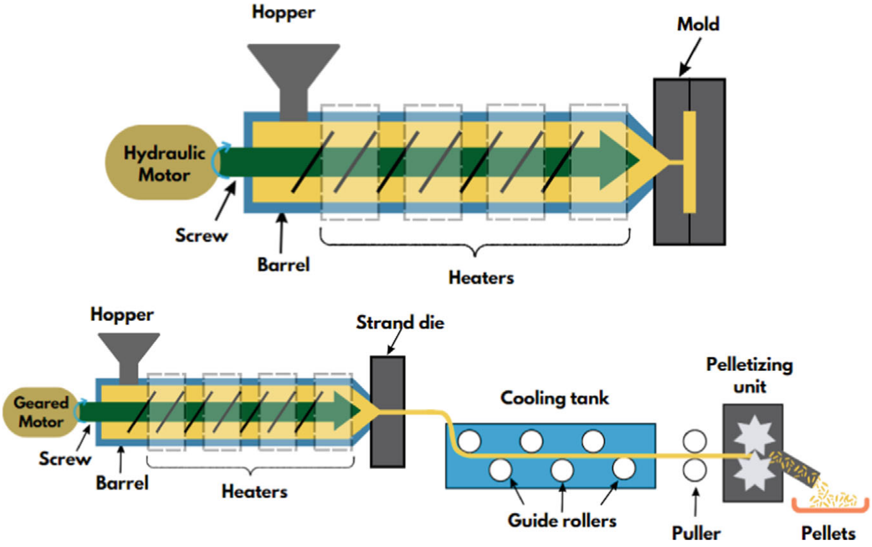


Fig. 14 Schematic of direct injection molding and extrusion-injection molding

an additional hopper might be present near the screw's end to introduce fibers later in the process, protecting them from heat and shearing forces within the barrel.

Extrusion-injection molding takes a two-stage approach. First, the process extrudes a continuous strand of polymer and chopped fibers, which is then chopped into pellets, as shown in Fig. 14b. These fiber-reinforced pellets become the feedstock for the second stage, where they are fed into a standard injection molding machine. Similar to the first method, heat melts the pellets in the barrel before injecting them into the mold cavity.

3.8 Compression Molding

Compression molding offers a compelling combination of speed, quality, and cost-effectiveness for manufacturing composite parts. This process involves placing the composite material between two molds (heat is optional) and applying significant pressure as shown in Fig. 15. The combination of pressure and heat (if used) cures the part, resulting in fast cycle times and a high degree of uniformity between parts. Additionally, compression molding has advantages in terms of design flexibility, allowing for the creation of complex shapes, and labor costs, as the process is less labor-intensive compared to some alternatives. The resulting parts often benefit from a smooth surface finish as well.

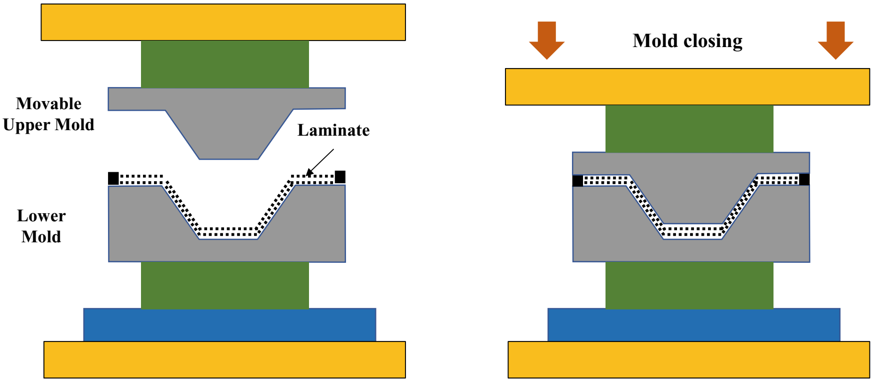


Fig. 15 Schematic of compression molding

3.9 *Melt/Solution Impregnation*

Thermoplastic composite preforms are pre-impregnated fibrous reinforcements produced by two main approaches, namely melt impregnation and solution impregnation. Melt impregnation (also termed as hot melt impregnation) is a widely used technique that involves pulling reinforcement fibers through a molten thermoplastic bath within a die. A constant tension is maintained on the fibers to ensure they are continuously fed and avoids tangles or breaks. The final fiber volume fraction in the prepreg is controlled by factors like the speed at which the fibers are pulled, the amount of molten plastic applied, and the die's opening size.

Solution impregnation (solvent-based impregnation) method utilizes a solution of a thermoplastic dissolved in a solvent to impregnate the fibers. The low viscosity of the solution allows for better penetration into the fibers. However, the solvent needs to be removed afterwards, making this process less environmentally friendly. Solution impregnation is more suitable for amorphous thermoplastics due to their looser molecular structure, which allows for easier dissolving compared to semi-crystalline thermoplastics.

The melt impregnation process (also termed as hot melt impregnation) is highly used pre-impregnation processes for the production of thermoplastic preforms. In this process, impregnation is achieved by passing reinforcement fibers through a thermoplastic matrix in a mold (die), as shown in Fig. 16. A uniform tension is applied on the reinforcement fibers throughout the process to ensure the continuous fiber pulling and avoid slackness, crossing or entanglement of fiber tows. The fiber volume fraction in these preforms is controlled by process parameters, including number of fiber tows, feed rate of thermoplastic melt, pulling speed, tension on fiber tow, aperture diameter, etc.

Solution impregnation, also known as solvent-based impregnation, is a technique specifically suited for amorphous thermoplastics. In this process, the thermoplastic matrix is dissolved in a solvent to create a low-viscosity solution. This solution is

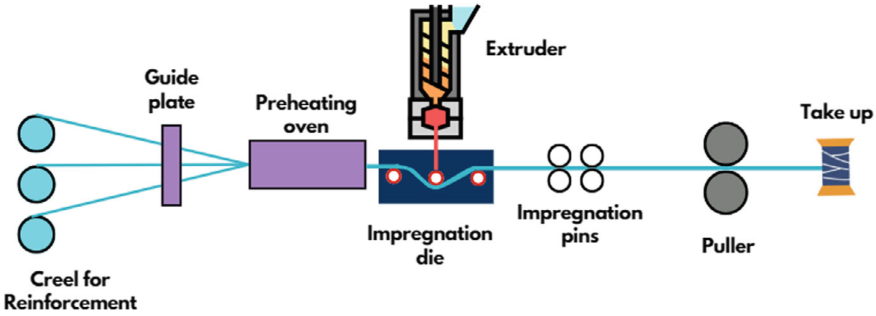


Fig. 16 Schematic of melt impregnation process

then used to impregnate the fibers. Since amorphous thermoplastics have a less dense, nanocrystalline structure compared to semicrystalline thermoplastics, they dissolve more readily in solvents, making this approach particularly effective for them. After the impregnation is complete, the solvent is removed from the material [25].

3.10 Commingling

Commingling offers a unique approach to creating thermoplastic composite preforms. This technique involves combining different continuous fibers into commingled-filament yarns. In the context of composite manufacturing, commingling is often used to blend reinforcement fibers with thermoplastics to produce these special yarns. The resulting commingled yarns can then be further processed into various preform shapes through techniques like stitching, weaving, or braiding. These preforms then become the starting point for manufacturing thermoplastic composite products using processes like compression molding. A key advantage of commingled preforms is their good drapeability, which is attributed to the inherent flexibility of both the reinforcement fibers and the thermoplastic polymer fibers [25].

The commingling technique is continuously advanced. Commingling can be achieved either at filament or yarn level. The filament level commingling approach is schematically shown in Fig. 8. The reinforcement and polymer filaments are produced and commingled before winding, producing a perfectly commingled yarn. This approach is more economical as compared to yarn level commingling, which involves doubling/winding of polymer filaments and reinforcement filaments together, which produces a side-by-side commingled yarn. It involves additional processes of packing, transferring or yarns and unwinding. The structure of both perfectly commingled and side-by-side commingled yarns is shown in Fig. 17.

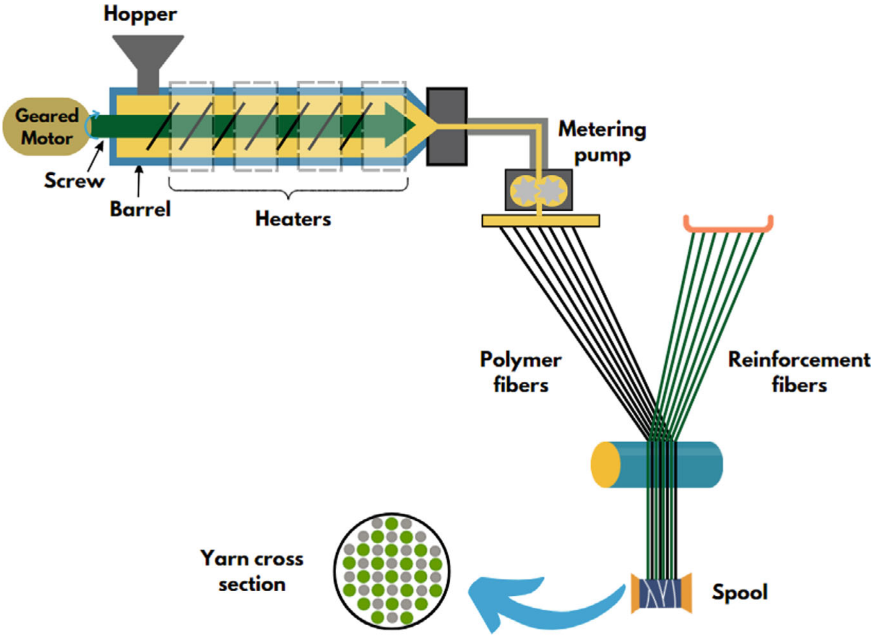


Fig. 17 Schematic of filament level commingling process

3.11 Selection of Fabrication Process

The selection of an appropriate composite fabrication process depends on three main parameters including raw material properties, product geometry and process economics, as shown in Fig. 18. Material properties include reinforcement form, matrix type and volumetric composition, and their effect has already been explained in Fig. 4. Product geometry is the main deciding factor in the selection of composite fabrication process. For example, filament winding is specific to cylindrical objects, only constant cross section parts can be produced by pultrusion, spray up cannot be used for more complex shapes, etc. Process economy is another leading factor in the selection of fabrication process. Some processes are too costly, in terms of capital investment, operating cost, mold cost, use of consumables, labor intensive, batch process, etc. All these parameters are carefully considered, and an optimum process is selected satisfying our material and geometry requirements, along with process economy.

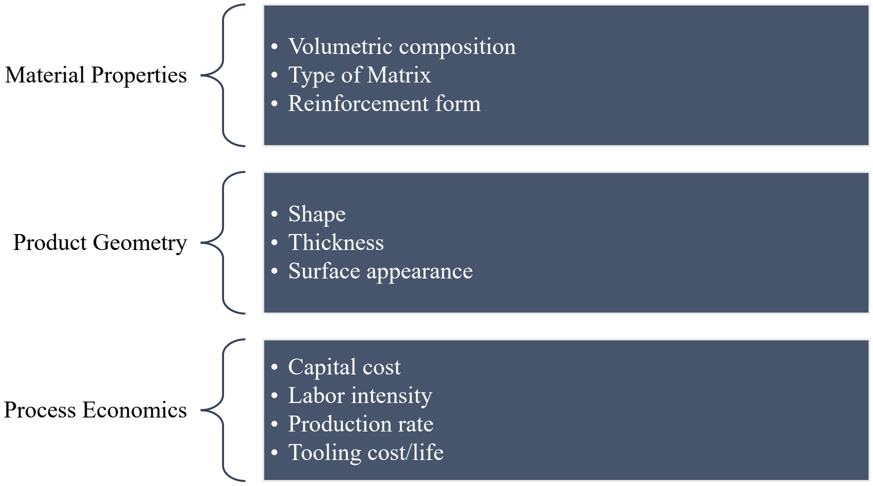


Fig. 18 Parameters affecting the selection of composite fabrication process

4 Properties and Applications

The composite materials are used owing to their ability to meet unique set of requirements specific to certain application areas. The most determined properties of composite materials include physical (e.g., density, voids, fiber volume fraction, etc.), chemical (resistance to acids, alkalis, etc.), thermal (e.g., thermal expansion, electrical conductivity) and mechanical properties (e.g., tensile strength, flexural strength, impact resistance). The requirements of a particular set of performance properties are decided on the basis of application area of the composite material. These properties are tested according to defined standard test methods [29], as given in Table 2.

5 Technological Developments and Future Trends

The domain of composite materials is experiencing a steady growth as well as exciting technological advancements. In terms of reinforcement material, researchers are exploring materials like high-performance carbon fibers and their hybrids with other fibers, sustainable fibers, and are exploring into incorporating nanomaterials for enhanced properties. Novel matrix materials are also being developed, focusing on bio-based polymers, shape memory polymers and self-healing polymers for sustainable and advanced applications of composites.

Manufacturing innovations are playing a crucial role in shaping the future of composites. Additive manufacturing techniques like 3D printing are enabling the

Table 2 Standard test methods used to determine the physical, thermal and mechanical properties of composite materials

Sr. No.	Category	Property	Test method
1	Physical properties	Density of polymer	ASTM D792—20
2		Void content	ASTM D2734—09
3		Constituent content	ASTM D3171—15
4		Moisture absorption	ASTM D5229—14
5	Thermal properties	Glass transition temperatures and enthalpies of crystallization and fusion	ASTM D3418—15 (by DSC)
6		Linear thermal expansion	ASTM E831—14 (by TMA)
7		Compositional analysis	ASTM E1131—20 (by TGA)
8	Mechanical properties	Tensile properties	ASTM D3039
9		Compressive properties	
10		- End-loading - Through shear at wedge grip interface - Combined shear and end loading flexural testing - Three-point bending test - Four-point bending test	ASTM D695 ASTM D3410M ASTM D6641M ASTM D7264 ASTM D6272
11		Impact testing	
		- Drop weight - Charpy - Izod	ASTM D7136 ASTM D6110 ASTM D256
12		Shear properties	
		- In-plane shear - V-notched rail shear	ASTM D3518 ASTM D7078

creation of complex composite structures with precise fiber architecture, while automated processes are improving production efficiency and consistency. Sustainability is a top priority, driving the development of eco-friendly approaches. Bio-derived resins and biodegradable fibers are being explored to minimize environmental impact. Additionally, research into closed-loop recycling processes for composites is gaining traction, aiming to reduce waste and create a more circular economy for these valuable materials.

6 Conclusion

Composite materials owing to their tailorable nature and versatile properties are used for a number of applications including sports, automotive, construction, aerospace and defense applications. This chapter comprehensively covered the different aspects of composite materials including its constituents (reinforcement and matrix) and their classifications, along with the material selection criteria. The fabrication techniques for thermoplastic and thermosetting polymer composites including open molding (hand layup and spray up), liquid composite molding (vacuum bagging, vacuum infusion, resin transfer molding), filament winding, pultrusion, prepreg, injection molding, compression molding, commingling and melt/solution impregnation process were also discussed in detail. Brief insights on the selection of fabrication process were also included in the chapter. It concluded with some key application areas, technological developments, and future trends.

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Two-Dimensional Nanomaterials

Asif Hafeez

Abstract Two-dimensional (2D) nanomaterials have emerged as an attractive class of materials that exhibit unique properties and a broad range of applications. These atomically thin, planar structures offer an exceptional combination of physical and chemical properties that makes them desirable for futuristic applications. This book chapter provides a comprehensive overview of the synthesis and properties of 2D nanomaterials. This chapter begins with an exploration of various synthesis and fabrication techniques used for 2D nanomaterials, covering both top-down and bottom-up approaches. Top-down approaches such as mechanical exfoliation, liquid-phase exfoliation, and electrochemical techniques enable the isolation of atomically thin individual layers from the bulk parent materials. Bottom-up synthesis strategies including chemical vapor deposition, and solution-based synthesis allow for controlled and scalable production of 2D nanomaterials. Furthermore, the chapter examines the structural and chemical properties of 2D nanomaterials, highlighting their distinctive characteristics. The high surface area-to-volume ratio present in these materials provides unprecedented adsorption and catalytic capacity. The lateral dimension of these materials allows for exceptional charge carrier mobility, creating numerous opportunities in electronic applications. The inherent flexibility and ability to intercalate different species within the two-dimensional lattice further expands the functionality of these materials. The chapter concludes by addressing the challenges and future research directions in the field of 2D nanomaterials, highlighting the importance of overcoming scalability, stability, and integration-related issues to unlock their full potential.

Keywords Two-dimensional nanomaterials · Liquid-phase exfoliation · Graphene · Boron nitride

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1 Introduction

1.1 *Background and Significance of Two-Dimensional Nanomaterials*

The characteristics of the material change significantly as they approach the nanoscale. Nanotechnology involves the use of materials ranging from 1 to 100 nm. To meet the requirements of a specific application the ability to precisely alter and tailor the atomic and molecular structure of nanomaterials is crucial. Furthermore, the performance and functionality of the nanomaterials are dictated by their dimensions, structures, and shape. Nanomaterials exhibit a diverse range of structural configurations, encompassing a vast array of morphologies and dimensionalities, each with its unique properties and potential applications [1]. Nanomaterials are categorized into four distinct types based on their dimensional configuration, zero-dimensional (0D), one-dimensional (1D), two-dimensional (2D), or three-dimensional (3D). 2D nanomaterials exhibit an exceptionally thin, sheet-like structure. These atomically thin materials have a thickness of only a few atomic layers, while their lateral dimensions are beyond 100 nm. Furthermore, these layered structures have strong intraplanar covalent bonds and relatively weaker interplanar van der Waals (vdW) forces. The strong intraplanar bonding provides structural integrity and stability within each layer, while the weak interplanar vdW forces allow for easy interlayer sliding and flexibility.

1.2 *Historical Development and Discovery of Two-Dimensional Nanomaterials*

The advancement in the area of 2D nanomaterials has led to a better scientific understanding, which has led to improving the synthesis techniques involved to fine-tune their unique nanostructures. The investigation of 2D nanomaterials was initiated after the successful isolation of graphene from graphite in 2004, which steered the exploration and development of a wide range of atomically thin two-dimensional nanomaterials that presented exceptional properties [2]. Metal–organic frameworks (MOFs), covalent organic frameworks (COFs), hexagonal boron nitride (h-BN) [3–6], graphitic carbon nitride (g-C_3N_4) [7, 8], layered metal oxides [9, 10], transition metal dichalcogenides (TMDs) [11, 12], black phosphorus (BP), silicene, and MXenes exhibit exceptional properties and a broad range of applications, their 2D-structures are depicted in Fig. 1 [13]. Because of their exceptional qualities and distinctive structural features, 2D nanomaterials are essential in many fields, including biomedicine, electronics, sensors, catalysis, energy storage and conversion, and catalysis. To manipulate the properties of 2D nanomaterials, the development of various synthetic techniques can be categorized as either top-down or bottom-up

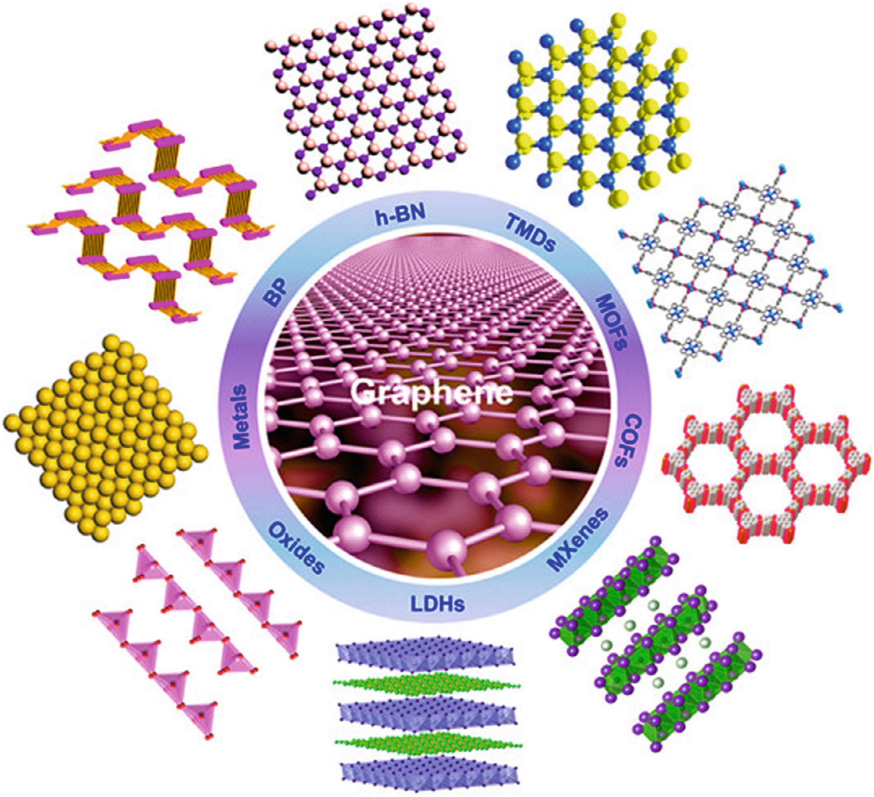

Fig. 1 Schematic representation of various kinds of two-dimensional nanomaterials [13]

methods. Top-down methods include mechanical cleavage, liquid-phase exfoliation, and ion-intercalation-assisted exfoliation. On the other hand, bottom-up methods encompass techniques like chemical vapor deposition (CVD) and wet-chemical synthesis.

2 Synthesis and Fabrication Methods

The methods used for the synthesis and fabrication of 2D nanomaterials dictate the quality, properties, and potential applications of these materials. The desired size and thickness, substrate onto which 2D material will be deposited, and degree of control over the growth process are crucial factors that must be carefully considered when selecting an appropriate synthesis technique for 2D nanomaterials. These key factors play a pivotal role in ensuring that the chosen synthesis approach aligns with

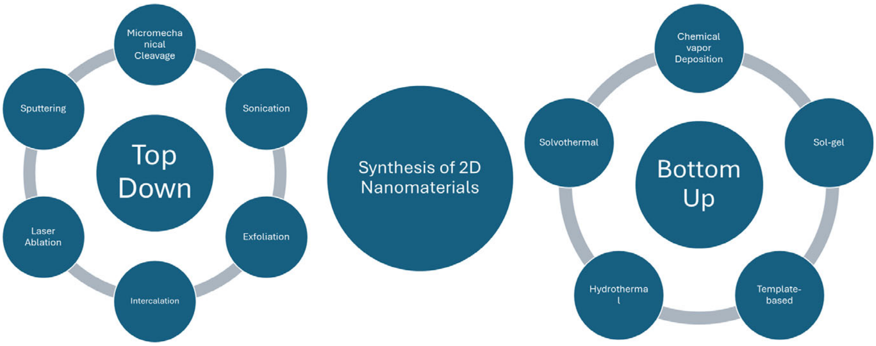

Fig. 2 Commonly employed approaches for synthesizing 2D nanomaterials: top-down and bottom-up methods

the specific requirements which enables tailored control over the synthesized nanomaterial properties [14]. The ultrathin two-dimensional nanomaterials are prepared by different synthetic techniques. There are two types of synthesis approaches for 2D nanomaterials: top-down and bottom-up, as shown in Fig. 2.

2.1 Top-Down Approach

The top-down technique is characterized by the reduction of large bulk materials into nano-sized particles. This subtractive method involves breaking down bulk nanomaterials, which are larger than 100 nm in all dimensions, into smaller structures using chemical and mechanical processes. In top-down approaches, the synthesis begins with bulk materials, and the layers are exfoliated or peeled off through various methods to obtain atomically ultrathin 2D sheets. Top-down approaches encompass techniques such as micromechanical cleavage, liquid-based exfoliation, and ion intercalation/exchange. These methods rely on the exfoliation of thin-layer 2D nanosheets from their parent layered bulk material. They are particularly suitable for bulk materials where the nanosheets are held together by weak van der Waals interactions [15]. However, besides being a facile synthesis technique for 2D nanomaterials, it is limited by the production of a broad distribution of particle shape and size.

2.1.1 Mechanical Milling

Ball milling is a notable and effective method employed in the production of 2D nanosheets. It is a fundamental technique that involves transferring kinetic energy from the grinding media to the material, leading to the separation of nanoscale sheets from the 2D nanomaterials, as depicted in Fig. 3. During this process, bulk materials are subjected to mechanical forces like grinding, shearing, or impact to reduce

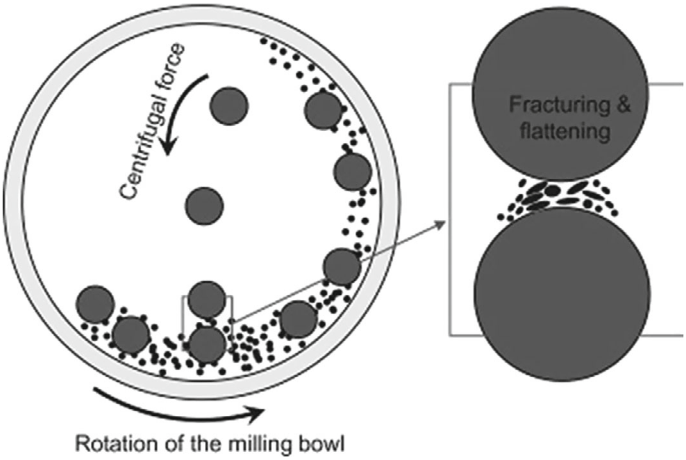

Fig. 3 Schematic of a high-energy ball mill [19]

them into nanoscale sheets. The rotation or vibration of the milling machine generates intense mechanical forces, primarily in the form of shear stresses. These shear stresses promote the separation and exfoliation of the layered structure in bulk materials. Mechanical milling enables the production of diverse nanoparticles and metal alloys, utilizing different materials. This process directly impacts the crystal size, particle size, and surface characteristics. Furthermore, these outcomes are influenced by the interaction between milling balls, milling time, ball-to-powder ratio, milling speed, and ball size [16]. An innovative and eco-friendly approach was developed for exfoliating graphene nanosheets by combining high-energy planetary ball milling with supercritical carbon dioxide. This method exhibited high efficiency and yielded graphene nanosheets up to 59%, resulting in highly dispersible flakes comprising predominantly less than 5 layers. The exfoliated graphene nanosheets showcased large graphitic domains and exhibited high electrical conductivity [17]. Two-dimensional (2D) nanomaterials, such as graphene and molybdenum disulfide (MoS_2), have unique properties due to their ultrathin thickness. Ball milling is an effective method for modifying materials at the nanoscale. Furthermore, the use of dry ball milling to fabricate MoS_2 nanopowders with excellent adsorption capabilities. The synthesized nanopowder exhibited excellent adsorption capacity for methylene blue and phenol, and the ball-milled MoS_2 nanopowders were found to be easily regenerated for reuse in dye adsorption [18].

2.1.2 Micromechanical Cleavage

The micromechanical cleavage technique, commonly known as Scotch tape exfoliation, is a widely employed method for generating thin flakes of layered bulk crystals like graphite. This technique leverages the mechanical force exerted by Scotch tape

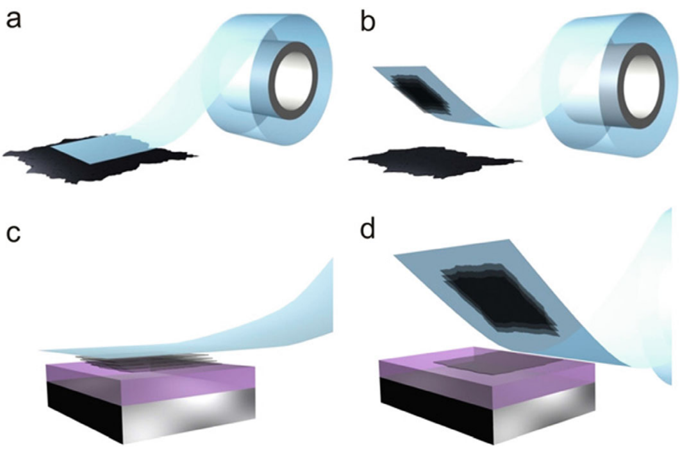

Fig. 4 The process of micromechanical exfoliation of 2D nanomaterials **a** adhesive tape is applied to a 2D nanomaterial, causing the top few layers to adhere to the tape, **b**, **c** the tape, carrying the layered material, is then pressed against a desired surface, **d** finally, when the tape is peeled off, the bottom layer of the 2D nanomaterial remains on the substrate [22]

to weaken the van der Waals interaction between the layers of the bulk crystal. As a result, single- or few layers of 2D crystals can be peeled off while maintaining the in-plane covalent bonds within each layer [20]. In the typical process, a bulk crystal is initially affixed to the adhesive side of Scotch tape. By repetitively removing the tape with another adhesive surface, thin flakes of the desired thickness can be obtained. The resulting thin flake, still adhered to the Scotch tape, is then transferred onto a clean target surface, such as SiO_2/Si. Subsequently, it is cleaved further by rubbing it with tools like plastic tweezers to separate the layers, leaving behind single- or few-layer nanosheets on the substrate. The final step involves detaching the Scotch tape, resulting in the isolation of mechanically exfoliated ultrathin 2D crystals on the substrate [21]. The optical microscope can be utilized to observe and identify the presence of these ultrathin 2D crystals, especially when suitable substrates are utilized. This technique provides a simple and accessible means of generating thin flakes of diverse 2D materials, facilitating the exploration of their distinctive properties and potential applications. It is important to acknowledge, however, that the Scotch tape method has limitations in terms of scalability and uniformity, particularly when aiming for large-scale production of high-quality 2D materials [20] (Fig. 4).

2.1.3 Liquid Phase Exfoliation

Exfoliation based on liquids is a collection of techniques that utilizes liquids as a medium to exfoliate 2D nanomaterials from bulk materials without the need for chemical oxidation. This encompasses a range of techniques that utilize liquid media for the exfoliation of layered bulk materials, going beyond ultrasonic exfoliation in organic solvents. These methods include liquid phase exfoliation facilitated by surfactants, ionic liquids, and salts, as well as electrochemical exfoliation in different liquid environments. Additionally, the shear exfoliation method is also a part of this category, as shown in Fig. 5. These top-down strategies are gaining more attention due to their facile nature and scalability for a wide variety of 2D nanomaterials. Based on mechanical forces, liquid phase exfoliation can be categorized into sonication, electrochemical, and shear force-assisted liquid exfoliation.

Sonication-Assisted Liquid Exfoliation

Sonication-based exfoliation in liquids encompasses a range of techniques utilized for the exfoliation of layered bulk nanomaterials into ultrathin 2D nanosheets in a liquid medium. Exfoliation through sonication is straightforward when there is a minimal difference in surface energy between the solvent and nanosheets, resulting in a lower mixing enthalpy. Thus, the surface energy of the solvent plays a crucial role in liquid-phase exfoliation. However, it is important to note that surface energy is highly dependent on temperature, which can be influenced by the intensity and duration of sonication. Enhancing the surface energy of the solvent can be achieved by

Fig. 5 The synthesis of 2D nanomaterials through direct exfoliation of layered bulk crystals using liquid-based methods [23]

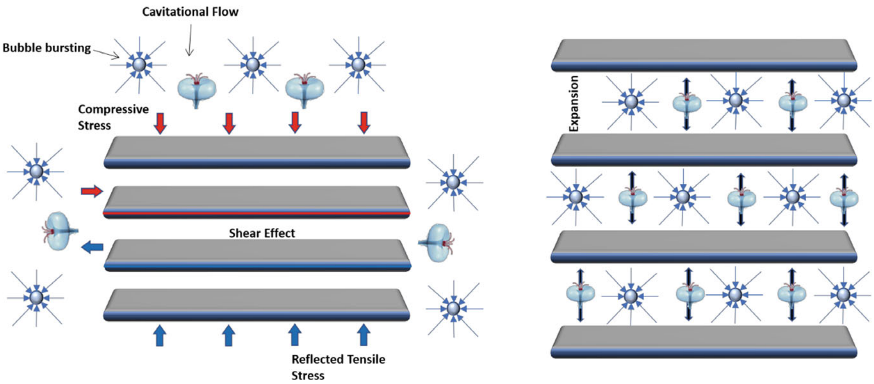

Fig. 6 Schematic illustration of exfoliation via sonication

incorporating co-solvents or solutes. Nonetheless, the use of harsh corrosive chemicals presents environmental risks and may introduce chemical impurities during the exfoliation process. The liquid-phase exfoliation through sonication is grounded on the liquid cavitation mechanism, the formation of small vapor-filled cavities in low-pressure areas i.e. between the nanosheet layers, as illustrated in Fig. 6. The cavitation-induced bubbles are distributed across the layered structure. The shockwaves and micro-jets are abruptly spawned as balanced bubble subsides resulting in compressive stress propagating throughout the 2D nanosheet body and an opposite tensile stress wave is reflected to the body. The unbalanced bubble bursting results in a shear effect driven to cleave the interlayers. Furthermore, a multitude of balanced and unbalanced subsiding bubbles results in exfoliated reduced dimensions nanosheets with edge and surface defects available for chemical functionalization [24].

Sonication-induced exfoliation splits bulk nanomaterials into few-layered nanosheets while enabling stable dispersion in various solvents. Liquid-phase exfoliation through sonication is based on the cavitation process, which is a relatively severe process creating localized hot spots of high temperature and pressures, and extreme temperature gradient areas due to rapid heating/cooling rates [25]. The sonication exfoliated nanosheets demonstrate defects on edges and basal planes due to the cavitational process. Liquid-phase sonication exfoliated graphene comprised of oxygen-containing functionalities bonded to the edge and hole-like defects in the basal planes [26]. Sonication operation conditions have a direct effect on defect sites and nanosheet size distribution. Shorter sonication time commences defects localized at the layer edges. Moreover, longer sonication time will rivet the basal planes [27]. Moreover, longer sonication time increased graphene nanosheet size distribution majorly comprising smaller nanosheets [28]. Many reducing-stabilizing agents including hydrazine [29], sodium borohydride ($NaBH_4$) [30], strong alkali [31], hydroquinone [32] and, ethylenediamine [33] have been employed for the effective reduction and exfoliation of various nanosheets in different solvent media [34]. Nevertheless, these agents are corrosive, toxic, and detrimental to the environment.

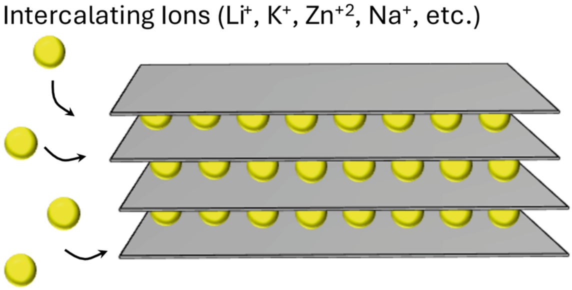

Fig. 7 Liquid-based exfoliation of 2D nanosheets through intercalation of ions

Urea being eco-friendly has been used as a reducing-stabilizing agent to prepare BN-nanostructures through bottom-up synthesis with B_2O_3 at 900 °C [35]. Furthermore, urea assists by reducing the liquid-phase exfoliation solvent surface tension and as a reducing-stabilizing agent in top–bottom synthesis of h-BN nanosheet by adsorbing on the BN surface and intercalating into the BN layered structure. The adsorption of urea on the surface and intercalation within the layers of the nanosheet weakens the strong van der Waals forces between the BN layers thus facilitating the exfoliation of the sheets from the BN flakes. This adsorption and intercalation of urea results in the wedging size reduction and exfoliation of the BN nanosheets. During the cavitational process of liquid-phase exfoliation, NH_2 groups attach to the edge and surface defects and prevent the restacking of BN sheets [6, 36, 37]. Additionally, isolation of few-layered BN nanosheets can be realized through the addition of amine group on edge and surface defects aids in triggering exfoliation and solubilization of h-BN nanosheets in polar solvents.

The liquid-phase exfoliation of 2D nanosheets by the ion intercalation is based on the principle of instigating cationic moieties such as Li^+, K^+, Zn^{2+}, Na^+, etc., in the interlayers of the bulk nanomaterials, as illustrated in Fig. 7. Intercalants, such as Li ions, play a crucial role in facilitating the exfoliation of bulk-layered crystals into 2D nanomaterials. When these intercalants are inserted, they significantly expand the interlayer spacings within the bulk crystals, leading to a drastic weakening of the interlayer interaction. As a result, the subsequent ultrasonication process becomes more effective in exfoliating the layered materials into 2D nanomaterials. The intercalation process impairs adjacent interlayer interaction by the introduction of a barrier in bulk nanomaterial. These ion-intercalated nanosheets are easily further exfoliated to single- or few-layers by mild sonication conditions. The exfoliated nanosheets can then be isolated through a centrifugation process. Gonzalez et al. (2018), obtained below 200 nm lateral-sized hydroxyl functionalized BN nanosheets from commercial grade h-BN nanosheets through intercalation of K^+ and Zn^{2+} cations, the process was coupled with a sonication-centrifugation technique [38]. The process can be tuned by altering the reaction time and temperature, initial size and concentration of the bulk h-BN crystals, sonication time, and, intercalation agents to obtain a desired number of layers, lateral size, and degree of crystallographic defects [39].

Chemical exfoliation is yet another method of sonication-assisted exfoliation which is aided by the usage of strong polar solvent which provides a synergistic effect to break bulk nanomaterials and readily yields mono and few-layered nanomaterials, which are essentially free of foreign matters like catalysts and the process is easy to be scaled up to large quantities [40]. Qiang et al. (2008) and Zhi et al. (2009) conducted a study where they successfully synthesized mono-/few-layered boron nitride nanosheets (BNNSs) using a combination of vigorous sonication and centrifugation [41, 42]. To increase the yield of boron nitride (BN) nanosheets, researchers have utilized highly polar solvents such as N, N-dimethylformamide (DMF) [42], N-methyl-pyrrolidone (NMP), and isopropanol (IPA) [40]. The utilization of highly polar solvents i.e., DMF, NMP, and IPA results in robust interactions with the bulk nanomaterial. Consequently, this leads to a significant improvement in the production of 2D nanosheets, facilitating their synthesis. To overcome the hazardous nature of polar solvents, water has emerged as an alternative solvent for the exfoliation of bulk nanomaterials. In a study conducted by Connell et al. (2011), water assisted the exfoliation process by hydrolyzing the planar defects and introducing hydroxyl functional groups which stabilized the nanosheet suspension [43].

Electrochemical Exfoliation

Electrochemical exfoliation is a synthesis technique employed to produce 2D nanomaterials. The method involves the application of an electric current to electrodes submerged in an electrolyte solution specifically chosen for the process. This electrical current causes the intercalation of ions into the layers of the material undergoing exfoliation, as shown in Fig. 8. Consequently, gas is generated at the anode or the interface between the electrode and electrolyte. The resulting gas expansion leads to the separation and thinning of the layers, producing high-quality two-dimensional sheets of the material. The notable efficiency and capability of electrochemical exfoliation in generating high-quality nanosheets, including graphene, make it an appealing choice [44]. This technique presents unique benefits compared to other methods, thanks to its simplicity, cost-effectiveness, and scalability. Electrochemical exfoliation, as a promising and scalable approach, enables the conversion of layered bulk materials into 2D nanosheets. The process involves anodic oxidation-cationic intercalation and cathodic exfoliation, utilizing a liquid electrolyte and an applied potential to induce structural expansion [45, 46]. Layered bulk materials possess robust covalent bonds within their planes and comparatively weaker out-of-plane bonds, held together by van der Waals interactions. By introducing cations or anions with high positive or negative charge, the weak interlayer bonds can be readily disrupted. As a result, the bulk material undergoes exfoliation, producing atomically thin 2D materials [47]. Exfoliated 2D materials exhibit tunable characteristics, including oxygen content, electrical conductivity, defect density, and thickness, which can be finely adjusted by modifying electrochemical parameters such as voltage and current, as well as the choice of electrolyte. It is noteworthy that successful exfoliation of various 2D bulk materials including graphite, BP, TMDs, GCN, MOFs, and MXene has been achieved using both anionic and cationic exfoliation and/or intercalation techniques.

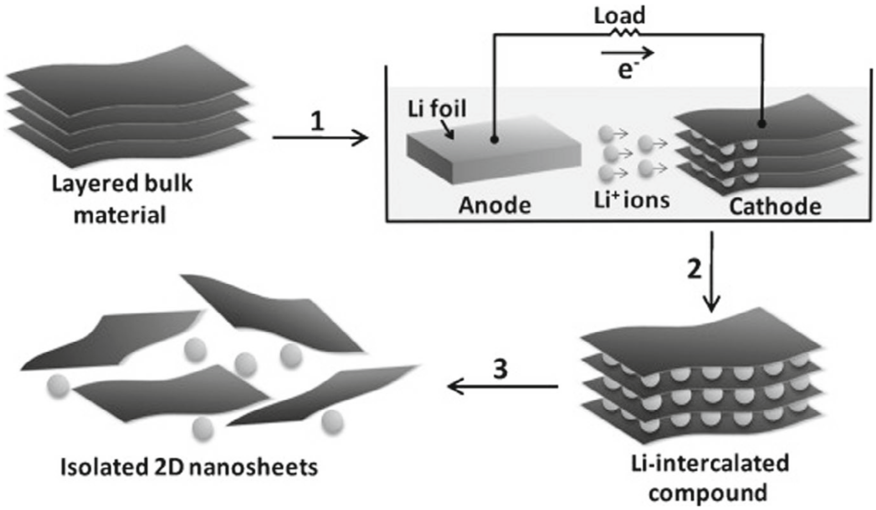

Fig. 8 The electrochemical exfoliation process is employed to fabricate 2D nanosheets from layered bulk materials [48]

Shear Exfoliation

High-shear mixing is a highly scalable method used for the solution exfoliation of 2D materials. In this technique, nanoparticle agglomerates are dispersed in a solution and exposed to viscous forces generated by high-velocity flow through a narrow channel. The viscous forces exert substantial shear forces on the 2D particles, leading to their exfoliation, as shown in Fig. 9. When combined with the weakening of van der Waals forces induced by the solvent solution, the shear forces in high-shear mixing effectively break the van der Waals bonds. Consequently, thinner sheets of the material are produced through the exfoliation process [49]. In the exfoliation process using high shear forces, the bulk layered materials are first treated with sulfuric acid. This treatment leads to the formation of intercalated intermediate products with weakened interplanar bonding. Subsequently, high shear forces are applied to exfoliate the layered nanomaterials, resulting in the production of thinner sheets [23].

2.2 Bottom-Up Approach

The bottom-up strategy involves the step-by-step construction of a substance, starting from individual molecules, atoms, or clusters. This approach is commonly used for industrial nano-powder production. Conversely, when the objective is to produce large-scale ultrathin nanosheets, the top-down technique is more appropriate. It is important to note that exfoliation techniques are primarily employed for materials that possess multi-layered bulk structures. In contrast, the bottom-up approach

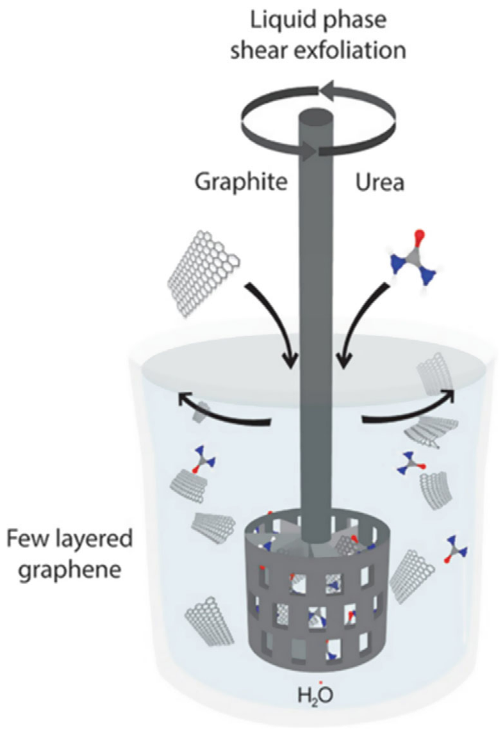

Fig. 9 Liquid-phase exfoliation of layered bulk material to a few layered 2D nanomaterials [50]

focuses on creating nanoscale components from atomic or molecular constituents. These constituents can react and grow in size or self-assemble into more complex structures. This bottom-up approach allows for the straightforward fabrication of 2D materials with desired chemical composition, size, shape, stacking arrangement, crystal structure, and edge or surface defects [51].

2.2.1 Hydro/Solvothermal Synthesis

Solvothermal and hydrothermal synthesis are versatile bottom-up methods used for the synthesis of nanomaterials in a liquid medium under high-temperature and high-pressure conditions. During this process, precursor materials are combined and placed in an autoclave reactor, as depicted in Fig. 10. The autoclave reactor operates under high-pressure conditions. In this method, the solvent plays a catalytic role in promoting the growth of nanoparticles [52, 53]. Hydrothermal synthesis utilizes water as the solvent, while solvothermal synthesis employs organic solvents. Both methods involve the crystallization process occurring directly from the solutions, which typically consists of two steps: crystal nucleation and subsequent growth. By carefully controlling various processing variables such as temperature, pH, reactant concentrations, and additives, it is possible to fabricate 2D nanomaterials with

Fig. 10 A general-purpose autoclave reactor. The hydro/solvo-thermal reaction occurs inside the PTFE cavity [57]

desired particle sizes and morphologies. The level of supersaturation dictates the balance between nucleation and growth rates of the nanoparticles. Furthermore, the modulation of these rates enables precise control over the size and morphology of the synthesized 2D nanomaterials [54]. Hydrothermal and solvothermal methods offer several advantages, including cost-effectiveness, the ability to produce a large number of nanomaterials, and the generation of highly crystalline nanocrystals (NCs) with precisely controlled dimensions. The combination of hydro/solvothermal techniques with microwave and magnetic field methods can achieve enhanced control and efficiency in the production of 2D nanomaterials [55]. Hydrothermal and solvothermal methods are effectively used for the preparation of various nanomaterials, including metal oxides, MOFs, and TMNs [56].

2.2.2 Chemical Vapor Deposition

Chemical vapor deposition (CVD) is a widely adopted bottom-up synthesis technique for the synthesis of 2D nanomaterials that require precise control over their size and morphology. The technique involves the formation of a thin film by chemical reaction over a heated substrate where the precursors are in the gas phase. CVD offers distinct advantages over physical vapor deposition methods like evaporation and sputtering. It relies on chemical reactions that enable adjustable deposition rates and the production of high-quality. In the CVD process, the reactant gases are introduced to the reactor. These gases can either undergo gas-phase reactions to form intermediate reactants and gaseous by-products, or they can directly diffuse through the boundary layer to the substrate surface. The reactant gases and intermediates then adsorb on the heated substrate surface and diffuse, leading to heterogeneous reactions at the gas–solid interface. This results in the formation of reaction by-products and the deposition of the thin film through nucleation, growth, and coalescence. Finally, the gaseous

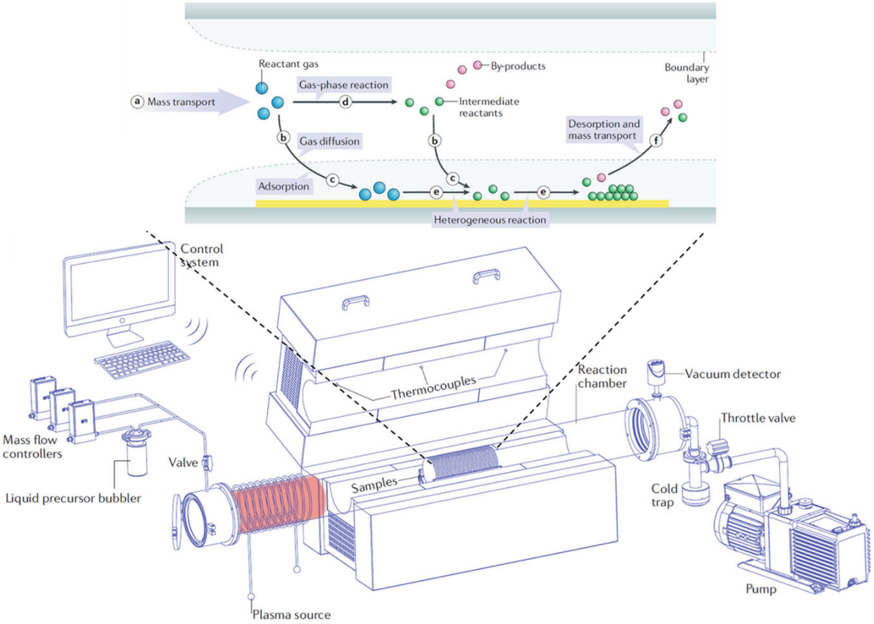

Fig. 11 Schematic diagram of a typical horizontal CVD system with a depiction of general elementary steps of a typical CVD process [58]

products and unreacted species desorb from the substrate surface and are carried out of the reaction zone, as shown in Fig. 11. The gas-phase reaction occurs at high temperatures or plasma for additional energy. By manipulating factors such as substrate selection, temperature, pressure, and gas concentration, it is possible to obtain thin film materials with varying sizes ranging from nanometers to millimeters. These films can exhibit diverse chemical and physical properties. CVD offers several advantages, including the production of uniformly coated films with high purity, low porosity, and excellent stability. While CVD is a versatile technique, it also has some drawbacks. CVD requires expensive instrumentation and generates toxic gaseous by-products during the reaction process. CVD can be categorized into different types, each with its unique characteristics. Some popular variations include plasma-assisted CVD, laser-enhanced CVD, and low-pressure CVD [58].

3 Structural and Chemical Properties

Ultrathin 2D nanomaterials, with their high aspect ratio, offer an incredible range of exceptional properties in terms of physical, chemical, optical, and electronics that set them apart from other nanomaterials. While certain properties can be generalized, it is crucial to acknowledge the diverse nature of these materials. Not all ultrathin

2D nanomaterials exhibit the same set of characteristics. For example, graphene demonstrates exceptionally high electrical conductivity, but it is not well-suited for semiconductor devices. In general, several unique advances have already been identified or revealed for ultrathin 2D nanomaterials. The isolation of electrons within two dimensions in ultrathin single-layer nanomaterials is a key factor that leads to their distinctive electronic properties. These unique electronic characteristics make ultrathin 2D nanomaterials highly suitable for optical and electronic applications [59]. Firstly, the strong intraplanar covalent bonding coupled with the atomic-scale thickness of 2D nanomaterials imparts exceptional mechanical properties in terms of strength and flexibility which makes them attractive for the development of emerging technologies [60]. Secondly, these 2D nanomaterials present ultrahigh-specific surface area which is attributed to their lateral size and their atomic-scale thickness. These distinctive characteristics make them highly attractive for surface-related applications such as energy storage and catalysis. This enhanced surface area facilitates improved interactions with reactants or electrolytes, leading to improved catalytic activity and energy storage capabilities in these types of applications [61]. Thirdly, the solution-based processability of ultrathin 2D nanomaterials is a huge advantage that enables the fabrication of high-quality freestanding thin films using facile techniques such as vacuum filtration, spin coating, drop casting, and spray-coating. This solution-based processability enables the applications of 2D nanomaterials in areas like energy generation and storage. The ability to form thin films through these simplistic techniques allows for scalable and cost-effective production of devices with desirable properties and performance [62]. Lastly, the high exposure of surface atoms in ultrathin 2D nanomaterials enables easy regulation of their properties and functionalities through surface modification and element doping. The ability to manipulate the surface allows for modifying 2D nanomaterial characteristics to meet specific application requirements. Through surface modification of these materials desired properties such as enhanced catalytic activity, improved electrical conductivity, and optimized optical properties are achievable [63, 64]. Some critical features of ultrathin 2D nanomaterials are discussed below.

3.1 Surface Area

2D nanomaterials are well reputed for their ultrahigh specific surface area which is attributed to the combination of large lateral size and atomic-scale thickness. Applications like energy harvesting, energy storage, and catalysis require a high surface-to-volume ratio which is an important attribute of 2D nanomaterials. In energy storage applications, the ultrahigh specific surface area of 2D nanomaterials provides a large active electrode–electrolyte interface, enabling efficient charge storage and rapid ion transport. This enhanced surface area is reflected in terms of improved energy density and storage capacity, which enables 2D nanomaterials application in supercapacitors. Furthermore, in applications entailing catalysis applications, the high specific surface area presents ample exposed surface atoms of ultrathin 2D nanomaterials which offer a larger number of active sites for chemical reactions. This facilitates improved catalytic activity and reaction efficiency, making them valuable for a wide range of catalytic processes. Ultrathin 2D nanomaterials have demonstrated excellent catalytic activities across a wide range of applications, including organic catalysis, electrocatalysis, and photocatalysis. For instance, single-layer rhodium (Rh) nanosheets are deemed highly efficient catalysts for organic reactions. The 100% surface exposure of Rh atoms in these single-layer nanomaterials provides an abundance of active sites for the reaction to occur, facilitating efficient catalytic conversion [65]. Graphene is known for its exceptionally high specific surface area, which can reach values as high as 2630 $m^2.g^{-1}$ [66]. This makes them highly attractive for applications that rely on surface interactions. Their high surface-to-volume ratio is a key advantage that makes them particularly attractive for developing next-generation drug delivery nanoplatforms [67]. This atomically thin interface facilitates enhanced interactions with drugs or biomolecules, leading to improved drug delivery efficiency and more targeted therapeutic effects [68].

3.2 Charge Carrier Mobility

2D nanomaterials exhibit excellent charge carrier mobility upon the application of an electrical field. This property is crucial in determining the charge transportation efficiency in an electronic device. The morphology of 2D nanomaterials, lattice defects, and interactions determines the charge transport efficiency. 2D nanomaterial having the ability to transport charge efficiently becomes a strong candidate for applications in electronic applications which also includes energy harvesting. 2D nanomaterials that demonstrate high charge carrier mobility are black phosphorus, 2D perovskite active layers, transition metal dichalcogenides (TMDs), and graphene. Graphene is known for its exceptionally high carrier mobility of as high as 10,000 $cm^2 V^{-1} s^{-1}$ at room temperature. This property makes graphene a promising material for high-speed electronic devices and transparent conductive electrodes. Similarly, few-layered black phosphorus exhibits a wide range of bandgap (~0.3–2.1 eV) and has shown considerable carrier mobility. The field-effect carrier mobility for electrons in few-layered black phosphorus has been measured at around 1000 $cm^2 V^{-1} s^{-1}$ [69]. These values indicate the potential of black phosphorus for applications in electronic and optoelectronic devices. The utilization of 2D boron nitride (BN) in combination with nano-fibrillated cellulose has led to the development of nanocomposite paper with remarkably high thermal conductivity. This nanocomposite paper has demonstrated a thermal conductivity of 145.7 W/mK, comparable to that of aluminum alloys. The two-dimensionality of the BN nanosheets contributes to their ability to facilitate the fast transport of electrons and ions, thereby influencing the thermal and electrical properties of the resulting nanocomposites. By incorporating appropriately doped 2D nanomaterials into desired nanocomposites, the thermal and electrical properties can be further adjusted and tuned. This highlights the versatility and potential for tailoring the properties of nanocomposites by leveraging the unique characteristics of 2D nanomaterials [1, 70].

3.3 Flexibility

Ultrathin 2D nanomaterials exhibit exceptional mechanical strength and flexibility which is due to their atomic-scale thickness and strong in-plane covalent bonding. The traditional strain sensors which are fabricated from semiconductors and metals are fragile and rigid. However, the flexibility of these 2D nanomaterials assists in designing and developing flexible electronic sensors and devices including wearable electronics [71, 72]. Graphene serves as a compelling example of exceptional mechanical properties in 2D nanomaterials. It exhibits remarkable breaking strength, with measured values as high as 42 $N\ m^{-1}$, and Young's modulus of 1.0 TPa [73]. These values demonstrate that graphene is not only the thinnest material but also possesses the strongest mechanical strength among known materials. In addition to its impressive mechanical strength, graphene also exhibits remarkable flexibility. It can endure elastic deformations of more than 20% without breaking, highlighting its excellent flexibility and resilience [73]. This property allows graphene-based composites to maintain their structural integrity and functional performance even when subjected to various mechanical deformations. This flexibility and robustness are particularly advantageous for the development of conformable electronic systems. While graphene has demonstrated excellent mechanical properties as an ultrathin 2D nanomaterial, it is not the only material in this category with such properties. Single-layer molybdenum disulfide (MoS_2) nanosheets exhibit remarkable mechanical properties, with a measured Young's modulus of approximately 270 GPa. This value is notably superior to that of bulk MoS_2, which is around 240 GPa. Interestingly, Young's modulus of these single-layer MoS_2 nanosheets surpasses that of steel, which is approximately 205 GPa [74]. The single-layered MoS_2 nanosheets exhibit superior mechanical properties that make them attractive for applications that require conformability like flexible electronics, nanomechanical devices, and structural materials. The high Young's modulus of these 2D nanomaterials indicates their ability to withstand large deformation making them suitable for applications demanding strength and resilience.

3.4 Intercalation Ability

The distinctive structural properties of layered 2D nanomaterials, and their well-defined and readily accessible interplanar spacing, allow the facile and reversible incorporation of a wide variety of interclating species. This ability to undergo intercalation is a beneficial attribute that opens vast opportunities to customize the material properties and functionalities [75]. The intercalation phenomenon observed in layered 2D nanomaterials, such as manganese dioxide (MnO_2), indicates its applications over a wide range of applications. Layered MnO_2 has been able to intercalate a variety of metal ions like K^+, Na^+, Li^+, and Mg^{2+} [76]. By modulating the interplanar spacing of these 2D nanomaterials, the accessibility of ion diffusion and transportation throughout the material can be delicately regulated. The ability of layered MnO_2 to reversibly intercalate and de-intercalate various metal ions enables its use in advanced energy storage devices. The reversible intercalation of Li^+ or Na^+ ions into the interplanar spacing of MnO_2 can facilitate the development of high-capacity, high-energy–density electrode materials. The controlled and reversible nature of the intercalation process enables the repeated charging and discharging of these battery systems, leading to improved cycle life and overall performance. The ability of MXenes to reversibly intercalate and deintercalate Na^+ and K^+ ions within their layered structure is a key attribute that enables their use as high-performance electrode materials in enhanced energy storage batteries with improved performance [77]. The ability of layered 2D nanomaterials to undergo intercalation can be extensively exploited in various sectors, including energy storage, environmental applications, catalysis, and medicinal applications. By intercalating different species, these materials can be tailored for specific functions, enabling advancements in energy technologies, environmental remediation, catalyst design, and drug delivery systems.

3.5 Functionalization

The inherent characteristics of 2D nanomaterials, such as their atomic-scale thickness and high surface-to-volume ratio, allow the modulation of their physical and chemical properties. The exposed surface atoms in these ultra-thin materials serve as a scaffold for their modification and control over their end-product properties. The process of surface modification allows for the introduction of specific functional groups, molecules, or nanostructures onto the exposed surfaces of 2D nanomaterials. Furthermore, it can customize their surface chemistry, electronic properties, and their ability to interact with surrounding entities [60]. The surface modification of 2D nanomaterials is achieved through both non-covalent and covalent interactions. Non-covalent interactions play a significant role in the functionalization of 2D nanomaterials by allowing the attachment of molecules, atoms, or ions to their surfaces. These interactions include vdW forces, H-bonding, electrostatic, π–π stacking, and/or a combination of these interactions. vdW forces involve weak attracting forces between atoms or molecules due to temporary electron density fluctuations. These forces can lead to the adsorption or binding of species onto the 2D nanomaterial surfaces. Hydrogen bonding involves the electrostatic attraction between a hydrogen atom attached to an electronegative atom and another electronegative atom. This type of interaction is particularly important in biological systems and can facilitate the adsorption or assembly of molecules on 2D nanomaterial surfaces. Electrostatic interactions occur between charged species, such as ions or polar molecules, and the charged surface of 2D nanomaterials. These interactions can be attractive or repulsive, depending on the charges involved, and can be utilized to immobilize or manipulate charged species on the material surface. π–π stacking interactions are particularly relevant for graphene and other 2D nanomaterials that contain conjugation and it occurs between aromatic systems and can lead to the stacking of molecules or conjugated systems on 2D nanomaterial surfaces [5].

Covalent interactions involve the formation of chemical bonds between the targeted species and the active groups present on the surface of 2D nanomaterials. This covalent bonding provides strong and stable attachment. The majority of the 2D nanomaterials contain -OH and -COOH functional groups on their surface which participate in chemical reactions and play an active role in the functionalization of the 2D nanomaterials [6]. These -OH and -COOH functional groups serve as reaction sites for further modification or act as anchor points for the attachment of other complex molecules. By selectively introducing functional groups the specific properties such as catalytic activity, chemical reactivity, or stability can be improved to suit desired applications.

4 Technological Developments and Future Trends

The past decade has witnessed remarkable progress in ultrathin 2D nanomaterials, broadening our understanding of their properties and unveiling a wide range of potential applications. These atomically thin materials with exposed surface atoms possess unique properties that have been extensively studied and utilized. The rapid advancement in the field of ultrathin 2D nanomaterials is driven by their diverse applications like electronics, energy harvesting/storage, catalysis, sensing, and biomedical applications [75]. These materials offer high surface area which is favored for facile functionalization to modify their electronic properties, reactivity, and stability. Which is highly desirable because it provides an opportunity to tailor specific properties for specific applications. These 2D nanomaterials can be synthesized through a wide range of synthesis techniques which enables the customization of their morphology. There are two approaches to synthesize ultrathin 2D nanomaterials which are top-down and bottom-up. Through the selection of an appropriate synthesis route and optimizing the synthesis parameters the morphology of ultrathin 2D nanomaterials is precisely controlled. The lateral and transverse dimensions influence the mechanical, electronic, and optical properties, while the crystal phase and crystallinity affect their stability and reactivity. The properties of 2D nanomaterials can be easily modified through functionalization, intercalation, and introduction of lattice defects, and dopants which change the interaction with the target species, electron band structure, and catalytic activity.

The field of ultrathin 2D nanomaterials has made a considerable advancement. However, there are still challenges to overcome, especially in the synthesis and control of their structural features. Achieving high-yield and large-scale production of ultrathin 2D nanomaterials that meet the requirements for industrial or commercial applications remains a key challenge. Current synthesis techniques frequently encounter constraints related to production yield, quality, quantity, and production rate. Another challenge is the precise control over the nanostructure of ultrathin 2D nanomaterials during synthesis. The physical and chemical properties are strongly associated with structural characteristics, such as size, thickness, crystal phase, defect density, and surface chemistry. Addressing these challenges requires progress in both comprehension and experimental techniques. Furthermore, developments in characterization techniques and computational modeling are also critical for obtaining insights into the growth mechanisms and directing the synthesis of ultrathin 2D nanomaterials with desired structures.

Ultrathin 2D nanomaterials present certain challenges to their long-term stability and durability, factors that restrict potential applications. The relatively low stability can be principally ascribed to the aggregation in liquid, oxidation in ambient conditions, and structural modification during chemical reactions. Two-dimensional nanomaterials exhibit limited storage stability when dispersed in liquid solutions, due to their inherent susceptibility for irreversible aggregation. This aggregation behavior significantly diminishes the advantages derived from their distinctive 2D structural features. The majority of ultrathin 2D nanomaterials are prone to oxidation when exposed to ambient conditions. This vulnerability results in structural decomposition and deterioration over an extended period. The oxidation process is initiated by exposure to oxygen or moisture in the surroundings which modifies the physical and chemical properties of the nanomaterials. Addressing these challenges will entail innovative synthesis techniques, surface modification strategies, and establishing durable encapsulation or stabilization strategies. Further advancement in ultrathin 2D nanomaterial is required to address these issues. The tremendous potential of 2D nanomaterials across a wide range of applications, from energy storage and conversion to electronics, sensing, and biomedical devices, will be realized, thus enabling a new era of advanced materials and technologies.

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Biomedical Materials

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Abstract This chapter provides a thorough introduction, a historical progression, and a full categorization of biomedical materials with a crucial role in contemporary healthcare is emphasized. Synthesis methods for metal-, polymer-, ceramic-, biomolecules-, and nanoparticle-based materials are described together with their unique mechanical, chemical, and physical characteristics. This chapter further explores the two domains of natural and synthetic biomaterials, explaining the various uses of each in the biomedical field. In the end, this chapter focuses on technology advancements and opens the door to creative ideas and improved medical interventions. The biomedical materials' future emphasizes the potential for groundbreaking discoveries and unexplored avenues for further research and development.

Keywords Natural biomaterials · Synthetic biomaterials · Physical and chemical properties · Biomedical applications

1 Introduction

Biomedical materials, also known as biomaterials, are unique materials created especially for use in healthcare and medical applications. Another definition of biomaterials is "any material used as an implant." To assure safety, efficacy, and compatibility when interacting with biological systems, including the human body, these materials have been carefully chosen or produced [1]. Biomedical materials make a vast array of medical devices, implants, drug delivery systems, and tissue engineering methods possible [2]. Biomedical materials have a significant influence on the state of contemporary healthcare and are at the intersection of science, engineering, and medicine. These materials are painstakingly crafted to work in harmony with the

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complex systems of the human body, promoting advances in medical technology and enhancing the quality of life for patients. Serving as the basis for implants, drug delivery methods, medical devices, and tissue engineering, they are now indispensable to the medical profession and hold the potential to advance healthcare while also extending and improving life [3]. The concepts of materials science, biology, chemistry, and engineering come together in the dynamic and multidisciplinary subject of biomedical materials science and engineering. Its main objective is to create materials that are effective, durable, and biocompatible while also being able to survive the difficulties presented by the human body. These materials are essential to many different medical applications, including dental implants, advanced prostheses, biodegradable sutures, localized drug distribution systems, and regenerative treatments [4]. Biomedical materials have played a significant role in the identification, management, and treatment of a wide range of medical diseases across the history of medicine. The unrelenting search for materials that can blend in perfectly with the biological milieu of the human body has propelled their progress. The development of biomedical materials has been characterized by constant advancement and ground-breaking discoveries, from the first experiments using materials such as glass, metals, and ceramics to the most recent advances in polymers and composites [5]. Biocompatibility, or the ability of biomedical materials to avoid causing negative reactions or damaging immune system responses, is one of their most important characteristics. When in touch with live tissues, they are carefully crafted to be accepted by the body and to have no negative consequences. Another crucial component of biological materials is their durability. They must endure the particular and frequently difficult circumstances found inside the human anatomy, which can be caustic, humid, and vulnerable to a variety of mechanical forces [6]. Moreover, the selection or development of biomedical materials is based on their specific functionality within a particular medical instrument or application. Depending on the intended use, they may have a variety of qualities including mechanical features, electrical conductivity, or biodegradability. Beyond these qualities, biomedical materials must also be compatible with sterilizing techniques and have the safety to interact with medications or other chemicals they could may encounter within the body [7]. Biomedical materials that are often utilized include polymers like polyethylene and polyurethane that are used in systems for delivering drugs, limb prostheses, and artificial organs, as well as metals like titanium and stainless steel that are used in implants for bones, dental devices, and stents. Biodegradable components like polylactic acid are employed in tissue scaffolds and sutures, whereas ceramics like hydroxyapatite are utilized in dental implants and bone transplants [8]. Biomedical materials are a fundamental component of medical progress, aiding in the creation of more secure and effective healthcare remedies. To solve a wide range of medical difficulties, researchers and engineers are constantly pushing the boundaries while improving and broadening the range of biomedical materials. Exceptional mechanical properties, superior physical and chemical qualities, sufficient wear and rust resistance, and osseointegration (for bone implants) are a few qualities that biomedical materials should possess [9]. It is necessary to consider other significant processes of interaction between the human body and the implant, such as the diffusion channel of foreign particles and atoms that travel from the implant into bodily fluids, tissue, and bone [3]. Following developments in recently formed fields such as biotechnology and medical technology, these biomaterials now have a higher standard [10].

The use of biomaterials is undoubtedly not a novel idea; in fact, the treatment of cranial abnormalities by the ancient Egyptians and Romans involved the use of gold and ivory, and in the 1900s, there were rudimentary applications such as the use of placenta in World War II [11]. Dr. Jonathan Cohen provided one of the first definitions of "biomaterial" in 1967 (Cohen, 1967). "There is no current agreement on what distinguishes biomaterials from others. I will include all materials, except drugs and sutures, which are used as implants". Cohen's definition fully excludes all categories of extensively used biomaterials, including "soft biological materials" like collagen, skin, and adipose tissues [12]. The term "biomaterial" was originally defined in a commonly recognized sense in 1974 AD at the sixth "Annual International Biomaterial Symposium" held in Clemson, South Carolina (US). "A biomaterial is a systematically, pharmacologically inert substance designed for implantation within or incorporation with a living system". Biomaterials are defined as a material (not necessarily a drug) or a group of substances, manufactured or organic in origin, which might be utilized for any time, in its entirety, or as a part of an entire system that treats, improves, or substitutes any tissue, organ, or function within the body. This definition is widely accepted and encompasses both inert and active substances. It was first presented during the 1982 National Institutes of Health Consensus Development Conference Declaration regarding Clinical Applications of Biomaterials, held in Bethesda, Maryland (United States) in 1982 AD (Patel and Gohil, 2012). In 1987 AD, Prof. David Franklyn Williams provided a unique and rather inventive description of biomaterial (Williams, 1987). "A biomaterial is a non-viable material used in a medical device, intended to interact with biological systems". The term "nonviable" refers to biomaterials that should not be comprised of or be applied in conjunction with "living tissues," although it does not specifically exclude pharmaceuticals. Any material or group of substances, except medicines, that may be utilized for an extended length of time and that replaces or augments any tissue, organ, or function within the body in part or entirely to preserve or enhance a person's quality of life [2]. Biomedical materials have a fascinating history that spans millennia and reflects humanity's never-ending ambition to advance healthcare and improve quality of life. Its roots may be found in the early civilizations of the Mayans and Egyptians, who made simple prostheses and dental restorations out of materials including wood, stone, and bone. An important breakthrough in dental technology came with the introduction of valuable metals like copper and gold during the Renaissance [13].

1.1 Classification of Biomedical Materials

Biomaterials are classified into three types depending on their chemical composition (metal, ceramic, polymer, and composites) and degree of contact with the biological surroundings (inert, bioactive, and bioresorbable) as shwon in Fig. 1. Another, less

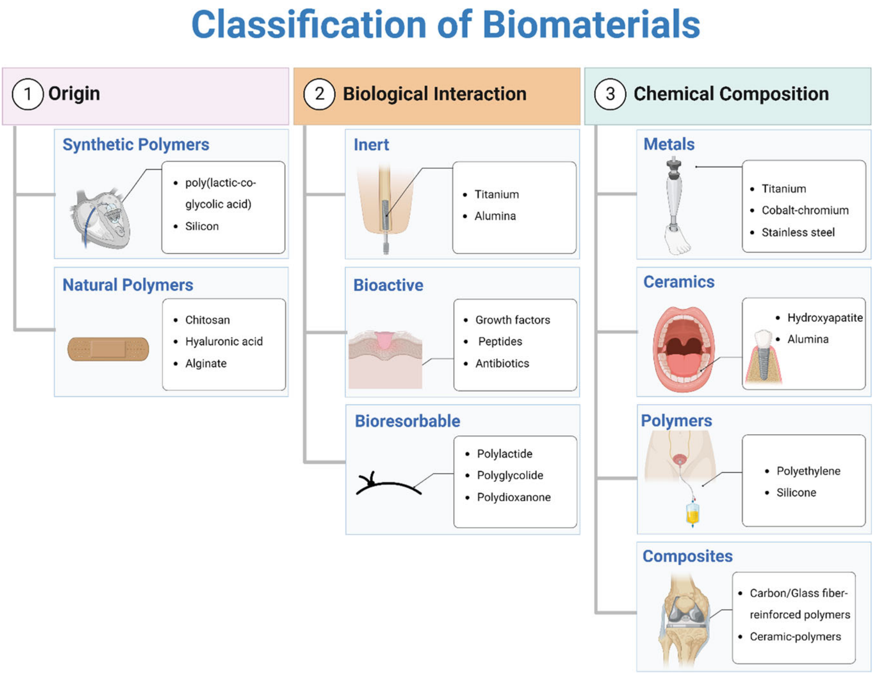

Fig. 1 Biomedical materials classification based on their origin, biological interactions, and chemical composition

common, categorization is based on "origin": synthetic or natural. It is not surprising that naturally existing materials were the first to be employed as a biomaterial, given that the technological expertise necessary to manufacture materials was acquired later [6].

1.1.1 Origin-Based Classification

Although metals and ceramics can also be classified as biomaterials, synthetic and naturally produced polymers and their application as biomaterials are the subject of a substantial research. When compared to metal or ceramic biomaterials, the structural similarities between synthetic polymers and the polymers found in tissues, such as polypeptides, may explain the latter's widespread application as biomaterials. Besides synthetic polymers, numerous naturally produced polymers are also used as biomaterials. Naturally generated polymers have the potential to be used in drug delivery systems and medical devices since they can aid in cellular activities such as adhesion, migration, proliferation, and differentiation, unlike many synthetic alternatives. Suitable biodegradable polymers with special qualities are quite valuable. When natural and synthetic biodegradable polymers are compared, it is discovered that the latter have less immunogenicity and are much more amenable to chemical modification, suggesting that they may present new opportunities in the future [11].

1.1.2 Biological Interaction-Based Classification

In biomedical metal production, surface treatments are often used to maximize the substance's contact with biological tissues. The surface qualities are improved by methods like plasma treatment, chemical coatings, or the application of bioactive compounds, which enhance interactions with biological entities and guarantees a more favorable reaction in the physiological environment and lower the possibility of unfavorable responses. Magnesium alloys and other biodegradable metals have attracted interest for certain uses. The controlled degradation of these implants within the body avoids the need for surgical implant removal. In addition, the production of metals used in dentistry, such as titanium and cobalt-chromium alloys, is customized to fulfill the unique requirements of the oral environment. These materials offer the biocompatibility and durability needed for crowns, bridges, and dental implants [14].

To achieve the required levels of bioactivity, porosity, and crystallinity and to ensure successful integration with biological tissues, these approaches are crucial [15]. In the process of creating ceramics, surface alterations are frequently used to improve their functioning. To enhance interactions with biological tissues, this may entail coating ceramics with bioactive materials or changing the properties of their surfaces. These adjustments are essential for encouraging improved integration and lowering the possibility of negative responses. Furthermore, composite constructions that combine ceramics and polymers to create a balance between strength and flexibility are another use for the manufacturing of ceramic materials. Another family of biomedical ceramics is called bioactive glasses, which are made using sol–gel or melt-quench techniques. These glasses have the unusual capacity to form a link with living tissues, which encourages the bone repair. Customizing compositions to attain certain degradation rates and bioactivity is a necessary step in their production [16].

A crucial factor in the manufacturing of biomedical polymers is biocompatibility. To minimize negative reactions and guarantee the material's general safety within the body, the selection of monomers and polymerization techniques strives to generate materials that blend in smoothly with biological systems. To satisfy particular medical needs, the resultant polymers frequently have adjustable mechanical qualities, degradation rates, and surface features. The process of modifying polymers for use in drug delivery systems entails adding bioactive substances to the polymer matrix. To achieve regulated release kinetics and maximize therapeutic efficacy while limiting adverse effects, this method necessitates accuracy. Drug payload protection and improved distribution to specific tissues are features of polymeric drug carriers including micelles and nanoparticles. Polymers are the building blocks of scaffolds used in tissue engineering, which facilitate tissue regeneration and cell proliferation. These scaffolds provide an environment that is favorable for cell proliferation and differentiation by imitating the extracellular matrix. Because of their biodegradability and biocompatibility, polymers like poly(lactic acid) (PLA), poly(glycolic acid) (PGA), and its copolymer poly(lactic-co-glycolic acid) (PLGA) are often utilized [17]. The area of biomedical material polymer synthesis is dynamic and always changing to satisfy the ever-increasing needs of contemporary medicine. In addition to improving already-existing materials, researchers work hard to develop new polymers that exceed the limits of mechanical strength, biocompatibility, and customized functionality. This multidisciplinary strategy, which unites materials science, biomedical engineering, and chemistry, is the key to opening up new avenues for medical treatment and enhancing patient care as a whole [18].

1.1.3 Chemical Structure-Based Biomaterial Classification

Metals are biomaterials based on chemical structure. The utility and value of metals and their composites have been recognized since the early nineteenth century. Metals with high mechanical strength and endurance, such as stainless steel, titanium, and cobalt-chromium alloys, are popular. They are resistant to corrosion, biocompatible, and frequently enable applications that bear weight. In surgical procedures like hip and knee replacements, stainless steel is often utilized. Because of its biocompatibility and strength, titanium is frequently employed in dental implants and orthopedic applications. Cobalt-chromium alloys are used in medical equipment such as stents and prosthetic heart valves. Load-bearing hip implants are made of titanium and its alloys, cobalt base alloys, and stainless steels (bio-steels) [19]. Stainless steel, cobalt-chromium alloys, titanium, and its alloys are frequently used because of their remarkable mechanical strength and biocompatibility.

Then there are biomaterials made of ceramics. Ceramics such as hydroxyapatite and alumina are well-recognized for their biocompatibility, hardness, and wear resistance. They resemble actual bone and are thus appropriate for specific applications. Hydroxyapatite is utilized to promote bone integration, in dental and orthopedic implants. Alumina is used in orthopedic components because of its high wear resistance. Ceramics are also employed in dental crowns, and bioactive glass is used to stimulate bone repair [20].

Polymers are another type of biomaterial based on chemical structure. Polymers with specific biocompatibility may be created, and they are lightweight, versatile materials like silicone, polyethylene, and polyurethane. The body breaks down some biodegradable polymers, such as PGA and PLA. Orthopedic components, such as joint replacements, employ polyethylene. Catheters, prosthetic heart valves, and blood vascular transplants all contain polyurethane. Silicone finds application in facial prosthetics, breast implants, and medical tubing. Biodegradable polymers such as PLA and PGA are used in scaffolds for tissue engineering and sutures [21]. A vital area of materials science is the synthesis of polymeric biomaterials, which has aided in the creation of scaffolds for tissue engineering, and drug delivery systems, along with cutting-edge medical equipment. This complex process entails the synthesis or manipulation of polymers, which are macromolecules made up of repeating subunits, to achieve particular characteristics that are suited for use in biomedical applications.

Table 1 Classification of biomaterials and their corresponding applications

Biomaterial	Example	Applications	References
Metals	Stainless steel, titanium, cobalt-chromium alloys	Hip and knee replacements, dental implants, pacemakers, stents	[19]
Ceramics	Hydroxyapatite, alumina	Dental and orthopedic implants, bone grafts, bioactive coatings	[20]
Polymers	Silicone, polyethylene, polyurethane, PGA, PLA	Catheters, prosthetic heart valves, drug delivery systems, tissue scaffolds	[21]
composites	Carbon/glass fiber-reinforced polymers, ceramic-polymer composites	Prostheses, dental products, bone plates, screws, artificial joints	[22]
Bioactive molecules	Growth factors, peptides, antibiotics	Tissue engineering, wound healing, drug delivery, regenerative medicine	[23]
Nanomaterials	Nanoparticles, nanotubes, nanocomposites	Targeted drug delivery, imaging, tissue regeneration, diagnostic devices	[24]
Hybrid composites	Polymer-ceramic composites, polymer-metal composites	Enhanced mechanical properties, controlled drug release, orthopedic implants	[25]
Bioglass	Bioactive glasses with SiO2, CaO, P2O5	Bone repair, dental applications, controlled ion release	[16]

Composites integrate polymers with reinforcing fibers such as carbon or glass to combine the strengths of several components. They provide biocompatibility, strength, and other customized qualities in a balanced manner. Composite materials are used in many different applications. For example, lightweight prostheses made of carbon fiber-reinforced polymers, dental products made of glass fiber-reinforced polymers, and dental restorations made of ceramic polymer composites combine durability with elegance [22] (Table 1).

1.2 Significance of Biomedical Materials in Healthcare

Biomedical materials play a critical role in modern healthcare, impacting many aspects of medical practice. These materials, which are designed for biocompatibility, serve as the foundation for medical advancements and aid in the creation of treatments and technologies that may change people's lives. Biomedical materials are essential for improving patient health, whether they are used in dental restorations or orthopedic applications. The customized characteristics of materials like metals, ceramics, and polymers make it possible to create prostheses, implants, and drug delivery systems, which enhance the quality of life for people with a variety of medical problems and advance therapeutics [26]. The significance of biomedical materials is also seen in tissue engineering and regenerative medicine, in which they provide the scaffolding necessary to facilitate tissue regeneration. This discipline has the potential to repair tissue damage and organ failure, providing patients with few therapy options with creative fixes [27]. Biomedical materials are used in diagnostics to help produce precise instruments and biosensors that make diagnostic processes accurate and productive. Their function in drug delivery systems also guarantees regulated pharmaceutical release, maximizing therapeutic effectiveness and reducing adverse effects. Biomedical materials play a major role in the fields of orthopedics and implantology by enabling the development of artificial joints, bone plates, and screws that help restore function and mobility. These materials play a key role in prostheses, implants, and restorations in dentistry, improving oral health and providing aesthetically pleasing results. In medical practice, a wide range of materials that come into direct and frequently prolonged touch with biological tissues are increasingly being employed to treat patients. Finding materials that meet functional requirements such as strength, stiffness, optical transparency, electrical conductivity, and fatigue strength is not too difficult. Finding materials that can carry out these tasks for an extended length of time more than twenty years, in some cases without degrading the material or causing unfavorable side effects in the body's tissues is exceedingly challenging [28]. The initial events that occur when a biomaterial is implanted in the body, are primarily concerned with the physicochemical phenomena that occur in times measured in seconds or minutes following contact between biomaterial and tissues, the effect that the presence of a foreign body has on the tissue surrounding the implant, which can be observed at any time that spans minutes to years, the changes noticed in the material as a result of its presence in the tissue. Bioengineering has come a long way, but it would not be possible without the availability of biomaterials, or amenable materials, without which it would not have made as much progress as it has. The worth of the biomaterials area is expected to increase at a compound yearly increase of 6/7% from 2014 to 2019, creating a $109.5 billion worldwide market in 2019, in anticipation of increasing needs within the medical and pharmaceutical sectors [29]. Immune rejection is the main obstacle to adopting these biomaterials since, in the current scenario, biocompatibility is necessary for lifelong implants and bone replacement in addition to the biomaterial's mechanical and biological properties. Numerous biomaterials have been identified so far, and because of their biocompatibility and biodegradability, they are widely used in medical research and biotherapy. It is important to remember that our ultimate objective is to supply medical devices, prosthetics, biomedical materials, and other things that will improve patients' health and welfare. After determining the demands of the patient, ideas are created based on physiological and anatomical processes that are well-known and how illness processes modify. These elements are then combined to start the design process. From the initial design criteria, configuration, prototype, production and assembly, test/use, reliability, and clinical trials follow. It is essential to keep in mind that implant retrieval and assessment are the final considerations in the design of medical implants. Through implant assessment and retrieval, failure modes and causes may be identified. This knowledge can then be used to influence future concept development, with new design requirements derived from implant retrieval and evaluation [30].

2 Synthesis of Biomedical Materials

Over the past few decades, biomaterials have been employed extensively in medical science. Many bodily tissues, including teeth, ligaments, bones, tendons, and others, have been successfully substituted by these biomaterials in the human body. As things stand, we have yet to see how these biomaterials will be used. Immune rejection is the main obstacle to employing these biomaterials since, in the current scenario, biocompatibility is necessary for lifelong implants and bone replacement in addition to the biological and mechanical properties of the biomaterial being utilized. Numerous biomaterials have been identified to date, and because of their biocompatibility and biodegradability, they are widely used in medical research and biotherapy [31]. The following qualities are essential for a good biomaterial: mechanical vigor, biocompatibility, and fulfillment of different chemical and physical criteria. Currently, a lot of work has gone into increasing the usefulness of artificial joints. However, the main goals are to prolong the life of implants or prostheses inside the human body and minimize wear [10]. At the vanguard of technological and scientific advancement, biomedical materials synthesis is a complex and multifaceted field that brings together the ideas of biology, chemistry, and materials science. The synthesis process is essential for customizing materials to fulfill the high requirements of mechanical integrity, biocompatibility, and functional specificity needed for a wide range of medical applications as the market for cutting-edge medical solutions grows. Fundamentally, biomedical material synthesis entails the synthesis or alteration of materials specifically intended to meet medical issues. An in-depth comprehension of biological systems serves as a foundation for the creation of these materials, taking into account the delicate interactions that exist between materials and live tissues [32]. Techniques for surface modification improve materials' interaction with the biological environment by further refining them. This might entail applying bioactive coatings strategically, chemically grafting, or plasma treating the material to change its surface characteristics. The synthesis process includes the addition of bioactive compounds in addition to the physical properties of materials. The medicinal value of materials is improved by this deliberate integration, whether they are used as scaffolds intended to promote tissue regeneration or as drug delivery systems. Biomedical materials are a harmonic fusion of technical innovation and scientific inventiveness. It represents a constantly changing effort to design materials that blend in seamlessly with the intricacies of human anatomy while promoting a new wave of medical devices and procedures that promise better patient results and a completely changed field of healthcare options. Biomedical materials are synthesized through a painstaking process in which materials are generated or altered to satisfy certain requirements for use in medicine. This procedure is extremely customized, taking into account things like mechanical qualities, biocompatibility, and the material's intended function. Biomedical materials come in a variety of forms, including composites, metal alloys, polymers, ceramics, nanomaterials, and bioactive compounds. Each of them has a unique synthesis processing method [33].

The first step in the synthesis of polymers for biomedical applications is the picking of monomers, which are polymer building blocks, depending on the required properties of the material. Many polymerization strategies are used, such as step-growth and chain-growth polymerization, among others. Long polymer chains are quickly formed when monomers react sequentially in chain growth in the polymerization process such as radical polymerization. On the other hand, step-growth polymerization entails the concurrent reaction of many monomers, progressively constructing the polymer structure [34]. Biomedical material metal creation is a painstaking process that is essential for the creation of medical devices and implants, where the mechanical characteristics, biocompatibility, and resistance to corrosion of metals are critical factors. This complex process entails several approaches designed to satisfy the demanding specifications of medical applications. Choosing metals and alloys according to their intended uses is frequently the first step in the synthesis process. With additive manufacturing, powder metallurgy, or casting, among other synthesis processes, exact control over the structure and qualities of the material may be ensured [35]. For biomedical metals to have the appropriate mechanical integrity, rigorous processing is required. For orthopedic implants, titanium alloys could be manufactured using additive manufacturing processes such as selective laser melting. These techniques enable the construction of intricate, patient-specific structures in addition to improving mechanical qualities. However, there are still difficulties in finding the ideal ratio between mechanical strength and degradation rate, calling for creative synthesis techniques. Biomedical metal synthesis is the process of producing prosthetic heart valves and stents using corrosion-resistant materials such as Nitinol (nickel-titanium alloy), which is important when it comes to cardiovascular implants. Other important variables considered in this process include blood compatibility and durability. The process of synthesis guarantees the creation of materials that are resilient to the changing circumstances found in the circulatory system.

The synthesis of biomedical materials in ceramics is an intricate and accurate procedure that is essential for creating materials used in the medical industry, especially in the sectors of dentistry and orthopedics. Because of their biocompatibility and similarity to the genuine bone, ceramics including hydroxyapatite, alumina, and bioactive glasses are frequently utilized. The synthesis entails several painstaking methods designed to satisfy the demanding specifications of biological applications. The bioactive ceramic hydroxyapatite is synthesized by techniques such as electrospinning, sol–gel procedures, or sintering. It is frequently utilized in bone replacements. Sintering and powder compaction are two methods used in the synthesis of alumina, which is prized for its remarkable hardness and wear resistance. Grain size and structure are meticulously manipulated during the process to maximize mechanical qualities, which qualifies it for orthopedic uses, like joint replacements. Ceramics are essential to the creation of dental implants, crowns, and bridges in dental applications. The synthesis of zirconia, a ceramic valued for its mechanical strength and biocompatibility, involves steps such as sintering and powder compaction, which guarantee the material's ideal qualities for dental restorations. Applications for composite ceramics may be found in orthopedic implants and dental restorations, where the mix of materials maximizes overall performance [36].

The production of nanomaterial-based biomedical materials is an extremely complex and state-of-the-art procedure that is essential to the advancement of medication delivery systems, medical therapies, and diagnostics. Nanomaterials are used in biomedical applications because of their special qualities and functions, which are generally defined by size at the nanometer scale. The process of creating nanomaterials for application in medicine involves a variety of methods, such as top-down and bottom-up strategies. While bottom-up techniques create nanomaterials from smaller components, top-down processes reduce bigger materials to nanoscale dimensions. Particle size, shape, and surface characteristics may all be precisely controlled using these techniques [37]. Nanomaterials are created and used in systems for drug delivery to encapsulate and provide therapeutic medicines with regulated release kinetics. Commonly utilized carriers that minimize adverse effects and enable targeted medication delivery to certain tissues include liposomes, nanoparticles, and micelles [38]. Nanomaterials aid in the creation of biosensors and extremely sensitive imaging agents for use in diagnostics. The optical and magnetic characteristics of magnetic, gold and quantum dots are engineered during synthesis to provide them with distinct advantages that improve their performance in imaging and diagnostic applications. Biomedical nanomaterials are frequently engineered to imitate biological structures or take advantage of certain molecular interactions. During the manufacturing process, surface functionalization entails the attachment of biomolecules or ligands to guarantee the nanomaterial's compatibility with biological processes and to facilitate specific interactions with cells or tissues. In the discipline of tissue engineering, scaffolds with nanoscale characteristics are made to direct cell activity and promote tissue regeneration. This is another use of nanomaterial fabrication. Nanofibrous structures are created via electrospinning and template-assisted techniques, which offer a biomimetic environment for cell proliferation [24]. Biocompatible polymers are further improved by adding nanoparticles, resulting in composite materials with complementary advantages. By fusing the distinctive qualities of nanoscale components with the mechanical strength of conventional materials, nanocomposites find use in a variety of biomedical devices and implants [39]. Customizing the surface of nanomaterials is essential to controlling how they interact with living things. Surfaces that have been functionalized with bioactive chemicals or polymers have improved stability, biocompatibility, and immune system evasion [40].

The complex process of synthesizing biomedical materials containing bioactive compounds has great potential for the creation of sophisticated therapeutic interventions, medication delivery methods, and tissue engineering structures. Enzymes, growth factors, and peptides are examples of bioactive molecules that are incorporated with materials to impart certain biological capabilities and increase their effectiveness in their physiological surroundings. The discovery and selection of bioactive compounds based on their predicted medicinal or regenerative properties is frequently the first step in the synthesis process. For example, peptides may be selected based on their capacity to replicate endogenous signaling pathways or stimulate particular physiological reactions. Growth factors are carefully manufactured to maintain their biological function and stability inside the material. They are essential in tissue repair and regeneration [41]. Materials containing bioactive compounds are frequently synthesized using conjugation or encapsulation procedures. Conjugation is the process of chemically attaching the bioactive molecules onto the matrix or surface of the substance to provide a steady and regulated release throughout time. Contrarily, encapsulation entails encapsulating the bioactive chemicals in carriers—like liposomes or nanoparticles—that provide regulated distribution and protection. The demand for individualized and focused treatments is what motivates the production of materials containing bioactive compounds. By interacting with particular cell types or tissues, these materials can promote regeneration processes or transport therapeutic medicines exactly to the desired location. Surface alterations that improve a material's biocompatibility and maximize its interaction with biological entities include the incorporation of ligands or polymers. The synthesis of materials containing bioactive compounds provides the regulated release of drugs in the framework of drug delivery systems, reducing adverse effects and enhancing therapeutic outcomes. Since materials may be created to specifically carry anticancer drugs to tumor areas, this targeted medication delivery strategy is especially helpful in the treatment of cancer. The goal of bioactive molecule-based scaffold creation in tissue engineering is to produce an environment that promotes cell adhesion, proliferation, and differentiation. To facilitate tissue regeneration, the material must be customized to resemble the extracellular matrix and include bioactive signals that direct cellular action [23].

In order to combine the special qualities of several materials for improved usefulness in medical applications, biomedical material composite synthesis is a complex and adaptable technique in materials research. Composites are carefully created to attain a mix of mechanical strength, biocompatibility, and customized features. They are frequently made of all polymers, ceramics, metals, or a combination. The first step in the procedure of making composites in biomedical materials is choosing the component materials according to the qualities that are needed for that particular biological application. For instance, materials exhibiting the flexibility of polymers and the strength of ceramics or metals can be created by mixing polymers with these materials. The synthesis procedures that guarantee a uniform distribution of components inside the composite include melt mixing, solvent casting, or additive assembly methods [42].

3 Properties of Biomedical Materials

As we have discussed before, biomaterials are composed of several kinds of recognized materials, such as natural and synthetic polymers, metals and alloys, ceramics, and glasses [43]. These materials find applications in various medical fields, such as bone and joint reconstruction, and dental replacement. Some desirable properties of biomaterials are shown in Fig. 2**.**

The bulk and surface properties of these materials have seen several advancements and modifications over time, creating a wide range of possibilities. The bulk of a biomaterial exhibits physical and chemical features of the material that persist throughout the implant's lifespan. To efficiently employ implants within the human body, the materials must exhibit an appropriate level of tolerance with the living organism, also known as a high level of biocompatibility. The term "biocompatibility" describes a biomaterial's capacity to carry out its intended function without causing harm or toxicity to biological systems while, in certain situations, evoking a suitable host response [44]. This indicates that the substance or its byproducts do not result in long-term inflammation, cell death, or loss of cell functionality. Because

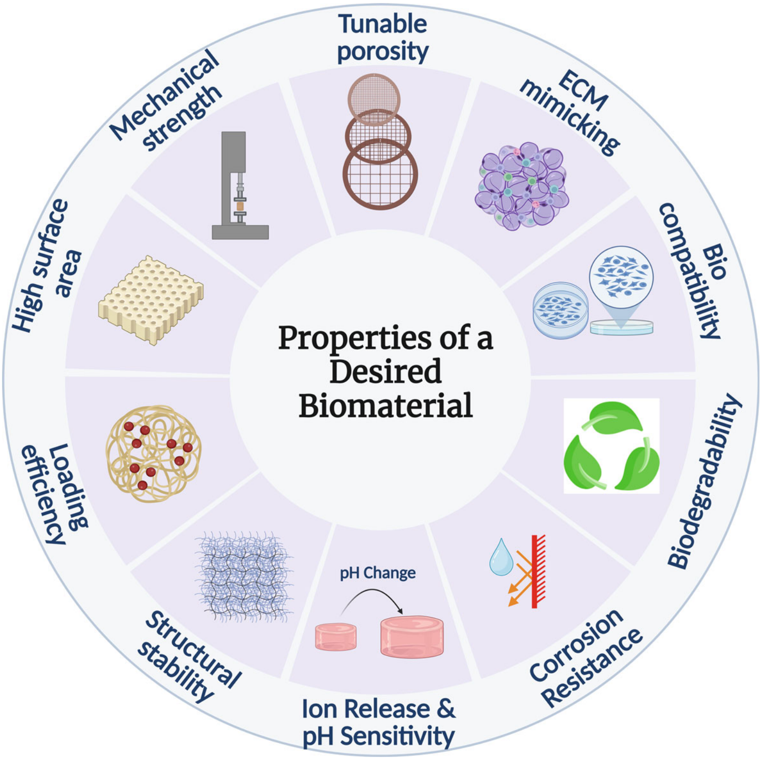

Fig. 2 Desired properites of biomaterials for optimum performance

biomaterials are subjected to the hostile effects of bodily fluids (enzymes, organic acids, etc.) and external elements in the human body, the standards for them are quite high. It should be highlighted that human tissue is very susceptible to foreign chemicals so it is possible that these substances may cause signs of poisoning or rejection. So, for novel biomaterials, good biocompatibility and functional qualities are essential. The biological environment, the mechanical, chemical, and structural characteristics of biomaterials, as well as the assessment process itself, can all have an impact on a material's biocompatibility [45]. The concept of biocompatibility has undergone significant changes recently, affecting active tissue engineering technologies and passive implant materials. The two well-recognized pillars of biocompatibility are biosafety and bio-functionality, which are enhancing bodily functions. When it comes to implantable and fracture fixation devices, the most critical aspect influencing their performance is the material's surface. This is extremely important since the device's surface interacts directly with the physiological environment of the host, hence a well-made and functional surface is required. Another vital factor to consider is mechano-transduction, which is related to the device's bulk properties. However, this primarily becomes a significant factor in the later stages of implantation and generally follows the initial surface interaction [46].

The unique properties of a particular biomaterial are defined by its atomic and molecular composition, which in turn dictates its chemical properties and how it interacts within a living organism. Like other materials, biomaterials exhibit certain physicochemical properties that must align with the intended use. Due to the biomaterial's inherent integrity and surface interaction with organs, these properties represent both the bulk and surface properties of the material. Biomaterials' bulk and surface properties are influenced by their structure, which is determined by how each of their atoms are bound together. At the atomic level, materials are distinguished by three types of strong (primary) interatomic bonds: covalent, ionic, and metallic. Many weak (secondary) bonds exist in addition to these three strong bonds, and they have a substantial impact on the characteristics of materials, particularly in synthetic and natural polymers [47]. The bulk and surface characteristics of biomaterials used in medical implants directly affect and, in some situations, govern the dynamic interactions that occur at the tissue implant interface. Compatibility encompasses these interactions and should be seen as a continuous, two-way process that occurs over the in vivo lifespan of the devices between the implanted materials and the host environment. Overall, the primary objective of using biomaterials in the field of medicine is to address, or replace tissues and organs like bones, muscles, and skin, as well as improve overall bodily functions. Achieving these objectives involves blending the characteristics of materials, the intricacies of the biological system, the design of medical devices, and adherence to physiological requirements. To achieve the desired functional outcomes, the application of biomaterials must effectively combine the mechanical, physical, and chemical properties of the biological system [48].

3.1 Mechanical Properties

Along with biocompatibility, mechanical properties play a significant role in the design of biomaterials before they are implemented and will ultimately influence the final result [49]. The main forces that materials experience are shear, stress, strain, and a combination of these. Hardness, creep, surface finish, corrosion, elastic modulus, yield strength, and tensile strength are some of the most crucial biomaterial qualities that need to be thoroughly examined and evaluated before implantation. The mechanical qualities are crucial for applications involving hard tissues. The mechanical qualities of a biomaterial are best defined by its modulus of elasticity, ultimate tensile strength, elongation to failure, and fracture toughness [50].

- The modulus of elasticity, often derived from the slope of a stress–strain curve, characterizes the material's stiffness [51].
- Ultimate tensile strength is a property that indicates how much load a material can bear before failing [52].
- Elongation to failure defines how much strain a material can withstand before failing [53].
- Fracture toughness is a crucial metric for assessing a material's resistance to crack propagation [54].

Metals have a high fracture toughness and are often highly rigid. Polymers have low stiffness and fracture toughness, which sets them apart from metals. Polymers, on the other hand, have high elongation to failure. However, because metals are quite rigid, this might be a drawback when it comes to bone fracture recovery because it can result in "stress shielding." Stress shielding is a process in which covering a bone with a stiffer substance causes bone loss. Stresses affect bone throughout the healing process. Under the tougher substance, the bone density reduces because the bone is essentially insulated from the stress. The mechanical qualities of a biomaterial are significant not just for themselves, but they can also influence cell adhesion and proliferation. A material that is transplanted should always have mechanical characteristics that are remarkably similar to the material that it replaces (i.e., tissue) [55]. Ceramics, like Bioglass, which are used as bone implants, are less robust and have a greater Young modulus than bone, they cannot be used to replace high-load bones like the femur or tibial bones. It is necessary to optimize a biomaterial's mechanical properties in relation to its mass density. As long as the material's cost is within reasonable bounds, the lightest option is always selected for a given volume and a given range of mechanical characteristics. It is anticipated that mechanical biocompatibility will become increasingly important in biomedical engineering and it will have a big impact on future advancements in the design of prostheses, grafts, and orthopedics. A better understanding and precise characterization of how biomedical materials and devices perform under severe deformation is required for determining mechanical compatibility. This refers to properly portraying their responses to different stress scenarios, such as uniaxial and multiaxial stress states, while taking into account their history-dependent, time-dependent, and nonlinear characteristics, such as anisotropy and time-dependence [56]. Furthermore, changes in the way that materials deform as a result of tissue growth and material absorption—including growth, remodeling, and property changes—must be taken into account in order to fully comprehend mechanical features. This method allows a detailed evaluation of the interactions between biological and synthetic components in the implant-tissue mechanical system. Furthermore, maintaining mechanical compatibility requires not only appropriate overall characteristics but also the alignment of microscopic deformation mechanisms with adjacent tissues. Therefore, in order to capture multiscale features, characterization must take into account both macroscopic and microscopic scales [57].

3.2 Chemical Properties

It is important to consider both the mechanical and chemical qualities of materials when developing biomedical applications. To function well, the chemical characteristics of biomedical materials are essential in medical and healthcare applications. These characteristics guarantee the materials' stability, safety, and compatibility with biological systems. The base of a particular property for a biomaterial is its chemical property. There are many different types of biomaterials known today, each with unique atomic and molecular structures that offer a broad range of chemical properties. From a chemical perspective, the goal is to produce materials that either do not react with their surroundings or, if they do, are shielded by appropriate layers of protection. Several important chemical characteristics must be taken into account when selecting a material for the application of biomaterials including biocompatibility, biodegradability, corrosion resistance, chemical stability, compatibility with other materials, ion release, and PH sensitivity [58].

3.2.1 Biocompatibility

Biocompatibility, as defined by biology, is simply the ability of synthetic or natural non-living materials to coexist with a living organism (human or mammal). A biomaterial implant must not react negatively with the surrounding tissues or host organs because it is meant to be used in close contact with living tissues. Other than this, the implanted material is supposed to promote a favorable cellular or tissue response rather than inhibit the activity of normal cells or cause any unfavorable local or systemic reactions in the recipient. The requirements for this biocompatibility are typically complex and dynamic, and they vary depending on the particular medical use. For instance, a screw or plate that has been specially made may be biocompatible during bone implant surgery, but it may not be biocompatible during skin applications [48].

3.2.2 Biodegradability

Presently, the human body uses several artificial and naturally occurring biodegradable biomaterials for tissue regeneration. The word “biodegradation” is often used deliberately to refer to substances that may break down via enzymatic or hydrolytic processes. When creating therapeutic devices, such as three-dimensional porous scaffolds for tissue engineering or controlled-release drug delivery systems, degradable biomaterials are the best options because there are two main benefits of using them as artificial implants. First off, using biodegradable materials removes the necessity for a second surgery since the breakdown products can be naturally eliminated from the body. Secondly, the utilization of biodegradable biomaterials could result in enhanced tissue recovery, as the biomaterial’s gradual loss of mechanical strength during degradation will continuously stimulate the healing of tissues [59].

3.2.3 Corrosion Resistance

Biomaterials are essential to human survival in times of sudden heart attacks, arthritis, osteoporosis, and other joint disorders, therefore corrosion of these materials is a critical issue in the field of materials research. An implant material’s capacity to withstand corrosion has an impact on both its longevity and performance, and it also plays a key role in determining its biocompatibility. The general rule governing metallic biomaterials has been “the more corrosion resistant, the more biocompatible,” except biodegradable metals. Many biomedical materials, particularly metallic implants, have to be resistant to corrosion when they come into contact with body fluids such as synovial fluid and blood. Material deterioration, the release of toxic ions, and tissue injury can all result from corrosion. Metallic implants can be alloyed and processed to withstand corrosion when used to replace tissue permanently or to degrade in a controlled manner when used in areas where tissue regeneration is intended [60].

3.2.4 Chemical Stability

The capacity of biomedical materials to retain their chemical structure and characteristics during changing biological environments such as tissues, body fluids, or other physiological conditions is known as chemical stability. The chemical stability of biomedical materials is determined by several factors, such as the choice of appropriate materials, resistance to degradation, biocompatibility, surface modifications, insight into chemical interactions, and long-term performance in biological environments. The efficacy and safety of implants, medical devices, and other biological applications depend on this stability. For the substance to last a long time within the body, chemical stability is necessary [61].

3.2.5 Compatibility with Other Materials

Chemical compatibility is a crucial factor to consider when combining biomedical materials with other substances, such as adhesives or coatings, to prevent unfavorable interactions between them. For implant applications, metallic materials including cobalt-chromium (Co-Cr) alloys, titanium (Ti), magnesium (Mg) alloys, and stainless steel (SS) are frequently utilized as biomaterials. Inadequate biocompatibility, a higher rate of deterioration, an inflammatory reaction, infections, a mismatch in elastic modulus, a high rate of wear, and shielding stress are some of the reasons why metallic implants might fail during surgery. Consequently, to solve this issue, a technique for enhancing the biofunctionalization of metallic implant surfaces must be developed. This technique must modify the surface and morphology of the materials without affecting the metallic implants' mechanical characteristics. Among other techniques, coatings applied to metallic surfaces provide a surface modification that effectively enhances implant material performance [62].

3.2.6 Ion Release and pH Sensitivity

Certain materials, such as orthopedic implants or dental fillings, have the potential to discharge ions into the surrounding tissues. It is important to carefully analyze the chemical characteristics of these discharged ions since they might have an impact on tissue health. A potential species that exhibit deformation or disintegration upon exposure to externally occurring acidic or alkaline environments are pH-sensitive biomaterials. Biomedical materials' sensitivity to pH is important because it can have a big impact on how well they function, how stable they are, and how they interact with biological systems. The pH-sensitive properties allow the formulations to alter their intra- or intermolecular forces in response to changes in the external pH, which triggers the release of payloads. Numerous biomaterials, including polymers, hydrogels, and nanoparticles, show pH-responsive activity, which makes them useful for a range of biological applications, including tissue engineering, drug delivery, and biosensing [63]. Creating biomedical materials that are both safe and effective requires an understanding and control of these chemical characteristics. While maintaining patient safety and well-being, researchers and engineers strive to modify the chemical properties of these materials according to the unique requirements of many medical applications [64].

3.3 Physical Properties

The basic qualities that dictate the behavior of biological materials in medical and healthcare applications are their physical properties. These characteristics are crucial for guaranteeing the longevity, efficacy, and safety of biomedical materials [65]. The following are some essential physical characteristics of biological materials.

Density measures the amount of mass contained in a specific volume. Low-density materials are frequently chosen in the biomedical sector to lower the total weight of implants and medical equipment. For instance, orthopedic implants frequently employ lightweight titanium alloys to reduce patient burden. Porosity describes a material's ability to hold empty spaces or pores. Controlled porosity is important in tissue engineering because it facilitates cell and nutrient penetration, which promotes tissue development inside a scaffold. For instance, porous scaffolds can help in bone regeneration in bone tissue engineering [66]. Mechanical strength refers to a material's capacity to bear loads without breaking down or deforming. Varying degrees of strength are needed for different purposes. Dental crowns must survive the pressures of chewing, whereas materials used in hip implants must tolerate the stresses of weight-bearing. Hardness measures the material's resistance to abrasion, deformation, or penetration. To endure the abrasive pressures applied during chewing, dental materials such as ceramic crowns need to be sufficiently robust. Elasticity is the ability of a substance to regain its previous shape after deformation [67]. For example, to guarantee appropriate mobility and functioning, materials utilized in artificial cartilage or joint replacements should resemble the natural elasticity of these tissues. The coefficient of friction measures the resistance of a substance to sliding or moving against another surface. Low friction is preferred for biomedical materials to minimize wear and tear in prosthetic heart valves, joint replacements, and other medical equipment. The thermal conductivity of a material tells us how well it transfers heat. Materials with reduced thermal conductivity can minimize excessive heat transmission to surrounding tissues in the context of orthopedic implants or prostheses, hence reducing injury or discomfort [68]. Radiopacity can be seen using X-rays or other imaging methods. This characteristic is essential for the manufacturing of medical implants that must be visible during imaging for diagnosis, such as coronary stents. Wettability describes a substance's reaction to liquids. For example, materials having hydrophilic qualities help to retain comfort and moisture in contact lenses. The surface roughness of a material can affect bacterial colonization, tissue integration, and cell adhesion. Several medical implants and devices may require surface roughness control to function properly [69].

However, recent research indicates that the area of biomaterials may be witnessing the rise of a strong new set of design factors. Scientists are looking more and more for physics-based ways to regulate biological reactions. As of right now, it is evident that a biomaterial's physical characteristics—like its size, shape, mechanical characteristics, surface roughness, and compartmentalization—have a significant influence on how well it functions in a biological context. Porosity and density, among many other physical characteristics, will also have a big influence on a material's functionality. It has been demonstrated that certain physical characteristics of particles affect several critical bodily processes, including phagocytosis, circulation, targeting, and adhesion. Biology itself provides the incentive for using physical characteristics to regulate biological activity [65].

4 Applications of Biomedical Materials

Biomedical materials are essential to many medical applications because they meet a wide range of healthcare requirements (Fig. 3). The two primary categories of these materials are natural and synthetic. Tissues, polymers, and extracellular matrix components are examples of biological sources from which natural biomedical materials are frequently derived. These materials closely resemble the natural environment of the body and offer biocompatibility and bioactivity. On the other hand, synthetic biomedical materials come in a variety of mechanical and chemical qualities and are specifically designed to fulfill certain needs. Because of their adaptability, synthetic materials can have exact control over properties like conductivity, strength, and rates of degradation. Biomedical materials play a vital role in the development of medical devices, drug delivery systems, tissue engineering, and implants, meeting essential demands in modern healthcare [70].

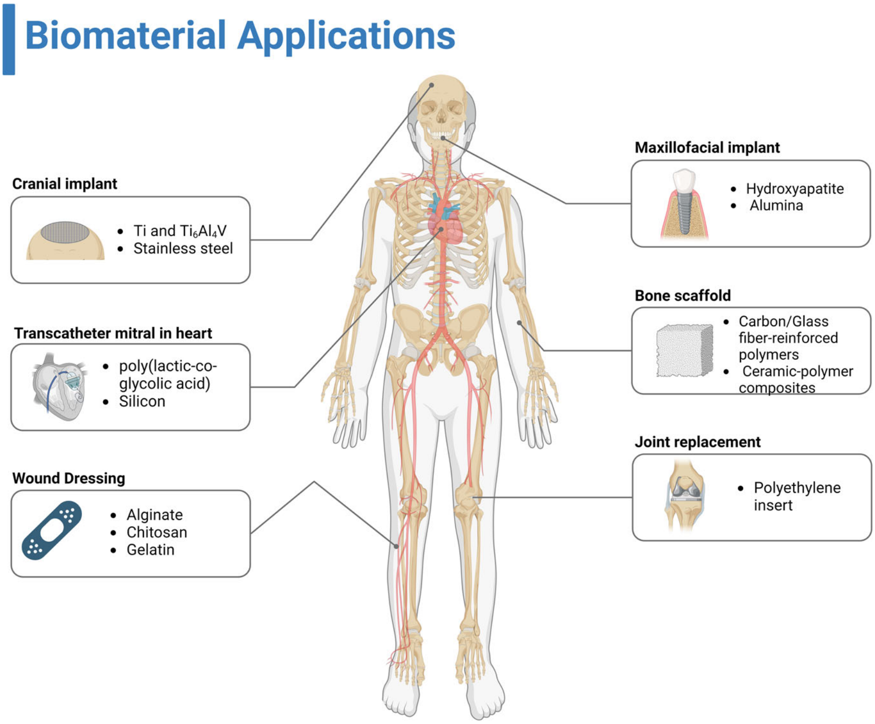

Fig. 3 Some potential applications of biomaterials in healthcare sector

4.1 Applications of Natural Biomaterials

Nature-based biomaterials come from living things including plants, animals, and marine life. Because of their intrinsic biocompatibility, they can be effectively incorporated into living organisms without causing any side effects. These materials are useful in a range of biological applications because of their distinct characteristics and functionalities. Based on their composition, natural biomaterials are divided into two categories: those based on polysaccharides, such as cellulose, chitosan, and alginate, and those based on proteins, like collagen, gelatine, and silk [71].

Both plant and bacterial cellulose have tunable mechanical, chemical, and physical characteristics in addition to bioactivity, and biocompatibility. Significant advancements have been achieved in the use of nanocellulose in lesion repair, as scaffolds for cell culture and tissue regeneration. Contrary to most other uses of nanocelluloses, biomaterials based on bacterial nanocellulose (BNC) have advanced from clinical trials into routine clinical practice. Their main application is in the management of non-healing ulcerations of the lower extremity, where it has been shown that using BNC biomaterials may shorten the healing period from an average of 240–390 days to 80 days. Antimicrobial compounds have also been embedded in nanocellulose by physical or chemical methods to create antimicrobial nanocellulose wound dressings. Chitosan is the second most common natural polymer on Earth, derived from chitin, a special biopolymer that has attracted a lot of interest lately due to its potential usage in tissue engineering applications [72]. Chitosan has the exceptional capacity to degrade naturally and to possess antibacterial, anti-tumor, hemostatic, and mucoadhesive qualities that allow it to provide ideal conditions for wound healing. It has also been demonstrated to offer potential in the delivery of drugs and vaccinations [39].

Alginate has shown significant promise as a biomaterial, namely in the areas of drug delivery, tissue engineering, and wound healing. It shows extremely promising gelling potential, ease of modification, and biocompatibility in hydrogel form. Because of its compatibility with both extrusion and inkjet printing processes, alginate is also one of the most often utilized biomolecules in 3D bioprinting. Its characteristics are similar to those of natural Extracellular matrix (ECM), allowing it to sustain cell growth [73]. Nowadays, collagen-based materials are preferred over other types of biomaterials in tissue engineering and regenerative medicine due to their high biocompatibility, low immunogenicity, and structural adaptability. Advances in extraction and scaffold structure have resulted in a growing variety of collagen uses in different fields such as wound healing, drug delivery, and tissue regeneration. Gelatin has been used as a cell, drug, and gene carrier because of its exceptional biocompatibility and biodegradability. These qualities make it a desirable material for tissue engineering and drug delivery applications. In contrast to collagen and its precursor, gelatin is less immunogenic and contains informative signals like the RGD (Arg-Gly-Asp) sequence, which encourages cell adhesion and proliferation. Because of its many functionalization options, gelatin can be easily and successfully crosslinked. It can also be combined with other materials (such as metal nanoparticles, carbonaceous materials, minerals, and polymeric materials with desired functional properties) to create composite materials with enhanced thermo-mechanical, physio-chemical, and biological properties. Moreover, some molecules can be chemically immobilized and physically combined with other biopolymers to create gelatin-based biomaterials [74]. For biomedical applications, silk-based biomaterials have shown to be one of the most adaptable and promising protein-based biomaterials. They respond exceptionally well to host tissues and exhibit remarkable mechanical, biodegradable, biocompatible, and cell-binding qualities. Silks derived from silkworms and spiders have proven to be highly effective in a variety of applications, including suturing, bone regeneration, tissue engineering, and enhancing the biocompatibility of implanted devices [75].

4.2 Applications of Synthetic Biomaterials

Currently, polymers find extensive usage in various biomedical applications, such as those where the polymer maintains close contact with cells and tissues for extended periods. The two most widely utilized polyolefins are polyethylene and polypropylene. These thermoplastics are resistant to chemicals, and microbes, and are hydrophobic and non-biodegradable. Blood storage bags, dilators, disposable hypodermic syringes, suture materials, medical vials, diagnostic devices, and surgical components, are used because they are affordable and exhibit good resistance to environmental stress cracking. Polyolefins are used in cardiovascular applications as blood supply housings and tubes. Moreover, polyethylene finds extensive application in the creation of porous, high-density polyethylene implants intended for cranial and face reconstruction. Polyethylene glycol (PEG) is a perfect material for use in biomedical applications because of its biocompatibility, flexibility, non-toxicity, and stealth qualities. Nowadays, PEG hydrogels are utilized for both drug delivery and cell encapsulation [76]. The two most popular synthetic fluorocarbon polymers utilized in medical applications are PTFE (Polytetrafluoroethylene) and PVDF (Polyvinylidene fluoride). They are inert thermoplastic, biocompatible, and have a low coefficient of friction. Vascular grafts, heart valve replacements, and mitral valve repair for myxomatous implanted prosthetic heart valve rings are applications for PTFE. PTFE is also utilized as the guiding catheter for the delivery of other devices, such as coronary stents. Due to its exceptional mechanical qualities and biocompatibility, silicone is a synthetic polymer that has been used extensively in the biomedical industry since 1940 for implantable devices [77]. Applications for silicone include orthopedic implants, shunts, catheters, drains, extracorporeal devices, different long-term implants, and specialty contact lenses. In addition, silicone is utilized as a coating for syringes, needles, and vials used for collecting blood. Additionally, Silicone tubing and membranes are also utilized in heart valves, blood oxygenators, kidney dialysis machines, and heart bypass machines [78]. Polyurethane (PU) is the most popular material for making blood-contacting devices, including prosthetic veins and arteries or heart valves. PU is crucial in the creation of numerous medical devices, from catheters to whole artificial hearts. Elastomeric polyurethane (PU) is also utilized in spine surgery to replace discs and stabilize spinal movement to alleviate compression on nerve roots. Polycaprolactone is used as a graftable tool for long-term drug delivery. Joints, scaffolds, and vesicle membranes are made of polycaprolactone. Drugs are being encapsulated in polycaprolactone for targeted drug delivery [79]. Poly Methyl methacrylate (PMMA) is a rigid polymer that is used in orthopedic applications such as arthroplasty, ophthalmology, and dentistry. Numerous medical areas of expertise quickly took advantage of its biocompatibility, stability, relative ease of manipulation, and low toxicity. PMMA has been utilized in the following applications: (1) filler for bone cavities and skull deformities, (2) contact lenses, (3) screw fixation in bone, and (4) stabilization of vertebrae in patients with osteoporotic fractures. Poly (2-hydroxyethyl methacrylate) polymer was first used to create soft (hydrogel) contact lenses. In addition to contact lenses, poly (2-hydroxyethyl methacrylate) is utilized in root canal fillings, drug delivery depots, burn bandages, intraocular lenses, vascular occlusion agents, cell encapsulants, nerve growth conduits, artificial corneas, bone repair materials and used as coatings on stents, sutures, and catheters [80]. Clinical graft materials such as sutures, bone plates, cartilage repair components, and cardiovascular repair covering frequently contain polyhydroxyalkanoate (PHA) and its copolymers. Because polyhydroxyalkanoate is precisely degradable and compatible with the living host, it is used in drug release applications. Polylactic acid (PLA) based biomaterials are widely recognized as the gold standard for many applications in orthopedic regenerative engineering due to their biodegradability, compatibility with cells and biomolecules, and ease of production. PLA is used in interior fixation components such as screws, rods, plates, and pins to hold fractured bones together and aid in their recovery. Because of polyglycolide material's excellent degradability, cell viability on support structures, and basic mechanical properties, they are widely used as support structures for tissue regeneration. For medical applications, PVC is useful because of its good strength, flexibility, crystal clarity, and low cost. Catheters, tubing, and blood bags are frequently made of PVC. PVA is utilized in tissue adhesion barriers, soft contact lenses, and artificial cartilage. Due to its remarkable barrier qualities, ethylene vinyl alcohol (EVOH) is suitable for dialysis bags and stormy pouching systems. It is more frequently used in implants and drug delivery systems [81].

In the last few centuries, materials of biological significance that function alongside natural tissues or artificial organs in the human body have been developed in addition to natural and synthetic polymers. Bioceramics, metallic biomaterials, and biocomposites are the materials of biomedical significance that are frequently used. Medical grafts have been the primary application of bioceramics. It helps more potently in the development of new bone tissue and has minimal toxicity. Ceramics such as orthophosphate, which is generally used to support tissue restoration and is also utilized to address bone repairs. Bioceramics like hydroxyapatites are used primarily as dental implants due to their exceptional rigidity. Bioceramics are characterized by their extreme lack of reactivity, rigidity, and brittleness, as well as their strong compressive strength but low tensile strength. Orthopedic implants and dental restorations are the main applications of bioceramics [79]. Metallic biomaterials have been used primarily in applications where load-bearing properties are extremely important, such as knee replacements, bone grafts, and dental implants. Because of their exceptional and prevailing mechanical properties, metallic biomaterials have been applied in many biomedical applications. The most common metallic biomaterials are alloys of titanium, molybdenum, cobalt-chromium, and iron (such as stainless steel). Stents, fracture fixation, and surgical equipment use stainless steel. Dental implants, pacemaker encapsulation, and bone replacement use titanium alloys. Dental restorations, heart valves, and bone replacement use cobalt and chromium alloys [82]. Composite biomaterials are most frequently employed, both in vitro and in vivo. It is simple to create these multiphase materials with different combinations of shapes and qualities. With the least amount of adjustment, certain material qualities can be produced with great precision by adjusting factors such as matrix type, constituent volume ratios, fiber particle size, geometry, orientation, and distribution. Hence, unlike metallic, polymeric, and ceramic biomaterials, composite materials have design flexibility and can be easily designed to have practically any desired property. Recently, many biocomposites have been investigated and approved for biomedical applications. The majority of natural tissues, including tendons, ligaments, teeth, bones, skin, and so forth, are biocomposites made of individual components whose quantity, distribution, and shape determine the final functions of the resulting biological tissues. To some extent, artificial composites of biomedical significance can be used to create artificial body parts that can replicate biological tissues [83].

5 Technological Developments in the Field of Biomedical Materials

By utilizing the special qualities of living things or imitating natural processes, technological developments in biological materials have revolutionized a wide range of fields.

5.1 Biomimetic and Smart Biomaterials

The biologically inspired biomimetic and smart biomaterials and systems that are currently under development imitate the extracellular environment and one or more natural functions represent the fourth generation of biomaterials. These materials offer novel approaches to disease treatment, promote tissue regeneration, and reconstruct body parts [84]. In contrast to much more complex homogeneous man-made composites with complex chemical compositions and architectures, new concepts are inspired by common design principles used by living organisms to develop heterogeneous structures with outstanding properties by combining soft and hard components from a fairly limited selection under mild synthesis conditions [85]. Biomimicry is not the same as bio duplication rather, it is inspired by natural materials and processes. By using multiple inter- and intermolecular noncovalent interactions, biomimetic approaches can be used to create synthetic smart biomaterials using conventional processing methods, or they can mimic natural structures down to the molecular hierarchical organization level based on biological autonomous self-assembly complex structures. Smart biomaterials have been developed to engage in biological interactions with adjacent cells and tissues, actively contribute to the regeneration of damaged tissue, react and respond to external stimuli, and support controlled drug release as well as the body's innate ability to repair and heal itself. It is not only necessary to produce smart biomaterials, but also smart designs of biomaterials systems, which involve smart approaches to drug delivery and tissue regeneration. Biomimetic self-healing biomaterials show promise for safer, more durable products and components by demonstrating the capacity to repair and regain functioning utilizing the resources that are naturally available to them [86].

5.2 3D Bioprinting

With the use of a 3D production technique called bioprinting, complex 3D functioning living tissues or artificial organs can be created by precisely dispensing cell-laden biomaterials. Though still in its infancy, bioprinting techniques have shown promise for producing a range of transplantable tissues, such as skin, cartilage, and bone, in regenerative medicine [87]. Similar to conventional 3D printing, three-dimensional bioprinting builds structures layer by layer. However, it employs biological materials such as cells, growth factors, and biomaterials as bioinks rather than metals or plastics. These inks which are used in bioprinting are made of living cells encapsulated in a biomaterial matrix that provides structural support and resembles the natural extracellular environment. Bioprinting technology is widely used in many fields, including drug screening, cancer pathogenesis, tissue bioprinting for clinics and transplantation, tissue engineering, and regenerative medicine [88]. Nonetheless, there are still technological obstacles facing modern bioprinting techniques when it comes to vascularization, innervation, regulated cell distributions, and high-resolution cell deposition in complex 3D tissues. A new technique called 4D printing is a novel method that improves 3D printing. In traditional 3D printing, objects are constructed by stacking materials in a three-dimensional space. 4D printing allows for the creation of materials with the ability to self-assemble, alter shape over time, or respond to external stimuli. In contrast to 3D printing techniques, 4D printing maintains greater quality, precision, accuracy, and performance capabilities while producing any complex object using a range of materials [89].

5.3 Nanomaterial Innovations

Recent developments in nanotechnology have made it essential to create novel materials with several uses. Nanomaterials have exceptional physio-chemical capabilities due to their reduced size, including enhanced surface area, molar extinction coefficients, controllable structure, tunable plasmonic characteristics, and magnetic and optical properties, with improved absorption and reactivity. These special properties of nanomaterials might enable a wide range of uses, including tissue engineering, biosensing, drug delivery, imaging, medical implants, and cancer treatment [90]. Nanomaterials improve imaging methods such as MRIs, CT scans, and biosensors for precise and quick diagnoses. They also act as sensitive probes for early disease detection. Targeted drug delivery systems provide accurate medication release to specified areas with minimal side effects in treatments. The development of scaffolds that replicate the natural environment of the body to promote cell growth, tissue regeneration, and organ transplantation is made possible by these materials, which are also essential to tissue engineering and regenerative medicine. Nanomaterials have the potential to completely transform healthcare by enhancing medication delivery, regenerative therapies, and diagnostics. They can also provide personalized and efficient solutions for a wide range of medical problems [91]. However, due to their limitations (such as non-biocompatible, poor photostabilities, minimal targeting capacity, side effects on other organs, inadequate cellular uptake, and small blood retention), nanomaterials remain difficult to use in the biomedical field for better therapeutics. As a result, new types of nanomaterials, referred to as “smart” nanomaterials, must be developed. Designed with special qualities that react to outside stimuli or changes in their surroundings, smart nanomaterials are a category of advanced materials. These materials possess the capacity to adjust, alter their behavior, or carry out particular tasks in a precise and regulated way [90].

5.4 Bioelectronics and Implantable Devices

Significant technological advancements in the field of bioelectronics and implantable devices have transformed the field of medical interventions through the development of biomedical materials. A new era of flexible and stretchable electronics has begun, utilizing substrates based on nanomaterials and materials like elastomers to enable devices to adapt to tissues and organs [92]. Because silicon and silicon compounds (such as silicon dioxide and silicon nitride), metals, and metallic oxides are so compatible with known microfabrication techniques, they have been the first-generation materials used in the creation of implantable bioelectronics. Unfortunately, these materials’ stiffness and inflexible mechanical qualities have made surgical implantation difficult and even damaged soft and flexible tissues and blood vessels. Afterward, flexible and soft materials were used since they may increase the biocompatibility and dependability of the devices. Silicone elastomer, parylene, polyimide, and PVDF-TrFE are examples of polymeric materials that are frequently utilized as substrates and provide consistent encapsulation of electronic sensing components in medical devices. Lately, a novel class of biodegradable materials has emerged for the creation of transitory bioelectronics, which serves as supporting encapsulants or transient electrodes. These materials' primary benefit is that their byproducts are securely absorbed by the body and they dissolve naturally in biofluids. As a result, they have been thoroughly researched to create new medical implant platforms. Furthermore, real-time biomarker monitoring has been made possible by the incorporation of biodegradable materials into sensors and actuators, and advances in soft robotics have made it easier to create prosthetics that are more natural-looking and useful. Treatment strategies have been completely transformed by the incorporation of responsive drug delivery systems into implanted devices, which enable precise and regulated drug release [93].

6 Future Prospects

Biomedical materials have the potential to revolutionize healthcare and treatment approaches in the future. Targeted therapies and customized treatments will be made possible by smart materials that react to particular stimuli, like pH or light, revolutionizing tissue engineering and drug delivery systems. The significant lack of transplantable organs will be addressed by the capacity to create functional organs and tissues through 3D bioprinting advances, which would boost regenerative medicine. Nanostructured materials and nanorobotics will play vital roles in precision medicine, diagnostics, and cellular-level treatments as nanotechnology continues to push boundaries. Bioinspired materials, drawing inspiration from nature, will imitate the persistence and adaptability of biological systems, opening the door to bioactive implants and self-healing surfaces. Advanced prostheses and implants will grow smarter as electronics and sensors are integrated. They will be able to monitor health parameters, control drug release, and wirelessly communicate with external devices. Stem cell therapies and materials for gene editing will be included in regenerative medicine, which might treat anything from tissue injuries to neurological problems. Materials will also be incorporated into wearables and other gadgets as part of data-driven healthcare, encouraging ongoing health monitoring and personalized treatment plans. Moreover, biomedical material's future depends on addressing challenging issues. Materials that mimic the structure of human tissues, such as blood vessels and supporting structures, must be developed. Enhancing material design will require an understanding of how cells behave in many dimensions, especially in intricate matrices and scaffolds. To design materials that function well with cells, it's also essential to take into account the size variations between cells and microscopic structures. Scientists want to develop safer materials that function better within the human body by understanding how these materials interact with the body's natural processes, such as healing and fighting infections. In the end, scientists hope to create materials that easily integrate into our bodies and enhance medical treatments by investigating the interactions between materials and our bodies.

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Material Characterizations

Muhammad Qamar Khan and Muhammad Abbas Haider Alvi

Abstract This chapter focusses on the classification and descriptive types of material characterization methods that are being used across various sectors, for quality control and assurance, product design, performance enhancement, as well as failure analysis, and assessment of the product's lifecycle. This helps to maintain the set standards since the characterization of the material to be used in the manufacturing process is an important aspect of quality control. Knowledge on material features is essential in the design of products and improvements in efficiency while avoiding failure. Savings can be done in determination of right material, doing away with extravagance, and compliance with necessary laws. Discovering new material and technology advances modification while nonetheless assessing influences of the environment and accommodating multiple uses. To conclude, this chapter has highlighted the importance of material characterization in driving up the quality and innovation of products, sustainability, and compliance in various sectors.

Characterization of materials is one of the analytical methods that is employed in ascertaining the properties of a material. Among them are mechanical properties such as strength, hardness, elasticity, thermal properties conduction—electrical conduction and etc. The testing of materials is basically done with an aim of assessing materials for their suitability for a specific application or not. This is very important especially in critical areas like manufacturing, construction, aerospace, automobile industries and others where the efficiency of the material used plays a significant role.

Material testing has many important applications in today's world including quality assurance, new product development, research, and more importantly, for ascertaining the safety and performance characteristics of a material for its intended usage. The findings from these tests are useful to engineers and scientists to assess the application of those material, view on the design procedures and whether it meets the

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set standards. This chapter covers various characterization techniques which help the reader to evaluate the appropriateness of the author's novel and commercial/industrial products for their intended use. These techniques have been grouped into four major categories; Structural, Surface, Mechanical, and Thermal analysis.

1 Structural Characterization

The techniques of characterization elucidated in this category explain the structure of atoms and molecules in a material. It is helpful in providing structural information of the material so that one can forecast its characteristics as well as its behavior. Sandwiched within this category of techniques are X-ray diffraction (XRD), and Fourier Transform Infrared Spectroscopy (FTIR).

1.1 X-ray Diffraction (XRD)

XRD is a non-destructive phase sensitive method originated from wave interference of X-rays which is scattered by atoms associated with the crystal lattice of a material. Let yourself think about aiming a spot of X-ray at a sample. If the atoms are arranged in simple patterns or lattices that are repetitive as in crystals then its interplay with X-rays will cause it to scatter in certain directions. Through the analysis of angles and intensity of these diffracted beams, the scientists are able to deduce spacing and organization of atoms of the crystal lattice [1].

The fundamental law that underlines the technique known as XRD is Bragg's Law whereby λ, d, and θ are the wavelength of X-rays, distance separating the atomic planes of a crystal sample, and the angle of diffraction respectively:

$$\mathrm{n}\lambda = 2\mathrm{d}\sin(\theta)$$

From the diffraction pattern, the kind of crystal structure, size of the unit cell and if the material has more than one phase, all can be determined [1, 2] (Fig. 1).

XRD is incredibly versatile and can be used to analyze a wide variety of materials, including [1]:

- Metals and alloys: Determine phases, find grain size and analyse stress and strain.
- Ceramics and glasses: Some features that are focused on by the method are: determination of crystal structure; measurement of the amount of amorphous phase; observation of phase transformations.
- Polymers and plastics: Identify crystalline constituents, and examine the orientation and the degree of crystallinity.

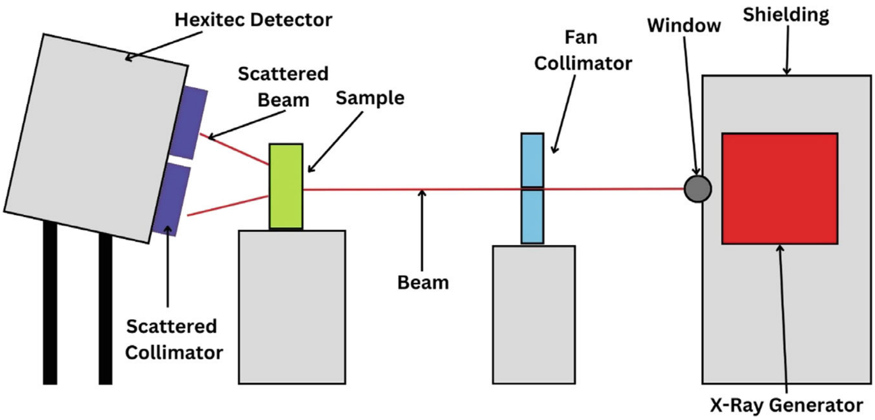


Fig. 1 XRD line diagram

- Biological materials: Protein structures must be analyzed, bones need to be examined in terms of their composition, interactions between a drug and a material must be studied.
- Nanomaterials: Analyze the arrangement of ions and phas in the solid, sample the size of the grains in the sample, and examine the imperfections.

An XRD pattern is a graph of the intensity of the diffracted x-rays against the angle of diffraction denoted as 2θ. Each of them represents a certain number of atomic planes in the profile of the crystalline lattice. From where these peaks lie and how intense they are was revealing information about the structure of the material [2].

There are various standard methods used in XRD, depending on the specific type of analysis and material being studied. Some of the most common methods include:

- Single-crystal diffraction: For studying crystals that are large compared with the unit cell in order to find out the exact locations of the atoms within.
- Thin-film diffraction: Used when it is necessary to study a thin film and a coating that is deposited on the substrate.
- Neutron diffraction: This is similar to x-ray diffraction but instead of using x-ray it uses neutron hence it provides complementary information to x-ray diffraction in some instances [1, 2].
- High-brightness X-ray sources: Synchrotron radiation and the X-ray free-electron lasers provide reciprocal information—high intensity of the probe, which makes it possible to carry out the analysis quickly, as well as the analysis of small specimens.
- Micro- and nano-XRD: They allow reducing the analyzed region of the material to very small details: the techniques open new opportunities in the investigation of nanomaterials and thin films.

- Computational XRD: The diffraction patterns can be mimicked with the help of advanced software and they can also assist in phase identification as well as structure refinement.

1.2 Fourier-Transform Infrared Spectroscopy (FTIR)

Fourier-transform infrared spectroscopy (FTIR) is one of the most valuable analytic technique for identification and characterization of the organic and polymeric materials and in some case of inorganic phase as well. The way this works is it will quantify the way that infrared light interacts with a sample and gives an indication of how the sample is molecularly constructed and what it is made of.

FTIR transmits a sample that samples the range of infrared light that can be sensed, which is a graph of how much (~). The given molecules cause the absorption of certain infrared wavelengths due to the vibrations and rotations of their molecules. When the absorption pattern is assessed, it becomes possible to determine the types of functional groups and chemical bonds in the sample (Fig. 2).

A wide range of materials can be analyzed using FTIR, including:

- Organic materials: Polymer, plastics, textile, drug, biochemical, foods
- Inorganic materials: These include minerals, use of ceramics and semiconductors.
- Gases: Air, emissions, gases used in drugs and medication.

An FTIR spectrum is a graph that has absorbance of infrared light by the sample on the Y-axis and the wavelength of radiation on the X-axis. The observed peaks in

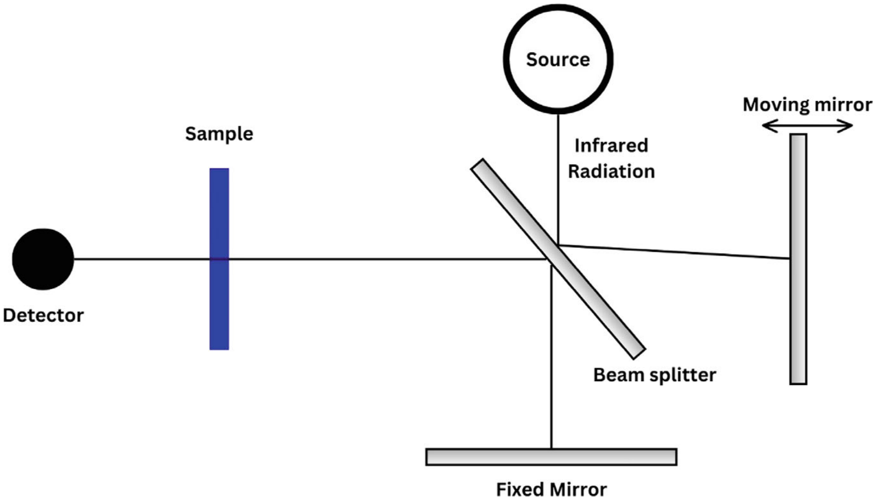


Fig. 2 Simple line diagram of FTIR

the spectrum reveal that functional groups and bonds that are inherent to the sample being analyzed.

Several standardized methods exist for FTIR analysis, depending on the material type and application. Some common methods include:

- ASTM E1252 is the standard practice of general techniques for Infrared Micro spectroscopy.
- The historic academic title of ASTM E1686 designation is: Standard Practices for Infrared (IR) Wavelength Calibration.
- This standard are Certified by: ISO 14044 Chemical oxygen demand (COD) determination Infrared spectroscopy method

The field of FTIR is constantly evolving, with new advancements improving its capabilities and accessibility. Some recent trends include:

- Micro-FTIR: Allows the sampling of miniature samples and yielding high spatial detail.
- Hyperspectral imaging: Joins the FTIR with imaging methods to acquire chemically related data with a specific location.
- Portable FTIR: This makes it possible to analyze the results of samples on-site without having to follow a series of step-by Step procedures so as to set up a laboratory.

2 Surface Characterization

The methods that have been covered under this category assist in mapping the topographical features of the material. Techniques that were used on the surface included Scan Electron Microscopy (SEM), Energy Descattering x-ray fluorescence (EDX), trans mission Electron microscopy (TEM) and contact angle with water.

2.1 Scanning Electron Microscopy (SEM)

The letters SEM as an abbreviation represent Scanning Electron Microscope, a tool that opens the opportunity to inspect the internal structure of the materials with the use of the micro and nanoscales technologies not less than 50 nm! It is a process as if one has a lens that focuses on the details and gives the view that he never gets to see with his naked eyes [3]. Suppose that instead of illumination beam the machine uses a beam of electrons to shine it over the sample. During the scanning process or (the process of relating the beam position to the sample) the beam produces different signals, they could be small lights in the form of flashes that give out information concerning the surface features of the material, the type of material and its chemical properties including its functionality. These signals are then converted to a clear picture or image on a computers screen to produce a microscopic view of the world [4].

- Electron Gun: Creates a very sharp and energetic beam of electrons [3].
- Condenser Lenses: Illuminate the sample by directing the electron beam on to it.
- Scanning Coils: Explain the movements when making adjustments across the sample's surface in the best way:
- Sample: Suspended conducting platform placed in the vacuum enclosure.
- Electron-Sample Interaction: They accordingly generate different signals as the beam impacts on the sample through the target-positioning beam. Secondary Electrons: Released from the sample due to energy transfer and the interaction-detected surface facets and morphology. Backscattered Electrons: The electrons were reflected by the sample, concerning atomic number and composition of the sample. X-rays: That are emitted at characteristic wavelengths associated with the species in the sample.
- Detectors: These are the motor and sensory signals that need to be acquired and translated into electrical signals.
- Computer System: Builds up and increases the intensity of the signal in order to form a clear picture of scanned areas (Fig. 3).

The versatility of SEM allows it to analyze a wide range of materials, including [3, 4]:

- Metals and alloys.
- Semiconductors and ceramics.
- Polymers and plastics.

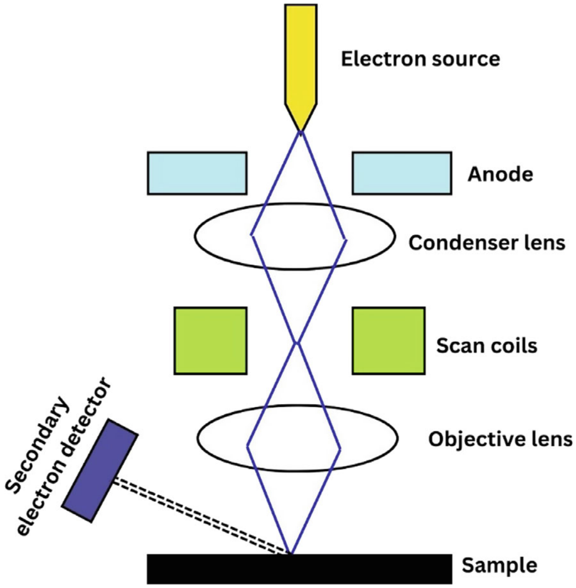


Fig. 3 SEM line diagram

- Cell and tissue types such as animal and plant cells.
- Rock/ore samples and other minerals.
- They include materials at atomic and molecular levels as well as composite and highly developed material systems.

Depending on the type of signal being detected, the resulting graph can look different. Here are some examples [3, 4]:

- Secondary Electron Image (SEI): Captures features of the earth's surface, including topographic features of higher resolution than any other technique.
- Backscattered Electron Image (BEI): High lights differences in atomic number and composition, which reflect more light for the heavy atoms.
- X-ray Spectrum: Determines the presence of the components in the sample using peaks at certain wavelengths.

Several standard methods are used in SEM analysis, but the specific protocol depends on the material and desired information. Some common steps include [3, 4]:

- Sample Preparation: Very often, constitutes covering non-conductive samples with a thin layer of metal to avoid charges accumulation.
- Mounting: Bringing the sample into contact with a conductive stage that is located inside the vacuum chamber.
- Setting Parameters: Selecting the right accelerating voltage, beam current, and magnification or scanning resolution.
- Image Acquisition: Reading through the sample and acquiring different signals to come up with the images as well as spectras.
- Data Analysis: Analyzing the data to get information about the external appearance and internal composition as well as other characteristics of the sample.

The field of SEM is constantly evolving, with new advancements pushing the boundaries of resolution, speed, and analytical capabilities. Here are some exciting trends:

- Cryo-SEM: Permits the imaging of the biological samples in the frozen state so that the samples retain their native morphology.
- Environmental SEM: Used to analyze samples under the conditions of the temperature, pressure, and the kind of gas within the chamber.
- Automated image analysis: Facial analysis is also possible using SEM images, but the data can also be numerate and analyzed by software for specific features based upon patterns.
- Super-resolution SEM: Beyond the get-go, this accomplishes a higher resolution than normal and brings out the smallest detail from an object.

2.2 *Energy Dispersive X-ray Spectroscopy*

Suppose you illuminate a material with X-rays and examine the response of the constituents in that material. Well, that is what EDS pretty much does! It ethics the sample with high energy X-rays that causes electrons to be ejected from the atoms in the sample. As these electrons move back to their original orbit, they lose energy in form of X-rays of certain frequency. Every sample diffractions a special pattern of X-rays and using EDS, EDS determines the type of elements and their intensity in the selected specimen.

- X-ray Source: Emits a narrow, powerful beam of X-rays, of very high energy.
- Sample: Substrate, which is mostly the material under investigation that is often deposited on an electrode.
- Detector: Collects the emitted X-rays from the sample, X-rays that have a wavelength proportional to the sample's interatomic distances.
- Multi-Channel Analyzer (MCA): CO—calculates the energy of the radiation the X-rays emit and transforms it into a spectrum.
- Software: Locates and measures the present factors according to their unique body wavelengths in the spectrum (Fig. 4).

The versatility of EDS allows it to analyze a wide range of materials, including:

- Metals and alloys: Phase
- Composition, Identification and Analysis of Corrosion Products
- Geologic materials: Exploring the mineral while examining the structures of the rock as well as analyzing meteorites.
- Semiconductors: Evaluating the structures of the device and determining the presence of unwanted material and dopants.
- Biological materials: Investigations on the elemental basis of cells, tissues as well as biominerals.
- Polymers and plastics: Classification of additives, evaluation of fillers, or examination or contamination.

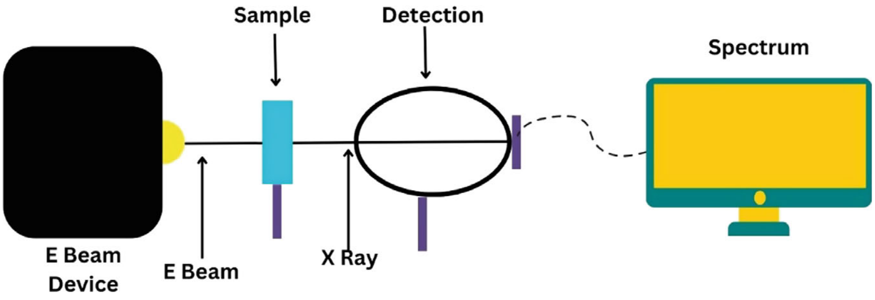


Fig. 4 Simple diagram of EDS

An EDS spectrum actually is a graph with the X-ray energy on the horizontal axis and intensity of emitted photons on the vertical axis. Every ingredient present in the sample has a particular point of energy, which is as good as a fingerprint. Relative amount of the mentioned element is defined by the height of the peak.

Several standard methods guide EDS analysis depending on the material and application. Some common standards include:

- E1283: Standard Practice for Using X-ray Fluorescence for Quantitative Elemental Analysis
- ASTM E2138: This is the standard practice that focuses on scanning electron microscope (SEM) based energy-dispersive X-ray spectrometry (EDS) procedure.
- ISO 13060: Energy-dispersive X-ray spectrometry (EDS)—part 2: Quality of results

The field of EDS is constantly evolving, with exciting innovations like:

- Micro-XRF: Gives even more localized elemental analysis with even lesser spot sizes.
- Hyper-spectral EDS: Enhances the number of resolveable spectra enabling better distinction of complex peaks that may be merged.
- Machine learning algorithms: Elevate elevation metrics; optimize peak search while enhancing its point-and-click component.
- Portable EDS instruments: Portable elemental analysis to take the tools of the lab to wherever they are needed out in the field.

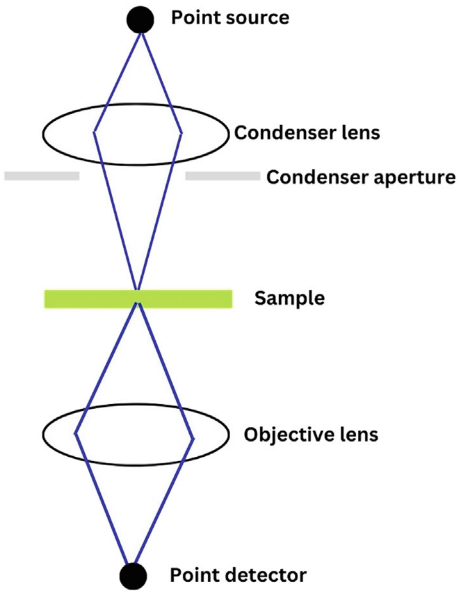
2.3 Transmission Electron Microscopy (TEM)

A TEM on the other hand, utilizes a beam of electrons instead of light to in order to illuminate a sample. Such electrons are much smaller than those of the photons which is light, and can allow the imaging of object details to as small as 0. 1 nm in size which is one ten thousandth the width of an average hair. The working principle is;

- Electron Gun: Creates a beam of high energy electrons.
- Condenser Lens System: Adjusts the position of the electron beam to coincide with the sample upon which analysis is needed.
- Sample: A very tact thin layer of material from which samples for analysis are prepared.
- Objective Lens: The transmitted electrons are then converged on to the detector by this lens.
- Detector: Digitalizes the electron signal and produces an image which is visible on the screen (Fig. 5).

The TEM's ability to analyze at the atomic level makes it suitable for studying a wide range of materials, including:

Fig. 5 TEM line diagram



- Nanomaterials: Including nanoparticles, nanotubes and other materials in nano scale.
- Biological materials: The examples of CCS include viruses, bacteria, and cells as the constituent compositions.
- Metals and alloys: Grain size and its distribution, the type and size of defects and phases present in the microstructure of materials.
- Semiconductors: Devices' constructions and their front end.
- Polymers: They include: Morphology Morphology is the physical structure of the soil which relates to the arrangement of the structural units in the soil mass. Crystallinity Crystallinity is the degree of order in the soil mineral structure and is related to the size, shape, and orientation of the mineral units that make up the soil mass.

These images are relatively amorphous, generally in black and white, and darker areas are the parts of the sample where more electrons interact. These images can provide a lot of information on the distribution of the material, its strength and on the presence of defects within the sample.

A number of standard procedures exist for the operation of TEM and the analysis of gathered data depending on the material in use and the specific application. Some common standards include

- This is ASTM E928: Standard Practice for Conducting Transmission Electron Microscopy
- ASTM E1404: Guide for the Execution of High-Resolution Transmission Electron Microscopy on Material

- ASTM E2463: Standard Practice for the Orientation Mapping of Polycrystalline Material, Crystallographic Grain, by Transmission Electron Microscopy

2.4 *Water Contact Angle*

A water contact angle tester simply refers to a great instrument used in measuring wettability on the surface basically by ascertaining for the contact angle between the water droplet and the surface in question. Imagine placing a tiny drop of water on a material: how it spreads or even the formation of droplets makes people interest in the designing of the material when coming into contact with liquids [5, 6] (Fig. 6).

The working principle of water contact angle tester is:

- Droplet Placement: The instrument carefully places a specific volume of water on the test surface The accuracy of the amount of water dispensed is excellent [7, 8].
- Image Capture: A digital video camera records the shape of the water droplet on the peaked surface.
- Contact Angle Calculation: There is a software which examines the droplet image and determines the angle of the water droplet with the surface. This angle is the contact angle and it gives useful information concerning the wettability of the surface concerned [5].

The contact angle reveals numerous insights [5, 6]:

- Hydrophilic vs. Hydrophobic: When the contact angles are low, the surface is said to be hydrophilic or water wettable where water spread out on the surface, whereas when high, then the surface is hydrophobic or water repellent where water just beads up.
- Surface Energy: This is very useful when determining the ability of potential interactions of the material/substrate with liquids, adhesives or coatings.
- Surface Modifications: Measuring the difference of the contact angle between the initial state and after adopting different surface treatments, which may include

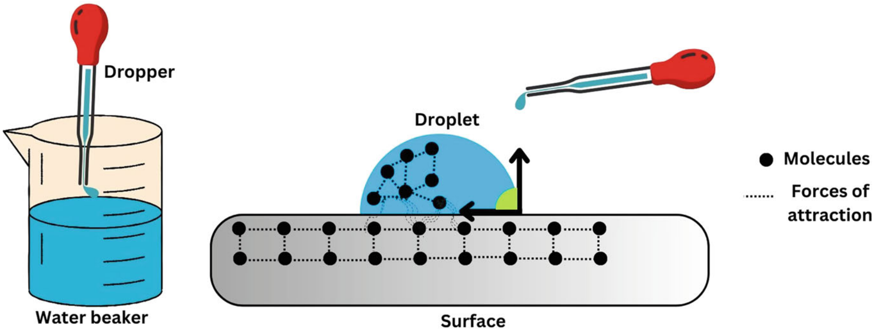


Fig. 6 Water contact angle tester

coating or cleaning methodologies, can determine the efficiency of existing changes.

Water contact angle testers find applications in diverse fields, including [5, 6, 8]:

- Materials Science: Metal, polymer, ceramic, and coating surfaces, and their properties.
- Textiles: Testing of coefficient of water repellency of fabrics and its finishes.
- Electronics: Surface treatment for enhancing drop wise of microfluidics and printed electronics.
- Biomedical devices: Studying of biocompatibility and adhesion for the implants and biosensors.
- Cosmetics: The evaluation of water resistance of makeup and skincare products/Something as simple as testing the water resistance of makeup and skincare products.

3 Mechanical Characterization

The methods covered in this category allow defining the mechanical characteristics of a material, its ability to perform in terms of strength both in static and dynamic usage. Methods included for mechanical characterization are tensile strength as well as Dynamic Mechanical Analyzer (DMA).

3.1 Tensile Strength

Suppose there is a device that exerts tugs on a substance with the intensity rising in steps to the point where the material completely tears. Well, that is approximately what any tensile strength tester does. It determines the extent to which a material can withstand tension before it fractures; it is very useful in ascertaining the material's strength and flexibility. These machines do come in various forms and sizes, but the general form comprises of [9]:

- Gripping mechanism: It maintains the position of the sample firmly and does not allow them to move.
- Controlled stretching unit: Uses the forces that pull at a steadily rising rate.
- Load cell: Measures the amount of force applied on a sample to the nearest unit.
- Extensometer: Observes the length of the sample when the tension is being applied and increased.
- Data acquisition system: Collects the force and displacement data within the test's progress.
- Sample preparation: The material sample is then made to measure and safely fixed onto the grips by means of a screw of clamping.

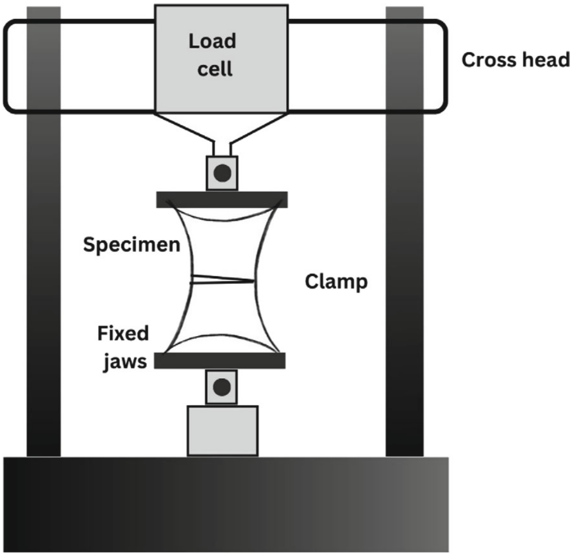


Fig. 7 Tensile strength tester

- Controlled stretching: The machine uses a pulling force that is gradually built up by the use of a motor or hydraulic system.
- Force and displacement measurement: The load cell determines an imparted force, while the extensometer evaluates a sample's elongation.
- Data acquisition: The experimental force and displacement data are stored by the software during the test.
- Analysis: It indicates such characteristics that specify the mechanical properties of the material such as ultimate tensile strength, yield strength, Young's Modulus and the elongation at break [9, 10] (Fig. 7).

Tensile strength testers can handle a wide range of materials, including [9, 10]:

- Metals: Rating hardness and toughness of wires, bars, sheets, and tubes.
- Polymers: Examining the tear strength of plastics, fibers, and insulated films as well as the stiffness of their films.
- Ceramics and glasses: Assessing the impact on tiles, plates, and composites and measurement of fracture strength and brittleness.
- Composites: Determining an overall capability, strength or properties of the material which is obtained by two or more materials bonded together.
- Textiles: Determining the tensile and tear properties of woven and knitted fabrics and yarns.

The graph generated by a tensile strength tester typically shows force on the y-axis versus elongation on the x-axis. It may have several distinct segments:

- Linear elastic region: Part of the curve at which the amount of the material increases as a function of the force exerted on it.

- Yield point: The condition where an object's material has started to undergo a change of shape that won't revert back to its original state no matter the applied force whether tension, compression or shear stress.
- Plastic deformation region: The material stretches still more without much of an increase in force.
- Ultimate tensile strength: The greatest force that the material can offer and still fail.
- Fracture: The place beyond which the material fails, that is the force is cut off suddenly.

There are several standard methods for conducting tensile strength tests, depending on the material type and application. Some common standards include [9, 10]:

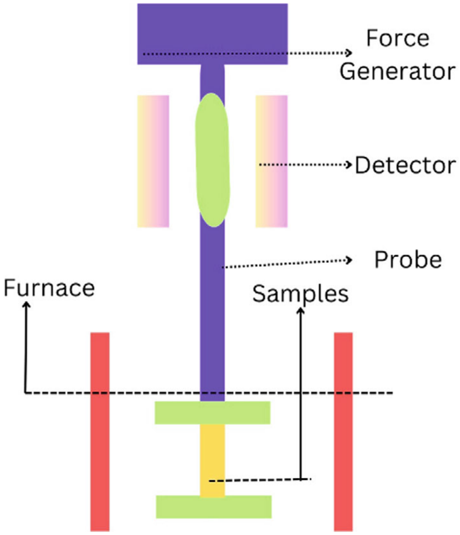
- ASTM D790: curing coefficient and elongation of flat pieces of rubber.
- ISO 527: for the assessment of tensile characteristic of plastics
- ASTM A370 deals with the definitions for mechanical testing of steel products.

3.2 Dynamic Mechanical Analysis (DMA)

Dynamic mechanical analysis is carried out to study the mechanical properties of a material depending on temperature, time duration or the testing frequency. It gives information about viscoelastic materials, which possesses both the wholly elastic and wholly viscous characteristics. The way of functioning of DMA is when an oscillatory force is applied on the material sample and then the response of the sample is recorded. Force is usually in the form of oscillatory and the change of shape (strain) of the material is monitored. The main measurements provide are the storage modulus (E'), loss modulus (E") and the damping factor tan δ. Storage Modulus (E') is the measure for the portion of the material's response which is purely elastic, showing how much energy there is stored in the material. Loss Modulus (E") is the material's phase angle tangent or the ratio of the viscous response of the material where energy is converted to heat. tan δ (Damping Factor) is the loss modulus divided by the storage modulus and qualifies the damping characteristics of the material (Fig. 8).

The material sample has to be prepared according to the required size and other characteristics. The sample is mounted on the DMA instrument. This is because the temperature is maintained to the 'T' so that the testing can be done over the required temperatures. Simple sinusoidal stress or strain is applied on the sample. The above mentioned instrument determines the resulting strain or stress and arrives at the storage modulus, loss modulus, and damping factor. The gathered data is subsequently processed to ascertain the viscoelastic characteristic of the material under test. There are various test methods which are still employed for examining the dynamic mechanical properties of various materials. For instance ASTM D4065 is applied for studying the dynamic mechanics properties of plastics and ASTM

Fig. 8 DMA principle



E1640 is used in the identification of Glass Transition Temperature by DMA ISO 6721 describes the method for determination of dynamic mechanics of plastics [11].

DMA is certainly implemented in multiple industries because it permits to gain a comprehensive understanding of mechanical characteristics of materials. When it comes to polymers and plastics, DMA is irreplaceable if the research asks for glass transition temperatures, viscoelastic properties as well as thermal stability. This information is important in the evaluation of how these material will respond when in use. In composites, DMA assists in determining the impact of the reinforcement materials on the mechanical properties to arrive at the ideal material performance. In the case of rubbers and elastomers specific characteristics such as damping behavior and performance can be gauged with the help of DMA besides being very useful in understanding how these materials are likely to perform in dynamic conditions. In the metals and alloys industry assessment of high-temperature mechanics and phase changes are based on DMA to identify the apt usage of materials under those conditions. DMA is useful in determining adhesives' bonding performance and their ability to hold well and thus reliability on their performance. It is also used in the biomedical sector where DMA is applied to the study of the mechanical characteristics of the biological tissues in order to contribute to the creation of medical devices, and materials that come into contact with tissues. In conclusion, DMA is a very general and multifunctional measuring technique makes a huge impact on understanding and creating the materials all types of industry [11].

4 Thermal Characterization

Thermal characterization methods describe how a material performs at various temperatures. Thermal characterizations techniques are DSC and TGA.

4.1 Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry refers to one of the thermal analysis techniques that is utilized to determine the heat flow which is related to the material changes as a function of time and temperature. It offers the information on the heat characteristics of the material including melting points, glass transition temperatures, crystallization, and specific heat of the substance. DSC records the heat flow of a sample and a reference as each is exposed to a defined temperature profile.

The sample and reference are heated or cooled at the same rate and any changes in heat flow needed to keep both at the same temperature are measured by the DSC instrument. Exothermic Transitions: When the sample liberates heat, let's say, as a result of crystallization. Endothermic Transitions: When the sample gains heat for instance in cases where the sample is melting or evaporating. The sample is weighed and put in a pan for the DSC analysis. A reference pan is also left blank or it is also prepared just for holding reference sample. Two pans are then placed into the DSC instrument. A particular heating, cooling rate is set for the equipment. The DSC measures the difference in heat flow between the sample pan and the reference pan while the temperature is varied. The obtained thermogram is then examined in order to determine the thermal events which took place and to evaluate the corresponding thermal parameters [12].

Several material properties are determined in accordance with various test methods using the Differential Scanning Calorimetry. For instance, ASTM E1356 is a Test Method for the Glass Transition Temperature of a material by DSC; ASTM D3418 covers the information on the determination of Transition Temperatures and Enthalpies of Fusion and Crystallization of Polymers by DSC; ISO 11357 is the standard test method for the determination of DSC of plastics [11].

DSC is used in almost all industries and fields to examine thermal properties of various materials due to the versatility that the technique offers. In the polymers and plastics in industry, the DSC is important for thermal analysis to measure the melting point, the glass transition temperatures as well as the crystallization pattern to enable developments of material with specific property profile for certain application. In the pharmaceutical industries, it applies in assessing purity of drugs, polymorphism, and thermal stability of the products in order to determine the effectiveness of the drugs that are introduced to the market. In food industry DSC is applied to measure fat content, melting profile, the stability of products, which is useful for checking the quality, and create new products. In the case of metals and alloys DSC aids in studying phase transformations and heat treatments which are vital in improving material characteristics.

In the chemical industry, it determines the rate of chemical reactions as well as thermal characteristics of chemical substances which aid in revealing how the chemicals will perform in various conditions. Besides, in research and development, DSC is applied to investigations of new materials and formulations for making new products as well as enhancing the existing products in different fields [11, 12].

4.2 Thermogravimetric Analysis (TGA)

TGA is used to observe the change in mass of sample as a function of time at a definite temperature in a particular environment. It is used in determination of resistance of materials to heat and the constituent elements [13]. TGA operates in a manner that the specific sample is heated under a controlled atmosphere of air or nitrogen or any other substance of choice and the change in weight is recorded. The sample is put in a high precision balance and is submitted to a furnace where the temperature is raised and/or maintained. This is still done all the time by the balancing of the weight of the sample following the changes of the temperature. The term Weight Loss can also mean deterioration, evolution, or desiccation. Weight gain can suggest oxidation or other reactions to be carried out in which the sample takes up gas.

A sample precisely weighed is put into that pan. This sample pan is then introduced in the TGA instrument. The amount of specific elements in air around the sample can also be controlled by replacing the air with an inert gas like nitrogen or reactive gas like oxygen. The sample is exposed to a certain heating rate, or the temperature is kept fixed (isothermal). The mass of the sample is recorded by TGA instrument at a specified temperature interval. The obtained thermogram which is the graphical between mass change and temperature or time is also used to study the thermal stability, composition, and reaction kinetics [14]. Some of the subtests are ASTM E1131 which covers Compositional Analysis by TGA, ASTM D3850 which entails Rapid Thermal Degradation of Electrical Insulating Materials by TGA and the thermo gravimetry of polymers, ISO 11358.

TG analysis is used in processing industries for determining the thermal behaviour and contents of different materials due to accuracy in result acquisition. For the analysis of polymers and plastics, the major use of TGA includes: thermal stability, composition and degradation temperature which must be understood to comprehend the efficiency and safety of the material. In pharmaceutical it is applied to establish thermal stability, moisture profile and compounds of drugs, which makes certain the effectiveness and durability of the drugs. The food industry applies TGA to determine or control the amount of moisture in food products, and the amount of fat and fat content, and other properties of food products, which are of importance with regard to quality and nutrition.

In Metallurgy, TGA plays decisive role in studies of oxidation kinetics and composition of metals and alloy to know thermal stability of material for selection and processing. In the chemical industry, TGA evaluates the reaction rate, the degree of purity, and thermal properties of chemical substances contributing to the creation and evaluation of chemical goods. Environmental analysis is facilitated by TGA by determining the composition of waste materials, soil samples, and other environmental samples for pollution and control of contamination. In composites, TGA is used in determination of thermal stability as well as the composition of composite materials particularly for use in high performance situations. Furthermore, in research and application, through the thermal analysis, TGA has very important contribution in the analysis of the thermal behavior of new materials and formulation for the innovations and advancement in material science [11].

5 Conclusion

When selected rightly; material characterization helps in ensuring that the materials being used within the production lines meet required standards and quality levels which assists in reducing variations within the production line. The analysis of the properties of a material through characterization is equally vital to the creation of new products. It helps in the identification of the right materials to be used for given processes. Mechanical, chemical, and physical analyses of various types of materials open the possibilities for improving the performance of goods in different industry sectors in terms of their durability and efficiency. Material characterization helps in the understanding of the failure behaviors of the material under analysis. It helps to enhance the design and manufacturing strategies inview of lessening on the issues that may reoccur in the future. Proper material characterization helps to make the right choices of materials for desired performance properties, avoiding both underutilization and overspecification. This can result into reduction of costs with regard to material procurement and processing for instance through outsourcing. Various sectors have an array of policies that have been put in place especially when choosing the materials to be used in products that will be in the market. The characterization of material assists in their compliance to such regulations to guarantee that legal problems do not arise, and the safety of the product is provided. It helps the researchers and developers to innovate new materials and new technologies. It is necessary to know properties of new materials in order to advance the technology in different spheres. Evaluation of the lifecycle impact of materials is also supported by the characterization of the material. This is necessary when choosing the appropriate impacts to assign to various products in terms of their effects on the natural environment. This is the type of field dependent behavior; different applications needs different material properties. This enables the optimization and orientation of materials to solve problems that various industries and domains present.

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Sustainability and Materials

Muzzamal Hussain and Ali Raza Shafqat

Abstract This chapter discusses the key aspects of sustainability in materials and extensively explores practices and concepts in sustainable materials engineering. Beginning with introduction and history of sustainability in materials, the chapter then discusses life cycle assessment (LCA) and stages of LCA. The application of LCA explores how the material impacts the environment, this section showcases the impacts of various materials like metals, alloys, polymers, ceramics, composites, nanomaterials, textiles, and biomaterials etc. including resource depletion, carbon footprint, energy consumption, and emissions. This chapter also includes materials recycling principles, challenges, and opportunities, providing examples of recycling metals, polymers, and composites. For further understanding of various examples of recycling and upcycling; current practices of upcycling provide insight into industrial adaptation. This chapter will be a valuable resource for educators, researchers, and industrial professionals to have an overview of sustainability in materials engineering.

Keywords Circularity · Life cycle assessment · Recycling · Upcycling · Resource depletion

1 Introduction to Sustainability

There are more than 140 developing nations working on various methods of meeting their needs of today; however, to mitigate the rising risks of climate change and rising implications for future generations' needs the UN has drafted Sustainable Development Goals. According to the premier definition of the United Nations sustainability means meeting the current needs without compromising the ability of upcoming

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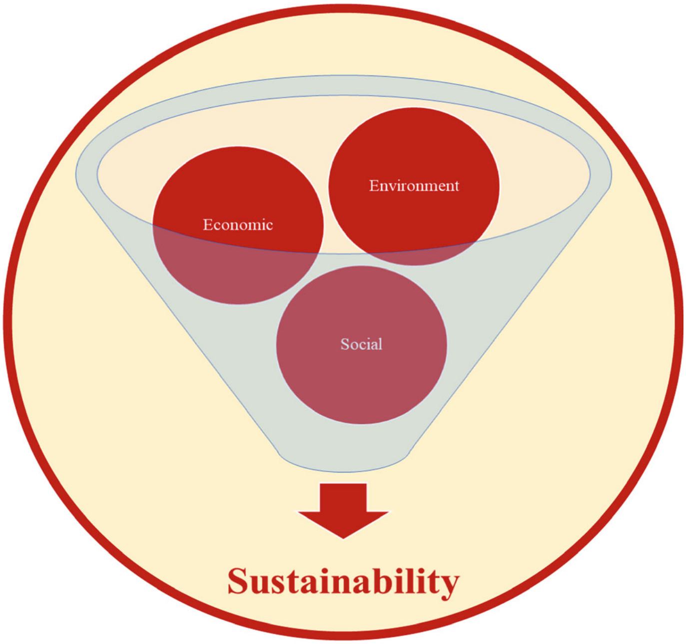

Fig. 1 The three pillars of sustainability

generations to meet their needs [1]. The three pillars of sustainability include people, planet, and profit as shown in Fig. 1.

The UN has drafted a framework of 17 Sustainable Development Goals (SDGs). These SDGs provide a layout and concrete guidance for individuals, companies, and nations around the world to meet their needs while avoiding the possibility of disturbing the Eco-System for generations to come. Overall, all SDGs are directly or indirectly linked to materials extraction, consumption, disposal, and recycling but the most relevant SDG to materials is SDG 12 “Responsible Consumption and Production”, whereas SDG’s 7,8, and 9 are also indirectly related to materials [2], the 17 SDGs of United Nations are drafted in Fig. 2.

SDG 12 is Related to sustainable consumption and production, in which materials are excessively involved. The population is growing at a fast pace while the materials are extracted, processed, and consumed at an even faster pace, if the global population reaches around 10 billion by 2050, three earths will be required to provide the same lifestyle as today. The lifestyle of today is not sustainable, the economic and social uplift during the last century produced a lot of environmental degradation that is dangerous to the planet in several ways. Now it’s time for governments to act and enforce legislation for reducing waste, promoting a circular economy and sustainable production policies [4].

Fig. 2 17 Sustainable development goals of United Nations [3]

1.1 Definition and Scope of Sustainability in Materials

Raw materials are the basic requirement for almost all industrial sectors whether it’s agriculture, forestry, medicine, textiles, mining, metallurgy, or any other sector. The raw materials are harvested, mined, or manufactured with a huge environmental effect. Usually, the raw materials are obtained from localities with poor jurisdictions, conflict, and poor law enforcement for labor business integrity and environmental standards [5].

Sustainability in materials revolves around the production, use, and disposal of materials in such a way that minimizes their negative impacts on the environment and society while maintaining long-term viability. Sustainable materials may have one or more characteristics of sustainability as shown in Fig. 3.

The sustainability of materials takes into account the material’s complete life-cycle from its extraction from the environment, passing through manufacturing, use, and ultimately disposal or recycling [7]. Sustainability in materials can ensure that materials are extracted and consumed in such a circular way that they get recycled, upcycled and repurposed in such a circular fashion that a never-ending supply of raw materials can be achieved forever. The key elements of sustainability in materials are mentioned in Fig. 4.

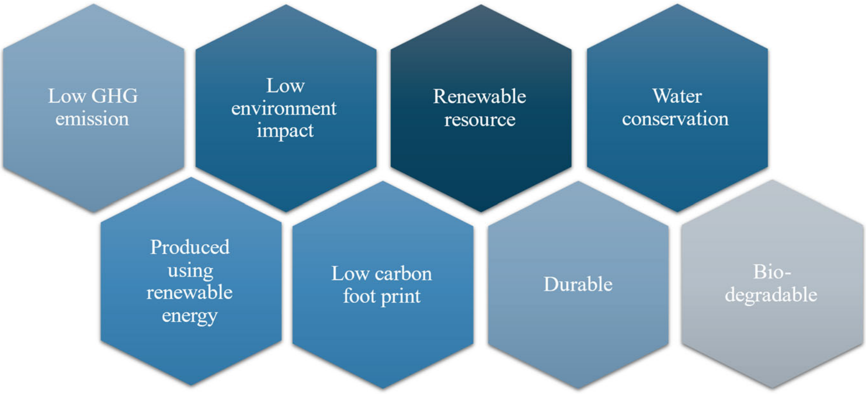

Fig. 3 Characteristics of sustainable materials [6]

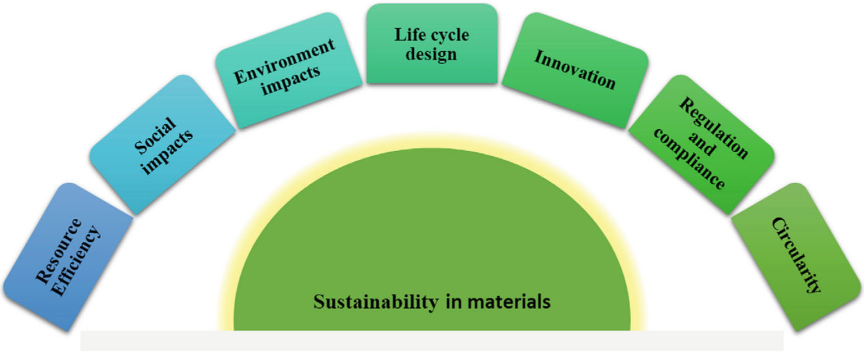

Fig. 4 Key elements of sustainability in materials [8]

1.2 Importance of Sustainable Practices in Engineering Materials

According to a report published in 2017, the global consumption of materials reached 90 billion metric tons and it will be doubled by 2050. Previously materials were extracted from Europe and America, but now raw material extraction has been shifted massively to Asia and Africa. The extraction of materials helps developing countries to meet their economic needs. The production of materials impacts the environment in various ways, these impacts include decreased water quality, habitat loss, landscape degradation, waste generation, and pollution [9]. Material extraction and production processes are energy intensive, for example, only the primary production of metals consumes nearly 8% of the total global energy [10]. Materials sustainability is critical because of its complex effects on society, the economy, and the environment. For reducing environmental degradation, conserving scarce resources, reducing the effects of climate change, and protecting biodiversity; sustainable methods in the production and use of materials are imperative. By encouraging ethical labor practices and social fairness, the sustainable practices also compile ethical standards in addition to environmental considerations. Companies that use sustainable materials not only satisfy the growing demands of environmentally sensitive customers, but also put themselves in a position to comply with regulations, reduce risks, and maintain long-term economic stability. In the end, the quest for materials sustainability represents a worldwide dedication to ethical resource management and a circular economy, tackling the inter-related problems of today.

1.3 Historical Context: Evolution of Sustainable Practices in Materials

Sustainability in materials is traced back to historical ages in which ancient patterns of cyclical materials and resource utilization were observed. However, after the industrial revolution and the abundant extraction of materials at low cost, huge negative impacts were observed on the environment. These impacts on the environment led to a global awakening and sparked the awareness that led to legislation in the 20th century. This awareness led to innovation and research on eco-materials and eco-design. The eco-materials and eco-design in engineering gained popularity in the late 20th century and led to highlighting the importance of ethical manufacturing, and transparency throughout the supply chain bought by globalization. The huge consumer demand of the 20th century initiated corporate sustainability initiatives, technological advancements, and circular economy principles. The devotion to sustainable practices was further upheld by international organizations and governments that led to the creation of materials having minimum negative impacts on the environment while keeping up the functionality and bringing a culture of constant efforts for a more sustainable future.

2 Socio-economic Impacts of Materials

The social-economic aspects of material extraction, production and consumption are huge, the social-economic impacts can be positive or negative. Along with the environmental impacts of materials, the socio-economic impacts of materials are also very important. The associated socioeconomic impacts of materials are listed in Fig. 5.

Materials have broad socio-economic impacts, for example, Materials influence market pricing, trade balances, and production costs of goods. The selection of materials can have an impact on job openings in the manufacturing sector as well as in associated industries indirectly. Patterns of land use, material resource exploitation,

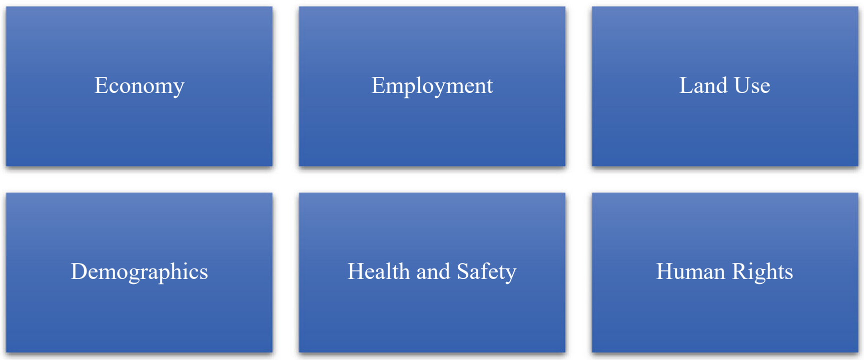

Fig. 5 The socio-economic impacts of materials acquisition [11]

and agricultural techniques, can be influenced by the choice of materials. Material's effects on housing availability, infrastructural development, and migration patterns can influence population dynamics. The choice of specific materials may have an impact on worker safety and health risks, exposure to pollutants, and product longevity.

Sometimes materials extraction can be linked to worker exploitation, indigenous land rights. Although material extraction can enhance the income and security situation in the locality from where it is being extracted, these impacts can be both positive and negative. On one hand resource extraction provides stimulus income and business opportunities to the local community but on the other hand, it also offers an unfair distribution of advantages due to bad governance. Indifference can further lead to conflicts, clashes, forced labor, and even escalated wars.

- Resource extraction impacts society in various ways, these impacts can also be positive or negative. On one hand resource extraction provides facilities for people living in resource-rich localities with a local infrastructure of power, water, and energy. However, due to the land and territory it occupies for harvesting or extraction of raw material, it impacts the local population by limiting their access to land therefore the leads to poor livelihood and food insecurities [12].
- Material extraction can also disturb the natural demography of the area because people migrate towards the area that offers business and job opportunities which have positive impacts, but due to demographic change, the imbalances can merge into gender disparity, financial disparity, and social cohesion, this can impact the population psychologically and can induce crimes and consumption of alcohol, drugs or prostitution.
- Most of the time the materials are extracted in dangerous working conditions and accidents are prone to occur, in most developing countries, health and safety legislations are weakly implemented due to which workers are exposed to dangerous working conditions and hazardous chemicals etc. that often have carcinogenic effects, most of the times when the industries exist in highly populated areas,

the nearby localities face problems like water contamination, land shortage and air polution.
- Material extraction and harvesting often contribute to human rights violations in various manners including slavery, forced labor, safety of vulnerable groups, respecting the local population, and preserving local aesthetics and culture.

3 Environmental Impact of Materials

3.1 Comparative Analysis

Almost all materials impact the environment in multiple ways, some of them impact more than others material; the impact of materials on the environment depends on multiple factors including extraction of raw material from natural resources, impact during manufacturing, impact during product lifetime, and end of life impact. Some materials may be Less toxic but can have more environmental impact due to lack of recycling infrastructure or non-environment friendly end-of-life of their respective products. Similarly, metals have long life spans and have the longevity of products that can have a significantly lower environmental impact than their alternative counterparts like plastics, but the environmental impacts of metal mining and refining cannot be neglected. A comparative analysis of various materials and their environmental impacts is provided in Table 1.

3.1.1 Carbon Footprint and Energy Consumption

The total amount of greenhouse gases (carbon dioxide and methane etc.) generated by a process is known as its carbon footprint. The production of material is one of the most significant sources of carbon footprints. Nearly half of greenhouse gases are produced by industry. The International Energy Agency (IEA) calculates the carbon footprint, energy use and greenhouse gas emissions from the production process of various materials including metals, polymers, textiles and, composites etc. [13] this calculated index can be helpful in determining the impact of the respective materials on environment.

3.2 Strategies for Minimizing Environmental Impact

3.2.1 Sustainable Sourcing of Raw Materials

Sustainable sourcing of raw materials is one of the most important and responsible business tasks that aim to minimize the environmental impact of a product and achieve sustainability [14]. Sustainable sourcing of raw materials can be implemented

Table 1 Comparative analysis of materials and their environmental impacts

Metals and alloys	
Positive impacts	Negative impacts
Durable and recyclable	Requires huge energy for extraction and processing
Strong mechanical properties	Produce toxic emissions during production
Ceramics	
Positive impacts	**Negative impacts**
High wear and tear resistance	Require high temperatures and huge energy during manufacturing
Long life and require less maintenance	Have limited or no recyclability
Polymers	
Positive impacts	**Negative impacts**
High strength, easy to shape, and versatile	Extracted from fossil fuels, have huge carbon emissions
If thermoplastic, they can be recycled	Take a long time for degradation
Composites	
Positive impacts	**Negative impacts**
Have high strength and can combine properties of different materials	Composites are multi-materials that are difficult to recycle
Can be designed for the specific purpose	Composite manufacturing processes are mostly energy-intensive
Textiles	
Positive impacts	**Negative impacts**
Composed of both natural and synthetic fibers, Natural fibers are eco-friendly and biodegradable while synthetic fibers provide extraordinary performance qualities and longevity	Highly resource-intensive production
Various eco-friendly and recyclable materials exist in textiles	Dyeing and finishing of textiles is a highly chemical-intensive process
Nanomaterials	
Positive impacts	**Negative impacts**
Have unique properties and possibilities	Limited knowledge of their environmental and health impacts is available
Improve material functionality and efficiency	Nanomaterials have energy-intensive manufacturing
Biomaterials	
Positive impacts	**Negative impacts**
Derived mostly from renewable origins	Low mechanical performance
Biocompatible and eco-friendly	May require separate end-of-life treatment

by the introduction of supply chain transparency, transparency can be implemented by tracking raw materials from their origins to production, production to end-user, end-user to disposal, and disposal to manufacturing again [15]. This process is also known as traceability, and it can help to ensure sustainability at each stage of production. Certifications like Forestry Workship Council (FSC) are fair trade certifications that can also be very helpful in maintaining sustainable sourcing. By introducing a circular economy, a product's life can be extended and after it's end of life is reached it can be upcycled, repurposed or recycled, hence circular economy, up to great extent can help in the reduction of virgin raw material demands. Sustainable sourcing can be achieved by closely working with suppliers to promote sustainable initiatives and encourage them to adopt eco-friendly policies, the massive warranties required to invest in companies and suppliers that support eco-friendly processes. Regular audits can be very effective in the implementation of sustainable raw material sourcing. By implementing sustainable sourcing, businesses can directly reduce the environmental footprint of their production processes and products. Companies may lessen their impact on the environment by favoring recycled or renewable resources, obtaining goods sustainably, and maintaining transparent supply chains. They can also concentrate on maximizing production procedures, using renewable energy sources, and energy efficiency. Designing environmentally friendly products is aided by lifecycle evaluations, and using circular economy and waste reduction strategies can maximize resource efficiency and can reduce waste throughout the production cycle.

4 Life Cycle Assessment (LCA) in Sustainable Materials Design

4.1 Overview of Life Cycle Assessment

The process of evaluating the impacts of a product on the environment over the complete period of its life by increasing it's utilization time and reducing liabilities is known as life cycle assessment (LCA) [16]. Lifecycle assessment is a useful tool to study the impacts of a product on the environment. The common elements of LCA's involve quantification of the burden on the environment by product; that includes the consumption of materials and the generation of emissions during the life cycle of product evaluation that impact any of these loads on the environment and the assessments of alternative opportunities for reduction of environmental impacts of the product [17].

LCA helps us quantify the environmental impacts of a product and lets us make better decisions for the preservation of our environment. LCA can be very helpful for designing a product, making decisions, purchasing materials, manufacturing, marketing, quantifying the environmental performance, benchmarking of product and industry, and policymaking. LCA is commonly conducted by a group of people in which different roles are played by different professionals like environmental experts, engineers, manufacturers, and purchasing teams along with many other stakeholders. Life cycle assessment is a complicated task and strict compliance exists in its practice. For example, international standards like ISO 14040 exist to define and restrain of qualification of the LCA process [18].

Keeping in view sustainability and materials life cycle assessment, keeping in view the extraction of material, the manufacturing process distribution and transportation, the lifecycle takes into account the use of a product that requires maintenance and the end of life of a material, all these are studied in context to all kinds of pollutions including air water, and land pollution, the global warming potential of each stage, the toxicity of material on environment and resource depletion etc.

4.2 Stages of LCA

There are four basic steps in conducting a life cycle assessment [19]:

1. The identification of goals and defining the scope of the study, take into account how big or how small part of a product life cycle will be assessed while keeping in view the purpose of life cycle assessment, this step establishes a system of comparison and the specific time of product life cycle to be studied.
2. The second step of the life cycle assessment involves the analysis of inventory. This step provides the identification of the materials involved, the energy flow into the product, and the product environment interaction. This step also considers the consumption of raw materials and environmental emissions.
3. In the third step, the quantification of inventory analysis (completed in the second stage) is done and all the impact categories are then normalized and weighed. In this step, the impacts and reserves of all the impact categories are recorded.
4. The fourth stage is the final stage of the life cycle assessment which involves intense review, determination of the data, reducing noise, and presentation of results.

The life cycle assessment of material can be conducted as a whole or in various stages, the complete life cycle can be broken down into short spans as shown in Fig. 6, these stages are often called stages of life cycle assessment.

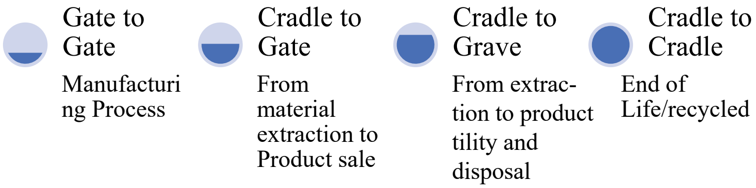

Fig. 6 Stages of life cycle assessment [20]

4.3 Application of LCA in Materials Science

Life cycle assessment is an organized tool for calculating the environmental impact of a process or material throughout its life cycle. From raw material extraction, manufacturing, utility, and, being trashed. Lifecycle assessment can be a very useful tool for analyzing material's impact on the environment. The applications of lifecycle assessment can be very helpful for the selection of material and product design, it can enable industrial professionals and scientists to make better decisions about the selection of material for a particular product based on energy consumption, greenhouse gas emissions, and resource utilization. LCA can also be very helpful for the optimization of industrial processes, the processes that have the highest impact on the environment can be optimized to reduce the overall impact of that product on the environment. The identification of the end of life of a product and its overall impact on the environment can help manufacturers decide on waste management strategies and recycling. Implementation of lifecycle assessment can help in maximizing the utility of a material (longevity), so it reaches its end of life slowly. LCA can also contribute to the development of circular economy strategies by using strategies like remanufacturing, reusing and, recycling and can help in the implementation of closed-loop material cycles. It is very difficult to understand the impact of materials on the environment without an organized procedure or tool like LCA. Applying LCA is also very helpful in policymaking and legislation as it provides an extensive perspective on environmental impacts and can be very helpful in the development and implementation of environment-friendly policies. By implementing LCA and analyzing the results, informed decisions can be taken by suppliers and procurement departments to lower the impact of their produced materials and products.

4.4 Assessing the Environmental Impact of Materials

Assessment of the environmental impact of materials is a very sophisticated and organized process based on the principles of life cycle assessment, it starts from the assessment of materials extraction from the environment, processing, use, and disposal. To determine the environmental impact of materials a generic eight-step strategy can be followed; the following steps are given below in Fig. 7 and explained afterward.

- In the first step, the scope and objectives of the lifecycle assessment are defined. This step considers the type and nature of the material, product or process to be studied for assessment of materials. In this step, we have to identify the material to be studied out of all the materials being used in the product.
- In the second step, we identify the stages of the life cycle including extraction of material, manufacturing, supply chain, product utility, and end of life, for this purpose we collect the data based on resource inputs, emissions, energy consumption, and waste generation during each stage of its life. Usually, primary

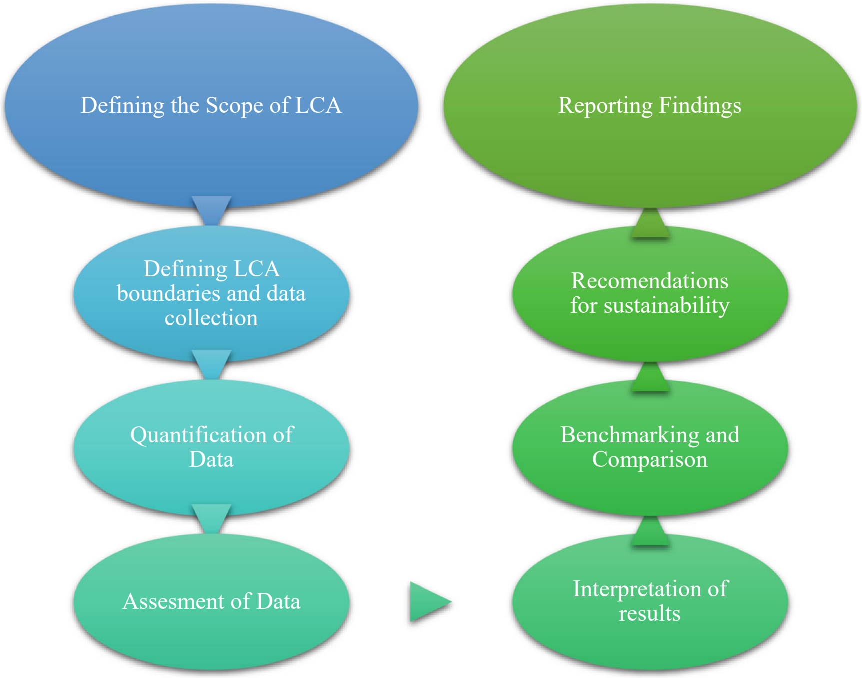

Fig. 7 Steps of life cycle assessment of materials [21]

data is used; centric to only one material used in the product. In this step clear boundaries are to be identified, which help us determine which part of the life cycle is to be studied and which are not required, the process of LCA should be kept as simple as possible avoiding all kinds of complexities.

- The third step identifies the categories of impact for which assessment is required, for example, resource depletion, GHG emissions and pollution at certain stage can be categories of interest. In this step, the impacts are quantified by converting raw LCA data into impact scores. The data is then normalized to make it comparable to all variables being studied. Normalized data is then weighed based on the priorities and importance of each variable.
- After quantifying, the data interpretation is carried out by quantifying the key contributors to environmental impact related to materials throughout the lifecycle, these steps help in identifying the room for improvement. In this step, noise is canceled out by adopting the sensitivity of variables and disruptions made to raw data.
- The 5th step comparative analysis is carried out by using benchmarks and alternative products or materials offering more sustainability. This step provides a bigger picture and helps us identify different scenarios, for example, changes in the manufacturing processes keeping in view their relative environment impacts.

- After the initial assessment is complete, specific areas and rooms for improvement are identified to reduce the overall impact of the material on the environment. In this step exploration and implementation of sustainable practices, energy-efficient processes, and recycling strategies of material are identified.
- In the final step documentation of lifecycle assessment is carried out by clearly mentioning the data, sources, methodology, and results of assessment. The most important essence of life cycle assessment is reproducibility and transparency; making this step the most crucial step of LCA. The results are finally presented and reported while providing assessment insights and recommendations for all stakeholders; including governments, industries, users, and scientists.

5 Recycling of Materials

5.1 Principles of Material Recycling

The process of collecting and processing materials, that could otherwise be trashed, and turning them into useful products is known as recycling. Recycling can be very helpful for the conserving environment and economy, the products that cannot be used again should be recycled. Recycling can help in the conservation of natural resources like water, minerals, materials, and other natural resources like land, fosil fuel reserves and, forests etc. [22]. By recycling materials, climate change can be avoided, energy can be saved, and pollution can be reduced.

Recycling has numerous benefits not only for the environment but also economy it can help create more jobs, establish new businesses, and introduce environmental justice, by recycling materials the negative impacts of material pollution on human health, property, aesthetics of localities and recreational facilities, and productivity of land can be preserved [23].

5.1.1 Challenges and Opportunities

Recycling is one of the most promising actions to preserve the natural environment by saving the air, water, and soil from pollution. Recycling also conserves nature by circulating and rotating the materials, thereby preserving the natural resources from becoming extinct or depleted [24]. However, recycling has several challenges and opportunities associated with different materials processes, etc. [25].

- The biggest challenge to the recyclability of materials is the mix-up of different recyclable materials with each other or with non-recyclable materials. Due to the lack of education of users or multi materiality of products, recycling mixed-up materials is nearly impossible or not possible without complex sorting systems or facilities.

- During the recycling of materials, health, and safety are very important for workers, working in the recycling industry; as recycling personnel may have to face chemical exposure, extreme heat, dust explosions, and exposure to moving parts and powerful equipment.
- One of the leading causes of the non-recyclability of materials is inadequate collection points and lack of services. Even after a lot of awareness many advanced cities also lack adequate services, A common example includes separate bins for recyclable and nonrecyclable materials. Due to the lack of these services, materials that can easily be recycled are difficult to collect and transport to recycling facilities [26].
- Another important challenge that hinders the way of recycling materials is the low market demand for recycled materials. Since the industrial age, extraction of virgin resources has become very cheap and easy, the virgin materials are available at such cheap prices that recyclable materials may seem costly and are even unmatchable to virgin materials when it comes to the cost–benefit ratio.

Various materials can be recycled depending on the collection facilities and recycling infrastructures. For example, the commonly recycled materials in the USA are shown in Fig. 8 [27].

The products can also be modified to get a new life and turned into a new product; this adds value to the waste of old products by using this waste to make a new product that has more value than the original value of all the materials used. It can be carried out in various fields by utilizing different materials separately or in combination to make new products, this mode of reusing materials can be implemented in various industries including the fashion industry furniture industry, materials industry, and many others [28].

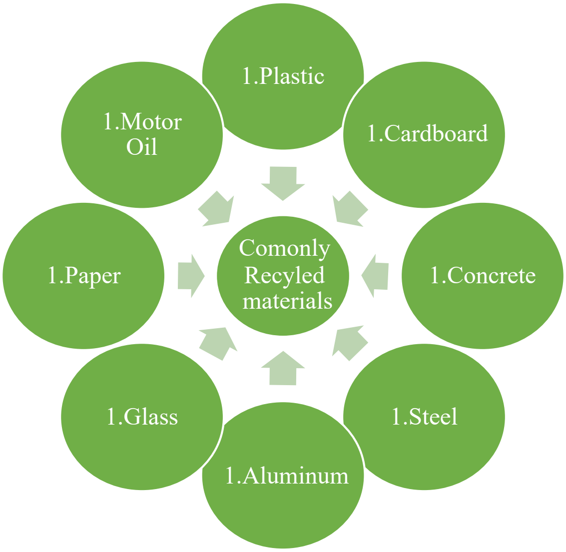

Fig. 8 Commonly recycled materials in the USA [27]

Table 2 A few examples of reused materials along with their precursor products and manufacturers

Waste product	Upcycled product	Upcycled by	References
Plastic bottles	Shoes	Rothy's	[29]
Spent grain	Container boxes	Alterpacks	[30]
Discarded hotel linens	Shopping bags	Reusedremade	[31]
Waste sails and PARACHUTES	Garments	Rewind	[32]
Post consumer textiles	Textiles	Loopworks	[33]
Fishing nets	Garments	Bureo	[34]
Electronics and plastic waste	Speakers	Gomi	[35]
Discarded shellfish shells	Helmets	Koushi	[36]
Discarded wind turbine blades	Concrete	Regen fiber	[37]
Waste plastics	Furniture	The new raw	[38]

Reusing materials can be very helpful in conserving the natural environment, it reduces the burden on natural resources and provides an alternative source of materials from old products that have already fulfilled their purpose and are destined for incineration or landfill. Some examples of commercial reuse of materials along with their final products are mentioned in Table 2.

Reuse becomes eminent especially when products are difficult to recycle or when recycling infrastructure and supply chains do not exist. It not only helps in the conservation of resources but also reduces pollution and generates economic benefits by turning products into something of more value than the original products. By reusing the materials multiple times, new businesses can be formed that do not only help conserve the environment but also produce socio-economic benefits.

6 Role Legislation in Materials Sustainability

The establishment of frameworks, standards, and regulations by legislation is essential in regulating material sustainability as it encourages environmentally conscious activities in many businesses [39]. In order to reach emissions targets, businesses must adopt sustainable materials and practices, as exemplified by the Paris Agreement, which aims to limit global warming and reduce greenhouse gas emissions. Similarly various countries have their own dedicated legislations to ensure environmental sustainability, just to name a few; the programs like the European Green Deal establish challenging objectives for a circular economy by promoting resource efficiency, waste reduction, and the use of sustainable materials, federal buy clean initiative of United States promotes use of sustainable materials in construction and procurement [40, 41], the South African environmental legislation guides consumption of materials while ensuring minimum impact on soil and water, management of waste and conservation of natural ecosystem [42], China's climate governance for carbon neutrality aims to achieve carbon neutrality by 2060 and consumer packaging legislation impose restrictions on using excessive packaging material to reduce carbon footprints [43, 44]. The legislation shapes the course towards a more sustainable future by encouraging innovation, promoting investments in sustainable technologies, and ensuring accountability for environmental repercussions.

7 Conclusion

Implementation of sustainability in materials can be very promising on one hand but on the other hand it is also very challenging when it comes to practicability. The advancements in recycling technologies present a huge potential for positive impact on the environment. Implementation of sustainability in materials is perfectly aligned with global environment goals and SDGs as outlined by the United Nations. The responsibility of implementation of sustainability in materials lies on the shoulders of industrial professionals, researchers, educators and policymakers to contribute positively and tirelessly to the sustainable future of materials. The journey towards sustainable materials in engineering is very interesting and diverse topic and this chapter can serve as a foundation for further exploration and implementation of sustainable practices in the materials industry. The challenges and opportunities for achieving sustainability in materials can be better understood by collaborative efforts between academia, industry governments, NGO’s and global organizations. Keeping in view the resource depletion, green house gas emissions, pollution and the future of upcoming generations; sustainability should be the guiding principle in the exploration of materials for today and tomorrow.

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