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Review article

Advances in lightweight composite structures and manufacturing technologies: A comprehensive review

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ABSTRACT

The field of lightweight composite structures has witnessed significant advancements in recent years, revolutionizing numerous industries through their exceptional combination of strength, weight reduction and versatility. This review paper provides a comprehensive and in-depth analysis of these ground breaking materials. It elucidates fundamental concepts of lightweight composite structures, exploring their composition, classification, physical and mechanical properties as well as recent strides in their engineering applications. Crucially, this review highlights the recent progress and developments of lightweight composite materials. From aerospace to automotive, from construction to sporting goods, these advanced materials are transforming various industries by combining strength with reduced weight. Emphasizing the role of lightweight composites in energy-efficient systems, the paper underscores their significance in resource optimization and sustainable engineering practices. A detailed examination of various types of composites, such as polymer matrix composites, ceramic matrix composites and metal matrix composites, will be presented, highlighting their specific advantages and applications. Moving forward, the review delves into the diverse fabrication methods employed to create these advanced materials. This comprehensive paper serves as a valuable resource for researchers, engineers, and industry professionals seeking to capitalize on the benefits of lightweight composite materials. By presenting a holistic view of composites' classification, properties, and recent advancements, this study fosters innovation and propels the integration of lightweight composite materials into diverse engineering applications, ultimately driving progress towards a more efficient, sustainable, and technologically advanced future.

1. Introduction

Many of us are unaware of how deeply materials are integrated into our society as we encounter various materials in our daily lives. Economic factors, logistics and societal expectations have shaped the evolution of materials over time. Our ability to create, understand and manipulate materials has greatly contributed to technological advancements, and the level of material development has

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played a pivotal role in the success of civilizations. In recent decades, the development of contemporary systems and components has increasingly focused on performance, energy efficiency, and responsible use of natural resources. Industries working with structural components have been actively striving to minimize energy consumption, leading to a shift from heavy conventional materials to lighter alternatives like lightweight metals, polymers and composites [1–3]. Lightweight materials are driven by the motivation to save weight, enhance portability and potentially reduce costs. Composite materials, in particular, have rapidly gained prominence in material science and engineering due to their appealing combination of toughness, stiffness, lightweight properties and corrosion resistance [4–6]. The usage of composites has shown significant growth, with an annual increase of approximately 5 % since 2013, as depicted in Fig. 1. This upward trend highlights the rising acceptance of composites in various industries, making them increasingly important for technological progress and meeting sustainability challenges. It is therefore essential to thoroughly understand composite materials and their potential in lightweight applications. This review provides essential insights, covering classifications, manufacturing technologies and various applications.

Composite materials, true to their name, consist of a combination of different materials, resulting in a material with properties distinct from its individual components [8,9]. Composites typically comprise a matrix and a reinforcement, and this combination enhances their overall performance. A classic example of composites is wood, where cellulose fibers provide strength and stiffness, while the lignin matrix transfers loads and maintains fiber positioning [4,10]. The history of composites dates back hundreds of years, with applications ranging from mud and straw buildings to animal skin clothing. Natural examples of composites can be found in human and animal bones, as well as wood structures. The unique characteristics of composites extend beyond the properties of their constituent materials; their geometries, sizes, alignments, distribution and concentration play a crucial role in defining their behavior. The interface region between discrete phases significantly impacts their interaction defining the composite material's behavior. Composite materials exhibit properties that differ from those of their individual components. The "rule of mixtures" helps predict attributes by establishing relationships between component qualities [11,12]. Moreover, the distribution of concentrations can vary even when component ratios are the same, indicating that composite properties should not solely rely on the average concentration.

The matrix phase of composites is continuous and soft, contributing attributes like ductility, thermal conductivity and formability [13]. In contrast, the reinforcement phase is typically stronger and stiffer, bearing the applied load within the composite. To fully comprehend their application and utility, a thorough investigation of their classification and distinguishing properties is necessary.

2. Classifications

Fig. 2 illustrates three major criteria for classifying composites. The first criterion is based on the matrix constituent, leading to three main classes: polymer matrix composites (PMC), ceramic matrix composites (CMC) and metal matrix composites (MMC). The second criterion involves the reinforcement phases or forms, resulting in fiber-reinforced composites, particulate composites and laminar composites. Fiber-reinforced composites can be further divided into composites with either discontinuous or continuous fibers. Additionally, fibers themselves can be categorized as long or short, depending on their dimensions and geometries. The third classification method is based on the scale and nature of the composite, giving rise to composites such as nanocomposites and biocomposites. These examples are only a few among various possibilities within this classification.

2.1. Based on matrix phase

The matrix material plays a crucial role as it binds the fiber reinforcement, distributes loads among the fibers, controls surface quality and defines the overall form of the composite. To be effective, the matrix material must be capable of permeating between the fibers and establishing a strong interfacial connection. It is vital that the matrix does not cause any harm to the fibers and that there is no possibility of chemical interaction between the matrix and the reinforcement. Depending on the specific application, the composite matrix can be composed of a polymer, a ceramic or a metal. Each type of matrix offers unique advantages and properties, allowing for a wide range of possibilities in composite material design and application.

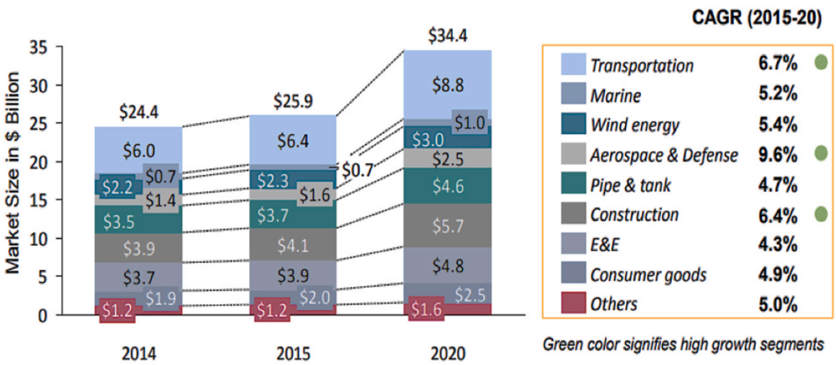

Fig. 1. Annual global composites materials market statistics and forecast. Reproduced from Ref. [7] (Creative Commons CC BY-SA 4.0 license).

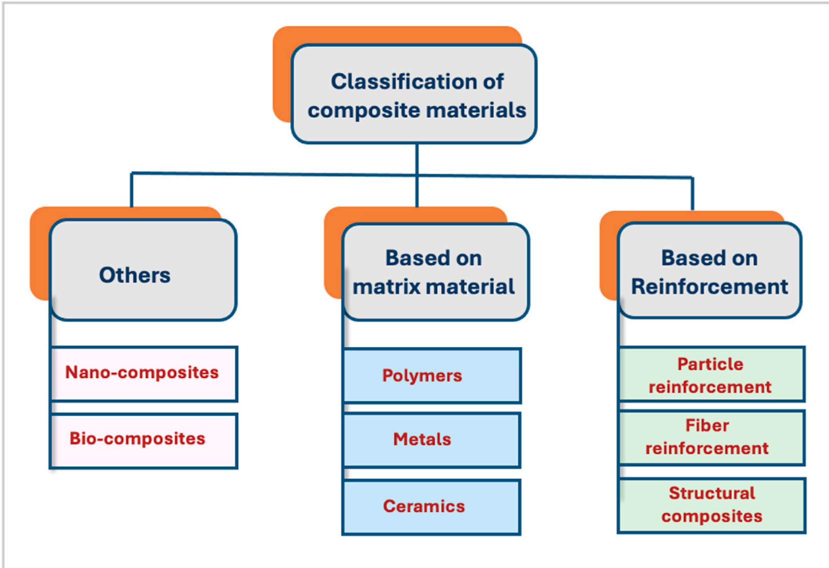

Fig. 2. Composite classification.

2.1.1. Polymer matrix composites (PMCs)

Polymers offer attractive qualities, such as ease of manufacturing, lightweight nature and physical properties [14]. Polymer composite materials, known as fiber-reinforced plastics (FRP), consist of a polymer matrix (resin) and reinforcing agents, typically fibers [15–18]. These composites can use either thermoset or thermoplastic matrices, each with distinct characteristics. Thermosetting matrices have a stable three-dimensional molecular structure and do not melt when heated; instead, they undergo irreversible chemical events that create cross-links between polymer molecules. Epoxies are commonly used thermosetting matrix materials in the aerospace industry for high-performance composites. On the other hand, thermoplastic matrices have linear chains that can be altered and reformed when in a melted state. They are heated, molded, extruded, or thermoformed during manufacturing and then cooled to retain their shape. Depending on the application, thermoplastics can be adjusted to exhibit stiffness similar to concrete or flexibility akin to rubber. To enhance the performance and reduce costs, additional fillers, additives, and modifiers can be introduced to polymer matrix composites (PMCs) to modify their characteristics. PMCs are generally considered low-cost composites due to their straightforward manufacturing processes and ease of handling [19,20]. Overall, the versatility and cost-effectiveness of polymer composites make them highly valuable in various industries.

2.1.2. Ceramic matrix composites (CMCs)

CMCs are materials composed of ceramic fibers embedded or enclosed within a ceramic matrix. The most common types of fibers used in ceramic matrices are carbon, silicon nitride (SiN), aluminum oxide (Al2O3) and silicon carbide (SiC) fibers [21]. The primary aim of developing CMCs is to overcome the weaknesses of monolithic and traditional ceramics, which are prone to cracking under mechanical or thermo-mechanical stresses due to minor imperfections or scratches. In contrast, CMCs exhibit improved fracture resistance, chemical stability and enhanced resistance to fracturing under heavy loads. As a result, CMCs are ideal for applications requiring high mechanical and thermal performance. CMCs achieve their increased mechanical characteristics through a unique mechanism wherein the matrix is the first to experience mechanical failure, preventing the brittle fibers from failing prematurely [22,23]. This phenomenon is the opposite of the strengthening process observed in polymer and metal matrix composites, earning CMCs the name “inverse composites."

2.1.3. Metal matrix composites (MMCs)

Metals are highly versatile engineering materials, offering a wide range of easily adjustable properties through the right alloy composition and thermomechanical processing methods [24–26]. Their widespread use in engineering is due to their strength, toughness and cost-effective manufacturing processes. Therefore, customized composites fabricated by adding reinforcements to metal may produce MMCs with excellent strength to weight ratio, enhanced specific stiffness, greater wear resistance and improved fatigue [27–29]. MMCs typically consist of metallic matrices, mainly aluminum and titanium, reinforced with ceramics (oxides and carbides) or other metals (tungsten and molybdenum) to ensure uniform distribution [30]. Composite materials offer the advantage of surpassing the property limitations of primary materials, such as specific modulus in metals (E/ρ), by incorporating elements from higher rows of Mendeleev’s periodic table. Fig. 3 illustrates different fabrication methods for MMC composites/hybrid composites, considering factors such as the physical, chemical and thermal characteristics of reinforcement and matrix materials, as well as the size and distribution of reinforcement particles [31–34].

2.2. Based on reinforcements

A variety of composites are composed of only two phases, the matrix, which is a bulk, and the homogeneous phase enclosing another phase called dispersion or reinforcement. The features of the constituents' phases, their relative quantities, and the geometries of the dispersed phase all affect composite materials. Herein, "reinforcement phase geometry" describes the shape, distribution, size and orientation of the individual particles or fibers. Based on their reinforcement, composites are classified into three categories: fiber-reinforced, particle-reinforced, and structural composites, each of which may have further subgroups.

2.2.1. Fibrous composites

In a fiber reinforced composite, fibers are the primary source of strength, whereas the matrix holds all the fibers together and distributes loading stresses between the reinforcement materials. The fibers carry the loads in their longitudinal directions. Occasionally, fillers and additives are introduced to facilitate production, provide unique features, or reduce costs in the final product. Common examples of fiber reinforcing materials include glass fibers, carbon fibers, beryllium carbide, beryllium, beryllium oxide, aluminium oxide and bio fibers [35–37]. In fiber reinforced composite there are two orientation extremes: a fully random alignment and a parallel alignment in the same direction. Fibrous composites can be further segmented into short fiber composites and long fiber composites. Composites with long fiber reinforcement are made up of a matrix and a dispersed phase in the form of continuous fibers with a significant length relative to the matrix dimensions. As they incorporate high levels of stiffness, toughness, and strength in a single material, these fibers lead to the enhancement of structural performance in polymers. On the other hand, short-fiber reinforced composites consist of short, variable-length and inadequately aligned fibers dispersed throughout a continuous-phase matrix [38]. Homogeneous fiber distribution is essential for achieving superior composite characteristics for all types of fiber-reinforced materials. Fig. 4(a–f) provides schematics of different types of fibrous composites, illustrating their structures and reinforcing fiber's orientations.

2.2.2. Particulate composites

A particulate composite consists of particles dispersed within a matrix, allowing for various particle sizes, shapes and configurations [39]. Concrete serves as a prime example of a particulate composite, with coarse rock or gravel aggregate embedded in the cement matrix. The aggregate provides rigidity and strength, while the cement acts as the binder [40]. Another example is car tires, where carbon black particles reinforce the poly-isobutylene elastomeric polymer matrix. The mechanical behavior of the composite depends on the type, shape, size and spatial configuration of the reinforcing phase. The dispersed phase may be produced during manufacturing by an internal reaction or may simply be combined with the matrix powder.

In large-particle composites, continuum mechanics describe particle-matrix interactions, where the particulate phase is stiffer and harder than the matrix and load transfer occurs from the matrix to the particles. The mobility of the matrix phase is frequently constrained near to each of these reinforcing particles. Dispersion-strengthened composites, on the other hand, strengthen through atomic or molecular interactions between particles and the matrix. This mechanism inhibits plastic deformation, resulting in increased hardness and strength, akin to precipitation hardening. Applications for particle-reinforced composites include road surfaces and other surfaces that need high levels of wear resistance. Particle reinforced composites have the benefit of being cost-effective, easily moldable and simple to manufacture [41,42].

2.2.3. Structural composites

A structural composite combines both homogeneous and composite materials [43], with their qualities influenced by the constituent materials' characteristics and the geometrical design of the structural elements. Two categories of structural composites are laminar composites and sandwich-structured composites, as depicted in Fig. 5(a and b).

Laminar composites consist of aligned and continuous fiber-reinforced polymers, with two-dimensional panels or sheets aligned for maximum high-strength [44]. These layers are stacked and bonded together, each oriented differently after the first layer to optimize strength. Plywood, for instance, consists of wood sheets with grain alignment at right angles to each other. Fabric materials like paper,

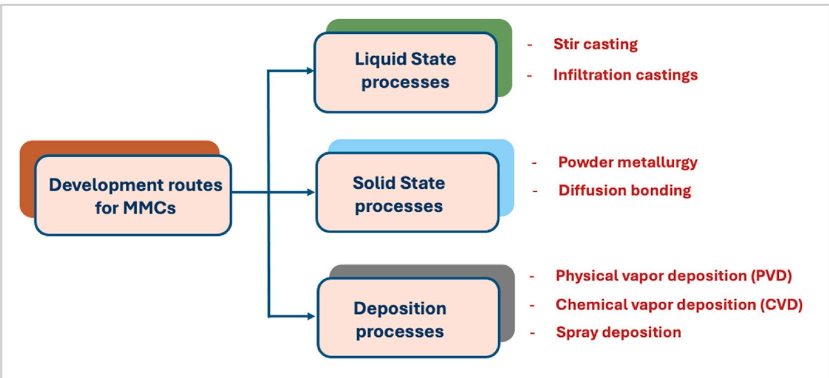

Fig. 3. Development techniques for metal matrix composites/hybrids.

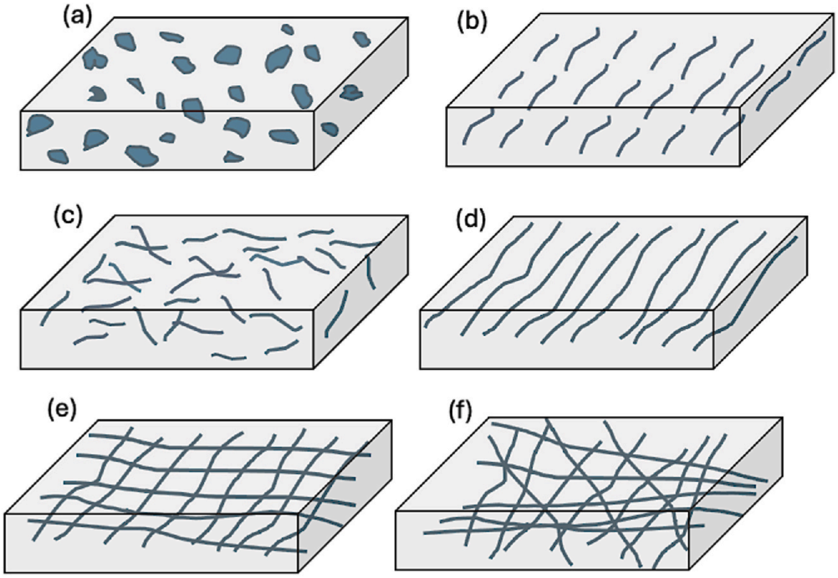

Fig. 4. Schematic of various composite materials classification and orientations: (a) particulate reinforced composite, (b) aligned discontinuous fiber composite, (c) randomly oriented discontinuous fiber composite, (d) aligned continuous fiber composite, (e) continuous fiber composites aligned in directions $0^{\circ}-90^{\circ}$ orientation angle) and (f) multidirectional continuous fiber composite.

cotton, and woven glass fibers enclosed in a polymer matrix may also be used for laminations.

Sandwich panels are designed to be lightweight yet strong beams or panels. They feature a unique composite structure, bonding lightweight and stiff skins to a thick core [45]. The outer sheets provide high strength and stiffness and are typically made of materials like titanium, aluminum alloys, steel, fiber-reinforced plastics, or plywood. The core, generally a low-strength material, contributes significant bending stiffness to the sandwich composite while maintaining low density. Core materials include open- and closed-cell structural foams (e.g., polyurethane, polyvinylchloride, polyethylene, or polystyrene foams), syntactic foams, balsa wood, and honeycombs. The core serves to support the faces and provide shear stiffness and strength, preventing the panel from buckling under transverse shear loads. Sandwich-structured composites are widely used in various applications due to their combination of strength

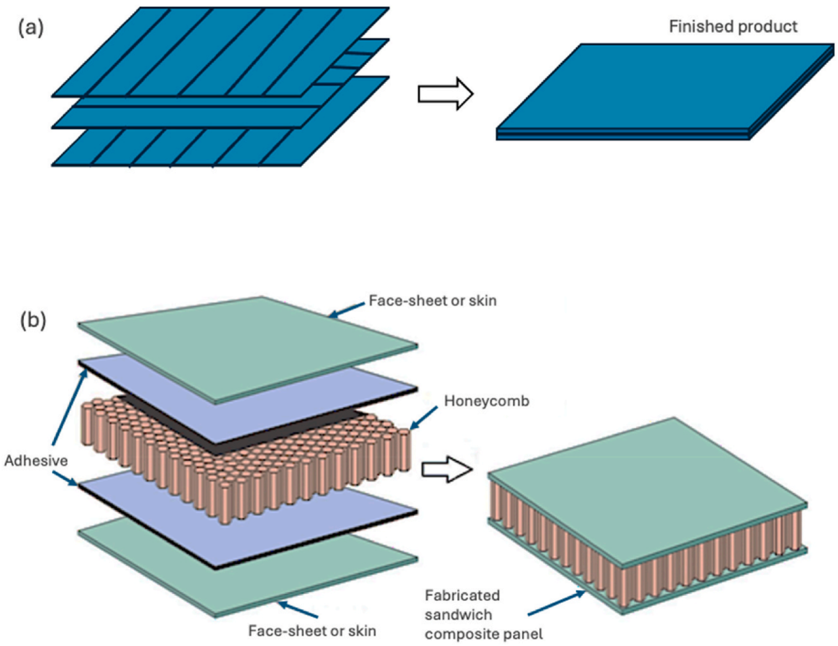

Fig. 5. Schematic illustrations of structural composites; a) laminar composite and b) sandwich panel composite. Reproduced from Ref. [43] (Creative Commons CC BY 4.0 license).

and lightweight properties.

2.3. Others

2.3.1. Nano-composites

A nanocomposite is a solid material composed of multiple phases, with at least one having one, two, or three dimensions in nanoscale size. Nanomaterials are influenced by the principle that when a material's constituent size falls below a specific threshold, some properties change, enabling the achievement of desired material qualities and synergy between constituents through nanoscale phase processing [46]. Nanoscience and nanotechnology offer remarkable opportunities for producing polymer nanocomposites by combining novel nanoscale fillers with polymers [47,48]. These nanocomposites provide potential solutions to overcome limitations in elemental compositions and stoichiometry control found in micro and monolithic composites. Due to their constituents, nanocomposites exhibit anisotropic characteristics and inhomogeneous reinforcing [49]. Nanocomposites offer several key advantages over other composite materials, including a high surface-to-volume ratio, allowing for small filler sizes and close spacing between fillers. They exhibit improved mechanical properties, high ductility without strength loss, abrasion resistance and superior optical properties [50]. However, challenges remain, such as cost-effectiveness and a need for a deeper understanding of the relationship between formulation, property, structure, and toughness [51]. Despite these drawbacks, nanocomposites hold great promise for various advanced applications.

2.3.2. Bio-composites

Bio-composite materials are composed of biodegradable polymers as the matrix and biodegradable compounds. Biodegradable matter refers to compounds that can be broken down by living organisms. These bio-composites typically utilize bio fibers, such as lignocellulose fibers, as fillers [52]. These fibers are usually derived from agricultural by-products and are combined with various polymer-based matrices. An overview of different bio-fibers used for the fabrication of bio-composites has been outlined in Table 1. The use of natural fibers as reinforcing materials in bio-composites has gained popularity in recent years due to growing concerns about environmental issues and sustainability [53,54]. Natural fibers offer superior physical and mechanical properties, making them highly desirable for industries seeking to reduce pollution, environmental harm and global warming. One significant advantage of natural fibers is their length and high cellulose content, resulting in high tensile strength and cellulose crystallinity. However, a drawback is the presence of hydroxyl groups (OH) in the fibers, which can attract water molecules and cause fiber swelling [55]. Despite this limitation, the increasing emphasis on eco-friendly materials has driven the interest in using natural fibers as a sustainable alternative in the production of bio-composites.

3. Manufacturing techniques

Fabricating composite components can be achieved through various methods, sometimes involving a combination of two or more processes [56,57]. The selection of production approaches depends on the type of fiber or matrix material used, with several methods developed to tackle specific design and manufacturing challenges associated with fiber-reinforced materials. Consequently, the choice of a particular method for a component will depend on the materials, the part's design, and its intended purpose. Herein, the fabrication methods discussed focus on composites based on the matrix phase.

3.1. Polymer composites manufacturing

An overview of polymer composite manufacturing methods is shown in Fig. 6, offering a clear representation of the processes involved in fabricating composites.

3.1.1. Open molding

In these polymer manufacturing techniques, the materials are processed in an open environment, they are exposed to air for curing and hardening.

3.1.1.1. Hand lay-up. The hand lay-up method, also known as the wet lay-up method, is one of the oldest and widely used processes for composite production due to its simplicity and minimal need for sophisticated equipment. In this technique, a gel coat is applied to an open mold, followed by layers of resin and reinforcement, such as woven, stitched, knitted, or bonded textiles, stacked until the

Table 1
Overview of bio-composite classifications.

Bio-composites/bio-fibers							
	Non-wood natural fibers					Wood fibers	
	Bast	Straw fibers	Seed/fruits	Leaf	Grass fibers		Recycled
Examples	Flax, kenaf, hemp, jute	Wheat, rice, straws, corn	Coconut, cotton, coir	Sisal, henequen, leaf fiber pineapple	Switchgrass, bamboo, bamboo fiber, elephant grass	Soft and hard woods	Magazine fibers, newspaper

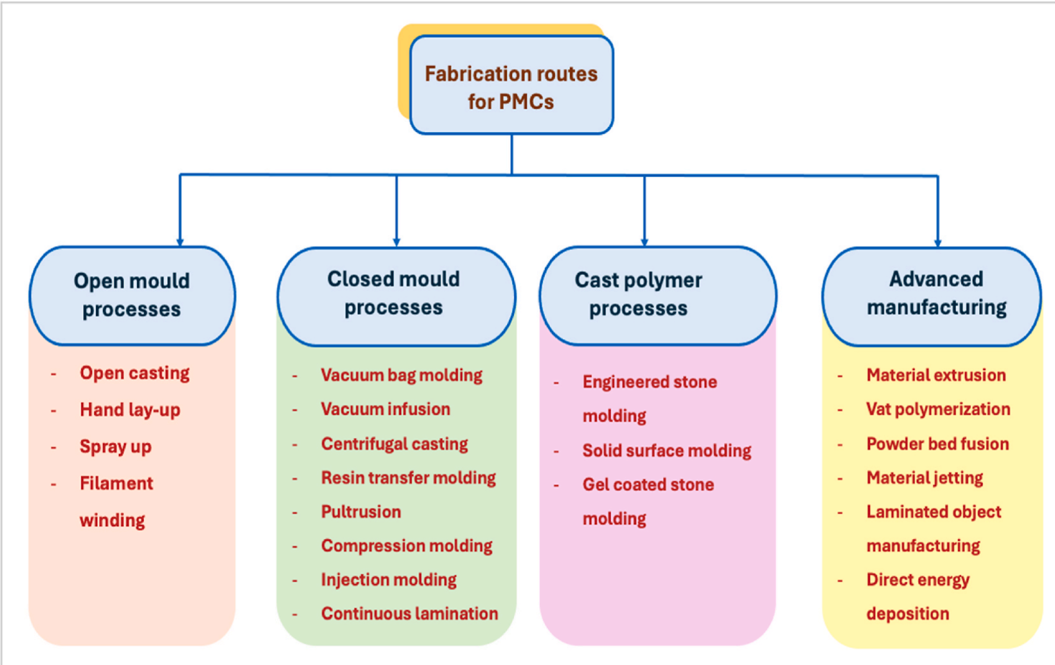

Fig. 6. Fabrication techniques for polymer matrix composite materials.

desired thickness is achieved [58]. Fig. 7(a) provides an illustration of a typical hand lay-up process. To avoid air bubbles, the resin is carefully applied using brushes and rollers. The curing process does not require heat, and the composite is left to cure at room temperature and pressure. The hand lay-up method has been utilized in numerous scientific studies to fabricate various types of materials [59–61]. However, this approach is labor-intensive and time-consuming compared to modern manufacturing techniques. The quality of the final product heavily relies on the skill of the fabricator.

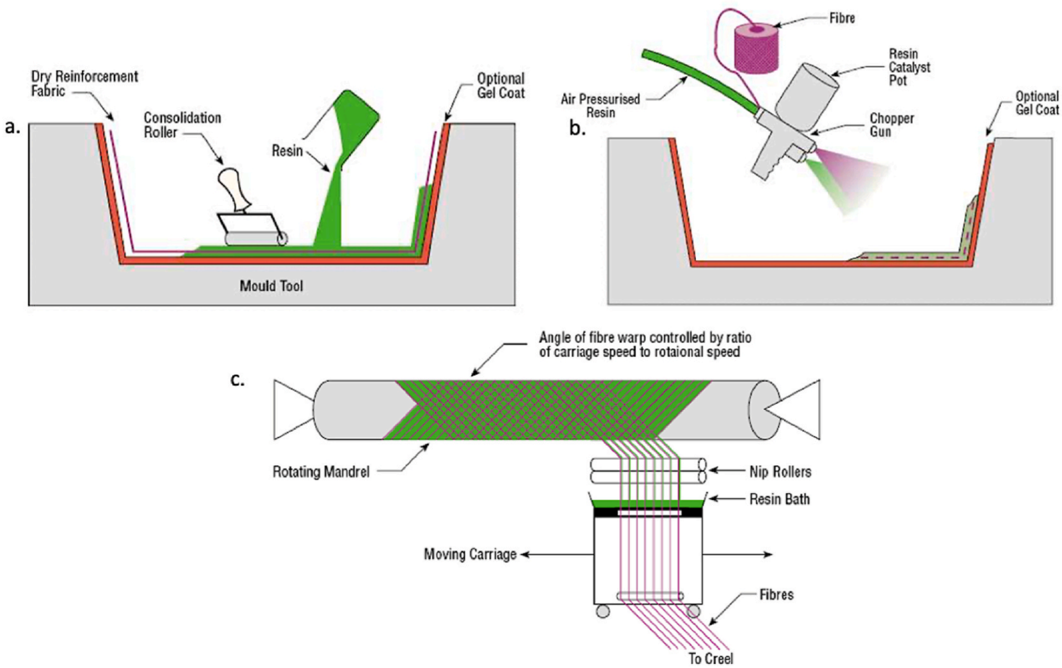

Fig. 7. Illustrations of open molding composite fabrication techniques; (a) hand lay-up, (b) spray lay-up and (c) filament winding. Reproduced from Ref. [66] (Creative Commons CC BY-NC-ND 4.0 license).

3.1.1.2. Spray up. As depicted in Fig. 7(b), the spray lay-up method involves spraying resin and chopped fiber using a handgun. A roller and brushes are also utilized to wet the fiber and remove air bubbles. The material is then allowed to cure at room temperature under ambient conditions. When applied to complex shapes, the chopped laminate from spray lay-up is faster and provides better conformability than manual lay-up [62]. The operator can control the coat's thickness and consistency through multiple passes during the spray-up process. This procedure is also automated and employs portable equipment, enabling on-site production [63]. However, the mechanical qualities of the final product are influenced by fiber orientation and constraints. One drawback of this method is the inclusion of small fibers, significantly limiting the laminate's mechanical properties. Additionally, resins with low viscosity are required for sprayability, which can compromise the resulting composite's mechanical and thermal qualities.

3.1.1.3. Filament winding. The filament winding method is an automated open molding technology that utilizes a spinning mandrel as a mold. As shown in Fig. 7(c), continuous fibers are drawn from a continuous roving and passed through a hot resin bath. These resin-impregnated fibers are then wrapped around a rotating mandrel, following the interior shape of the desired product [64]. Once sufficient layers are applied, the laminate is ready for curing, and the mandrel is removed. Filament winding is commonly used to integrate two-dimensional reinforcement with other processes and devices, as well as three-dimensional reinforcement. It is particularly effective for creating symmetrical shapes and results in composite materials with exceptional strength due to the high fiber loading and oriented strength properties achieved through various fibers, resins and winding processes [65]. This method is often employed in the fabrication of pipelines, oxygen tanks, automobile drive shafts, spherical pressure containers and helicopter blades. The polymer matrices used in filament winding are primarily thermosets.

3.1.2. Closed molding

3.1.2.1. Vacuum bag molding. Vacuum bag molding is a primary composite manufacturing process widely used in the aerospace sector to create laminated structures [67]. This method is an improvement over the wet lay-up procedure as it applies pressure to the laminate after laying it up to enhance consolidation. A flexible plastic sheet or elastomeric membrane, known as a vacuum bag, is wrapped around the wet laid-up laminate. A breather fabric allows air volatiles to be removed within the vacuum bag and across the mold's corners. Using a vacuum pump, the air underneath the bag is removed, eliminating trapped air and excess resin through external pressure, resulting in a higher proportion of reinforcement. A peel ply is used to absorb some resin during the curing process, and once curing is complete, it is removed, providing the desired surface finish. Vacuum bag molding improves the mechanical characteristics of open-mold laminates by eliminating trapped air, leading to laminates with consistent consolidation and lower void content [68]. This fabrication method has been successfully utilized in various studies [69,70].

3.1.2.2. Vacuum infusion. The Vacuum Infusion Process (VIP) involves forcing resin into a laminate using vacuum pressure [71]. First, the mold is carefully prepared and a gel coat may be applied to prevent sticking. Then, the reinforcement cloth is placed into the mold, followed by a peel ply and a perforated cloth (infusion mesh) that helps distribute the resin throughout the mold. A vacuum bag is placed over the content and sealed, and a vacuum is applied to remove all the air from the mold, ensuring there are no leaks. Once a complete vacuum is achieved, the resin is injected into the dry components through well-positioned tubes. As the resin is drawn into the mold, the laminated material compacts, leaving no space for additional resin. Despite its straightforward design, the vacuum infusion process requires careful planning and strategic design to ensure quick and uniform infusion without any dry spots. The rate of infusion depends on factors such as resin viscosity, flow distance, media permeability and the level of vacuum. Proper selection of materials, resin flow pattern, flow media, and vacuum port locations is crucial in producing high-quality parts [72–74].

3.1.2.3. Resin transfer molding. Resin Transfer Molding (RTM) is a low-pressure, low-temperature manufacturing technique used for composite materials and components. It involves a mechanically clamped, rigid, two-part mold (male-female) [75,76]. Before the molding process, a measured quantity of polymeric material is melted in a heated transfer pot. The resin and catalyst mixture is then injected into the mold cavity containing reinforcement fiber or preform using a "piston & cylinder" arrangement in the transfer pot. Pressure is applied to force the melted polymer resin through preheated nozzles into the mold cavity. The mold is sealed until the resin fully hardens. Once the resin has set, the final component can be removed from the mold. Variations of this technique, such as vacuum infusion, vacuum-assisted resin transfer molding and combinations with autoclaves, offer different approaches to delivering resin to the reinforcement within the mold cavity. To ensure efficiency, parameters like heating duration, melting temperature, applied force, materials, and cooling time are carefully controlled and monitored [76].

3.1.2.4. Centrifugal casting. Centrifugal casting, also known as rotor molding or rotational casting, is a method used to produce hollow one-piece items. The process involves filling a thin-walled mold, made of composite or metal, which can rotate in two perpendicular directions, with a mixture of resin and reinforcing powder [77]. The four main steps in the centrifugal casting process for composites are loading, heating, cooling and unloading, as shown in Fig. 8 [78]. The mixture of polymer and reinforcing materials melts and coats the interior of the spinning mold while being heated in an oven. Centrifugal force ensures that the mixture remains pressed against the cylindrical mold's interior wall throughout the process until curing. Once the powder has fully melted, the temperature is gradually lowered to solidify the components. Afterward, the mold is opened and the finished product is taken out. This method is particularly useful for creating hollow items with consistent wall thickness and is commonly used in various industries to manufacture items like tanks, pipes, and other cylindrical shapes.

3.1.2.5. Pultrusion. Pultrusion is a manufacturing process in which a bundle of reinforcement fibers coated with resin is pulled through a heated die block to carry out the polymerization process [80]. The process, illustrated in Fig. 9(c), differs from extrusion in that it involves pulling the components through the dies instead of pushing them. Pultrusion allows for the production of goods with a consistent cross-section and offers several advantages over other composite fabrication techniques. These benefits include lower production costs, high production rates of approximately 5 m/min, improved efficiency and the ability to create profiles of virtually unlimited length [81]. However, during the pultrusion process, the physical and chemical characteristics of the resin system change concurrently, leading to temperature variations and curing shrinkage in moderately thick pultruded profiles. This necessitates a deeper understanding of the relationship between process conditions and final attributes. To enhance the process's effectiveness, there have been several changes and adjustments made in recent years [82–84]. Pultrusion is widely used in various industries for creating a wide range of composite products, such as rods, tubes, and beams, with consistent dimensions and excellent mechanical properties.

3.1.2.6. Compression molding. Compression molding is a widely used method in composite fabrication, where material is molded into a confined shape by applying pressure and heat. In this process, a charge material is introduced into an open, heated mold chamber, and then the press is closed to apply pressure and heat for curing. The process is illustrated in Fig. 9(b). Compression molding can be categorized into two types: sheet molding compound (SMC) and bulk molding compound (BMC), depending on the shape of the input material. SMCs are typically in the form of 5 mm thick sheets, while BMCs are larger, pelletized sheets ranging from 20 to 50 mm in thickness.

To achieve the desired shape and dimensions of the molded items, proper and optimal application of temperature, curing time and pressure is crucial [85,86]. Inadequate pressure can lead to poor adhesion between the fibers and matrix, while excessive pressure can cause fiber breakage. Similarly, maintaining the temperature too high or too low can alter the characteristics of the fiber and matrix materials, affecting the quality of the final product.

Additional variables such as mold wall heating, the speed of mold plate closure and de-molding time also impact the production process. Controlling the quantity of polymer is essential for ensuring consistent homogeneity in the molded product. Preheating the charge before placing it in the mold has become a common practice to soften the polymer and expedite production.

3.1.2.7. Reinforced reaction injection molding (RRIM). At first look, the only distinction between reaction injection molding (RIM) services and resin injection molding services appears to be one word. However, RIM uses chemical reactions to make parts that are substantially more durable, resilient, lightweight, sophisticated, and adaptable than those made by traditional injection molding. RIM is a manufacturing method for the direct polymerization of components in the mold via a mixing-activated reaction [87,88]. In RIM, two reactive monomeric liquids are mixed and then injected into the mold, where polymerization and phase separation occur, leading to the hardening of the component.

For composite manufacturing, a variation called Reinforced Reaction Injection Molding (RRIM) is utilized **(shown in** Fig. 9a**)**. In RRIM, reinforcing agents such as mica and glass fibers are added to the blend before injection into the mold. These reinforcements reduce polymerization shrinkage, thermal expansion and sag of the composite at higher temperatures, while enhancing crucial parameters such as tensile elongation, tensile strength and stiffness. Specialized equipment is used to mill or chop the fibers before introducing them to the polyol resin in the RRIM process. Typically, very short fibers between 0.2 and 0.5 mm in length are used in RRIM to produce components [89]. Some composite fabricators also use glass flakes instead of the usual chopped or milled fibers in the

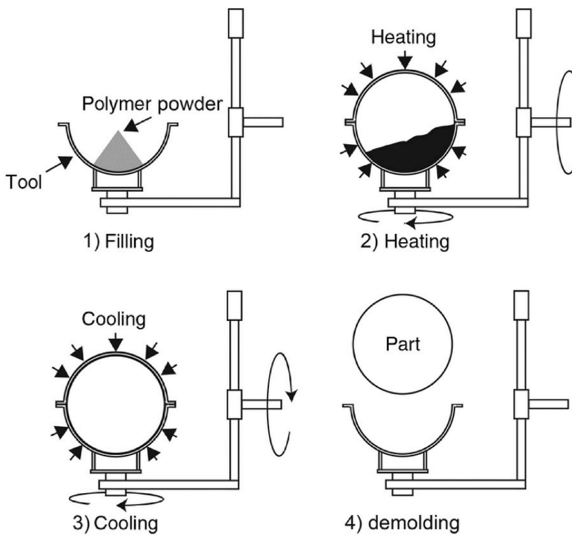

Fig. 8. Overview of the major processing steps in the centrifugal casting of composite materials; (1) loading, (2) heating, (3) cooling, and (4) unloading. Reproduced from [79] (Creative Commons CC BY-NC-ND 3.0).

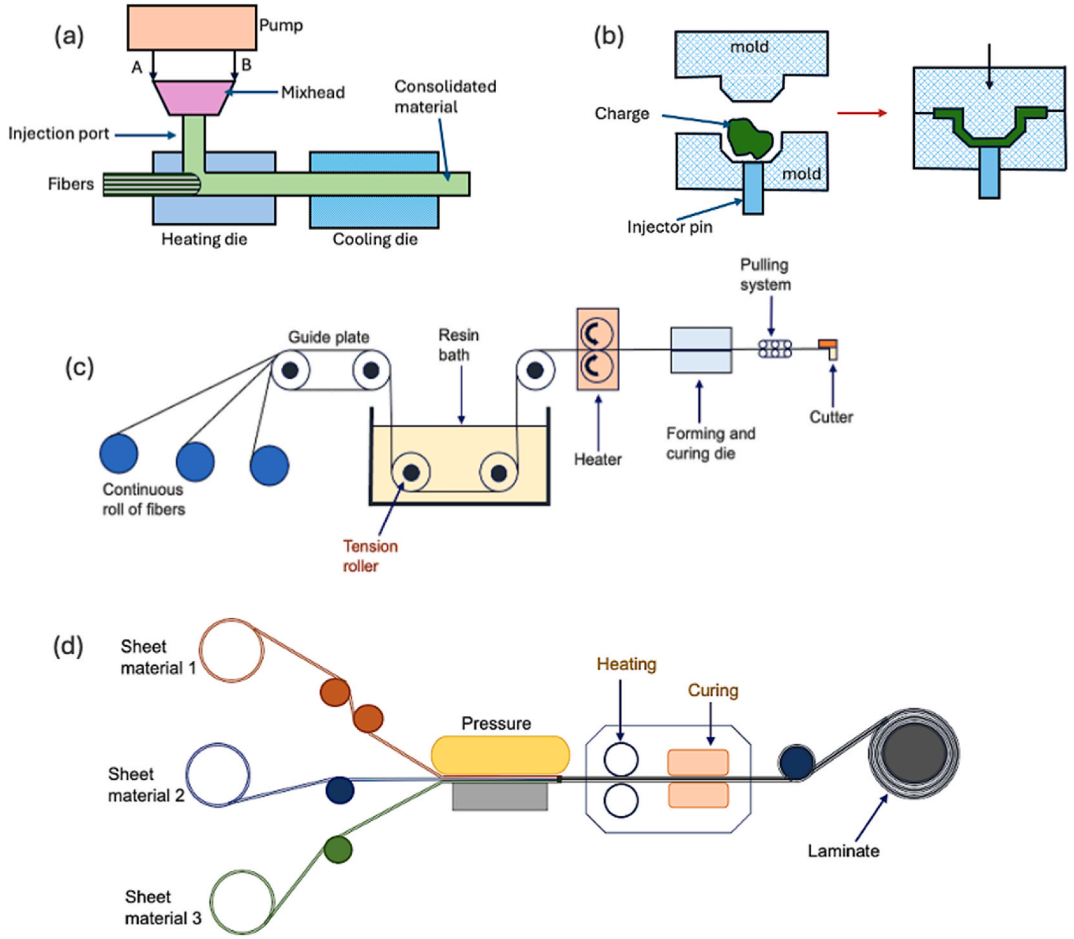

Fig. 9. Illustrations of various closed mold composite fabrication methods, reproduced from [4] (Creative Commons CC BY-NC-ND 4.0); (a) Reinforced reaction injection molding (RRIM) process, (b) compression molding process, (c) Pultrusion casting, and (d) Continuous lamination.

RRIM method. RRIM provides an effective way to create high-performance composite components with enhanced mechanical properties.

3.1.2.8. Continuous lamination. The lamination process involves stacking multiple materials to create a composite structure with the desired strength, stability and appearance. Continuous lamination **(shown in** Fig. 9d**)**, an automated technique, controls thickness and resin content by impregnating reinforcements with resin and guiding them through forming rollers [90,91]. The reinforcements are aligned, resin-impregnated and layered to achieve the required mechanical qualities. The lay-up is then compressed and hardened under pressure and heat before being coiled for further processing. This method produces panels and sheets used in various products such as truck trailers, structural panes, and skylights.

The stiffness of a composite laminate is influenced by its stacking order and material characteristics, which determine its macro-mechanical behavior. Designers must tailor the laminate's stiffness and strength to withstand applied loads and meet performance requirements. Traditionally, laminate layers are given consistent fiber orientation angles, resulting in constant stiffness. Common fiber orientation angles include 0, ±45, and 90°, driven by production capacity and historical certification [92,93]. However, advancements in manufacturing techniques now allow for fiber tows to be deployed in any direction, providing greater flexibility in laminate design.

3.1.3. Cast polymer molding

Cast Polymer Composite materials are a type of nonporous, low-maintenance surface commonly used for countertops, basins, sanitary ware and other sanitation furniture [94]. They serve as a versatile alternative to various interior ceramics. Unlike many composites, cast polymers typically do not incorporate fiber reinforcement and are tailored to meet specific strength requirements for particular applications. The distinguishing factors of Cast Polymer Composites lie in their polymer matrix, filler type and the specific manufacturing processes employed to create these products.

3.1.3.1. Solid surface molding. Solid surface molding, also known as densified casting, involves using vacuum-mixing techniques to create void-free matrixes, resulting in a material with a uniform and consistent surface when cut, polished, or sanded [95,96]. This method can also include compression molding in a large hydraulic press. Solid surface products are made from resin and filler but lack a surface gel layer. Various polymeric resins such as acrylic-polyester blends, polyester, and filled acrylic resins are used to create solid surface materials, with fine alumina trihydrate (ATH) filler being a common choice [97]. The filler loading in solid surface products typically ranges from 50 % to 65 %. To enhance the physical characteristics and achieve a stable result, these products are post-cured at high temperatures. Solid surface materials are known for being homogeneous and nonporous, and they can be designed to mimic various aesthetics and cosmetic effects, including natural granite stone.

3.1.3.2. Gel coated cultures stone molding. A gel coat is a specialized polyester resin substance used to provide an outer protective covering to materials, offering weathering resistance (UV stability), chemical resistance, and water resistance [98,99]. It plays a vital role in enhancing the aesthetic appearance and longevity of the component. By utilizing a resin-matrix casting method and applying a gel-coated surface, various cultured stone products can be created. During the processing, the gel is sprayed onto a mold surface, allowed to cure, and combined with various fillers to reinforce the composite [94]. Pigments can be added to achieve a desired background color with a solid hue and veining resembling natural stone. The resin is then poured into the mold, and vibrations are used to compact and level the matrix. Once the part has cured, it is removed from the mold.

3.1.3.3. Engineered stone molding. Engineered stone refers to cast items made of polymer casting resins and natural stone elements. In this molding procedure, a small quantity of resin and small pieces of stone are mixed and transferred into the mold cavity [100,101]. To achieve low porosity, a vacuum-assisted press method is used to remove air from the matrix, followed by compression of the formation. The combination of genuine stones and thermoset resin in the material matrix results in exceptional durability, strain resistance, low thermal expansion, high heat resistance and scratch resistance. Unlike traditional fillers, the engineered stone matrix binds thermoset resin to relatively larger natural stone particles. Usually, a small amount of resin (8–15 % by weight) is blended into the stone particles. This manufacturing process allows for the creation of products that resemble natural stone, with some products designed to have brilliant colors [102]. Engineered stone materials include engineered quartz, marble and polymer concrete. The increasing popularity of engineered stone fabrication is driven by the growing demand for sustainability in various technical fields. For example, Gomez et al. [103] conducted experiments on creating artificial marble from discarded dolomitic rock using unsaturated polyester resin as a raw material. Barreto et al. [104] aimed to create engineered stone using quartz powder residues, glass packaging scrap, and epoxy resin to reduce waste.

3.1.4. Advanced manufacturing techniques

The term "advanced manufacturing" (AM) refers to production processes that utilize automation, software, computation and novel technologies to create new products and improve existing ones [105]. AM techniques are particularly valuable in the production of composite materials due to their versatility in selecting reinforcement particles, fiber types and orientations. Unlike conventional methods, AM allows for the efficient use of biobased materials, making it suitable for industries such as automotive, aerospace, medical and packaging [106]. Innovative techniques and sophisticated equipment in AM lead to faster cycle times, reduced scrap, integrated features and lower energy consumption. Additionally, AM processes like additive manufacturing enhance performance, recyclability,

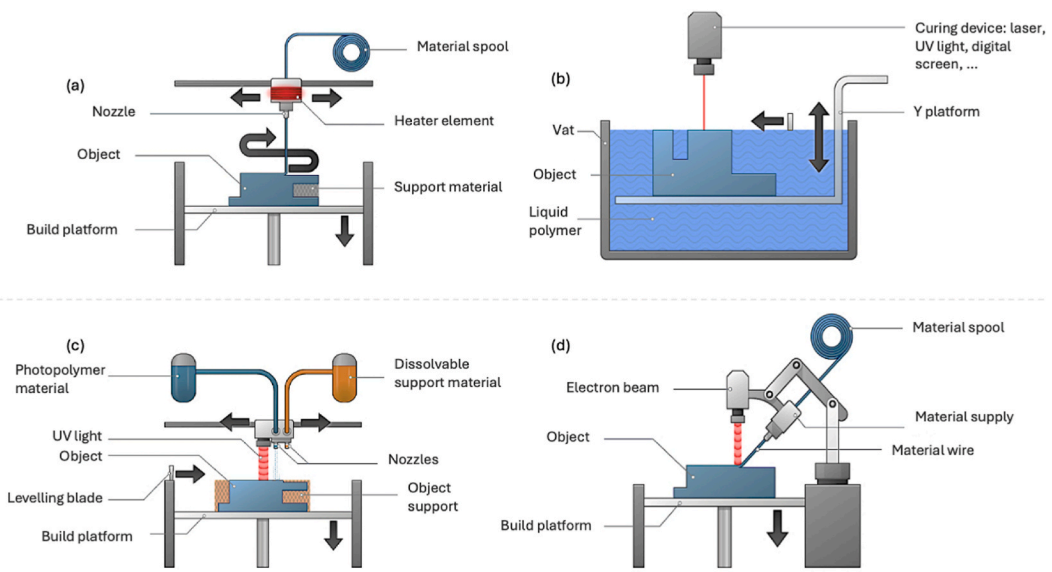

Fig. 10. (a)Material extrusion, (b) Vat polymerization, (c)Material and binder jetting and (d) Direct energy deposition (DED). Reproduced from Ref. [119] licensed under CC BY 4.0.

and cost-effectiveness in composite manufacturing [107–109]. The use of computer-aided design systems enables complete mechanization and automation of the fabrication process. Fig. 10(a–d) illustrates some of the different categories of AM fabrication technologies. With the implementation of AM techniques, the limitations of traditional approaches in composite manufacturing can be overcome, leading to advancements in various industries.

3.1.4.1. Material extrusion. Material extrusion is one of the most common and widely used additive manufacturing (AM) methods, following the ASTM (American Society of Testing and Materials) standard. It involves selectively depositing a thermoplastic polymer filament through a nozzle onto a movable build platform, following a computer-aided design (CAD) model. This method encompasses processes like fused filament fabrication (FFF) and fused deposition modeling (FDM) [110,111]. During extrusion, the filament is in a semi-liquid state, and it solidifies as it cools down. Material extrusion is considered the most cost-effective and user-friendly AM technology, using environmentally and structurally stable materials [112].

3.1.4.2. Vat polymerization. Vat polymerization is an additive manufacturing technique that utilizes a vat of liquid photopolymer resin to build the model layer by layer. Ultraviolet (UV) light is used to cure or harden the resin as needed, and a platform is used to lower the object as each layer is completed and dried. This process is enabled by digital light processing technologies and employs photolithographic cross-linking to create solid free-standing objects from photosensitive liquid thermosets [113]. Unlike powder-based processes where support is provided by the unbound material, vat polymerization does not have structural support during the build phase. Therefore, additional support structures are required. This method includes various technologies such as multiphoton polymerization (MPP), digital light processing (DLP), stereolithography (SLA), continuous liquid interface production (CLIP), and continuous liquid interface production (CLIP). Vat polymerization is capable of high-resolution printing; however, the range of available materials is currently limited.

3.1.4.3. Powder bed fusion (PBF). In powder bed fusion, also known as selective laser sintering (SLS), the process involves selectively sintering or fusing powder layers using a laser beam [114]. This method uses semi-crystalline polymeric materials that can soften with a moderate temperature change and show a noticeable change in viscosity. Sometimes, amorphous properties can also be observed in the thermoplastic polymers used in SLS. One advantage of this technique is that it does not require support structures, as the surrounding powder layer can support overhangs. The most commonly used semi-crystalline material in powder bed fusion is polyamide 12, also known as nylon.

3.1.4.4. Material jetting and binder jetting. Material jetting is a manufacturing process that utilizes an inkjet head to selectively deposit build materials, such as photopolymers and thermoplastics, as droplets on a build platform [115]. As the nozzle moves horizontally across the build platform, it releases tiny droplets of the photopolymer material. UV light is then used to cure the layers. After the printing process, post-processing is carried out to remove the binder and crystallize the feedstock material and constituent powder. This results in a solid and functional 3D printed object. Material jetting is known for its ability to produce high-resolution parts with fine details and multiple material properties.

3.1.4.5. Laminated object manufacturing (LOM). Laminated Object Manufacturing (LOM) is a technique that involves bonding materials in the form of sheets made from synthetic polymers or paper to create composite products [116]. The sheets are a key component of the additive manufacturing (AM) process. Various thermoplastics, such as PMMA and PC, as well as polymer-based composites, can be used to construct objects using the LOM process. Additionally, with the use of polymer additives, intricate and complex ceramic components can be fabricated using LOM [117]. This method allows for the creation of layered objects with different materials, providing versatility and the ability to produce unique composite structures.

3.1.4.6. Direct energy deposition (DED). Direct Energy Deposition (DED) is an additive manufacturing process that involves the melting and bonding of materials, which are supplied in the form of wire or powder, by directing thermal energy, typically in the form of a plasma arc or laser [118]. While DED can be applied to polymer composites, it is more commonly used for metals and is known for its capability to achieve high volume deposition rates. This method is often employed for repairing components and can also produce compositional gradients, allowing for the creation of complex and customized structures.

3.2. Metal composites manufacturing

The ultimate qualities of any composite are significantly influenced by the manufacturing process used in its fabrication. The production of high-quality MMC products involves various processes. The primary procedures employed in the industrial production of MMCs can be categorized into three groups: solid-state processes, liquid-state processes, and deposition processes, as illustrated in Fig. 3.

3.2.1. Solid-state processes

Solid Phase Processing (SPP) is an innovative method for producing various metal products by utilizing specific temperatures and pressures. This technique has the potential to reduce the energy intensity of manufacturing and create high-performance components at a lower cost. There are two fundamental approaches to implementing SPP: diffusion bonding and powder metallurgy.

3.2.1.1. Powder metallurgy. In the powder metallurgy (PM) process, metal powder is mixed with reinforcing alloys in specific proportions, either manually or using machinery. The mixture is then poured into compact dies and forged to achieve the desired shape and size through either cold pressing or hot pressing [120]. This processing method is appealing because it involves lower temperatures, allowing for better control of interface kinetics.

PM has been used to create various nanocomposites with different materials serving as the matrix or reinforcing agent. For instance, a study by Kumar et al. [121] found that PM process parameters, such as sintering temperature, duration, and compaction pressure, significantly influence the engineering properties of aluminium matrix composites. Similarly, Uzun and Cetin [122] and Karthikeyan et al. [123] used PM to investigate the effects of alloying elements by varying the composition percentages. These studies showed that process variations can greatly impact the mechanical properties of the metal composite.

3.2.1.2. Diffusion bonding. During diffusion bonding, two components that are to be welded together are clamped with their surfaces touching. This process relies on the solid-state diffusion theory of materials science, which states that, over time and at high temperatures, the atoms of two solid metallic surfaces combine [124]. Diffusion bonding is a straightforward joining technique that is controlled by three interconnected process parameters: bonding temperature, dwell time, and bonding pressure. Several researchers have successfully used this method to create high-performance materials, including Ni/Ti reactive multilayers [125], Al5(TiZrHfNb)95 high entropy alloy [126], SiC/2024 Al [127] and Alloy 617 [128].

Before welding, the material surfaces must be machined to the smoothest finish and kept free of chemical impurities or other debris. Any material intervening between the two metallic surfaces could hinder proper material diffusion. Once clamped, the parts are subjected to pressure and heat for an extended period. Diffusion bonding occurs in three streamlined steps at the microscopic level:

- Asperities on the two surfaces make microscopic contact and plastically deform before the surfaces come into full contact.
- Elevated temperatures and pressure accelerate the creep process in materials, causing grain boundaries and raw materials to move. The voids between the two surfaces diminish into isolated pores.
- Material starts to diffuse across the border between the abutting surfaces, creating a bond.

3.2.2. Liquid-state processes

In the liquid state processing of MMCs, preheated reinforcements are introduced into molten metal (the matrix) and mixed appropriately [129]. This is followed by an appropriate casting procedure. However, there are several prominent issues associated with MMC processing in the liquid state, including wettability, chemical reactions, particle dispersion and interfacial couplings at the matrix-reinforcement interface [130]. The MMCs typically process liquid states using infiltration and stir casting.

3.2.2.1. Stir casting. The stir casting process involves starting with the creation of a melt of the desired base material, followed by adding the reinforcing material and stirring to achieve the desired dispersion. To prevent gas entrapment, the reinforcing particles are typically fed using an injection gun [131]. This method is considered one of the best fabrication techniques for producing metal matrix composites with greater uniformity, and it is a cost-effective approach for creating large near-net-shape items. For successful stir casting, it is crucial that the liquid metal and the reinforcing particles are well-wetted. Proper wetting ensures that mechanical force is transferred to the reinforcement without causing particle breakdown, resulting in a more uniform distribution [132]. The production of composites utilizing the stir casting method is a growing area of research, with more studies focusing on the procedure's parameter optimization. For instance, Tamilanban and Ravikumar [133] undertook investigations to find the optimal stirring speeds for SiC reinforcement particles in the Al matrix in terms of mechanical and wear performance. In Jojith and Radhika's research [134], which focused on the fabrication of titanium and molybdenum hybrid composite by stir casting, the homogeneous distribution of the strengthening particles was observed. The investigation showed an improvement of hardness and tensile qualities. Additional studies of stir casting composite fabrication include Kanth et al. [135] fabrication of Al-Zn/fly ash/SiC reinforced composites and Chitharthan et al. [136] exploration of the mechanical and tribological properties of LM13 aluminum alloy reinforced with Aluminum Oxide and Boron Carbide. Venugopal & Karikalan [137] utilized stir casting manufacturing for the development of hybrid composites (AA6061-TiO2-SiC) for brake pad applications in automobile industries. All these investigations found that adding reinforcements increased the composite's strength properties and hardness, but at the expense of ductility.

3.2.2.2. Infiltration castings. The term "infiltration" refers to the process of introducing a liquid substance into the pores of another material. In the context of composite fabrication, infiltration casting is a liquid-state process where a prepared dispersed phase is placed in a molten matrix metal that fills the void between the dispersed phase inclusions [138]. This process involves combining two molten flow paths: one where molten metal fills the spaces between particles in a packed column and another where molten metal passes through the surfaces of filler particles. When the flow resistance of the first route exceeds that of the second route, the infiltration process is complete [139]. The driving force behind an infiltration process can either be the capillary force of the dispersed phase (spontaneous infiltration) or external forces applied to overcome the resistive forces (forced infiltration). Fig. 11(a–d) illustrates several distinct infiltration casting procedures. The success of the infiltration process depends on various factors, including the alloy composition, surface morphology and material of the preform, temperature, and duration. The amount of liquid alloy that wets the reinforcement is influenced by these variables. Infiltration casting has proven effective in producing alloy foams for mechanical and functional applications. For instance, El Sayed et al. [138] conducted an experimental examination of the infiltration casting process variables to fabricate Al-A356 alloy foams. Gecu and Karaaslan [140] investigated the tribological behavior of a melt-infiltration cast

AA7075 aluminum matrix composite reinforced with 304 stainless steels. Their findings suggested that next-generation, inexpensive, and environmentally friendly bimetal composite products have the potential to replace traditional MMCs due to their superior microstructural and tribological properties.

3.2.3. Deposition process

Deposition processes involve the spraying of molten metal droplets with reinforcement materials onto a substrate, followed by allowing the material to solidify. This method offers the advantage of producing products with fine grain size and desired microstructures. However, it also has some drawbacks, such as the lack of continuity in the reinforcement, limited shapes that can be produced, and higher production costs. Some examples of deposition processes include physical vapor deposition, chemical vapor deposition and spray deposition.

3.2.3.1. Physical vapor deposition (PVD). PVD is a vacuum deposition method used for the fabrication of thin coatings and films. In this approach, metal is vaporized through high temperature or plasma in a high vacuum and then deposited as a coating at low pressures onto electrically conductive substrates [142]. While this technology allows for the production of coatings ranging from thousands of nanometers to just a few nanometers, it may not be suitable for manufacturing MMCs due to the time-consuming nature of the process. There are two main categories for PVD:

- Electron Beam Evaporation and Deposition (EBED): In the EBED process, a high-energy electron beam (EB) is generated from a gun, which vaporizes the matrix material, causing the metal vapor to settle and bond with the fibers.
- Sputtering Techniques: In sputtering, gas ions, such as argon, bombard a target material (reinforcement) and cause atoms to be knocked off and deposited onto a base or substrate material, forming the coating.

3.2.3.2. Chemical vapor deposition (CVD). Chemical Vapor Deposition (CVD) is a technique that involves exposing the substrate to one or more volatile precursors, which then react or decompose on the surface of the substrate to produce high-quality, high-performance solid materials, typically under vacuum conditions [143]. In the CVD method, chemical reactions take place between the deposited organometallic or halide chemicals and other gases, resulting in the formation of non-volatile solid nanomaterials on the substrates. One distinctive feature of CVD is the multidirectional nature of material deposition onto the substrate.

3.2.3.3. Spray deposition. This technique utilizes a high-speed inert gas jet to spray atomized tiny molten metal droplets with reinforcement across a stationary metallic substrate [144]. Injecting short fiber reinforcements, particles, or whiskers into the spray results

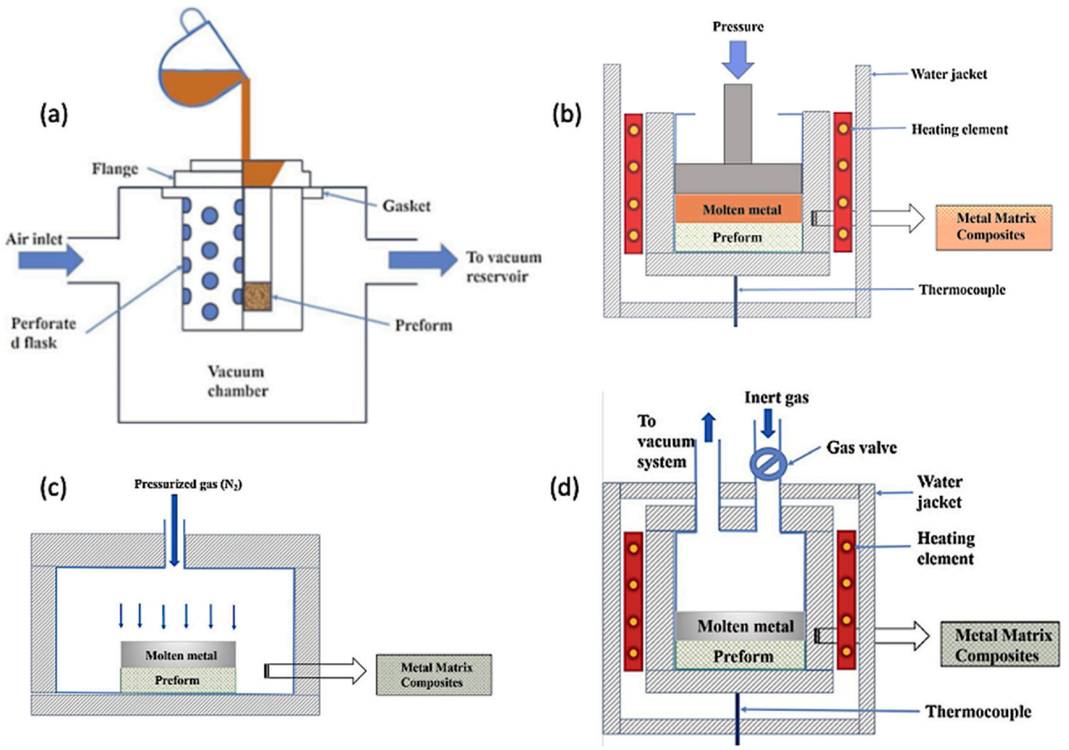

Fig. 11. Schematics of infiltration variants depending on the driving force; (a) Melt infiltration, (b) Pressure infiltration, (c) Gas pressure infiltration and (d) Vacuum pressure infiltration [141] (Reproduced with permission from Elsevier: Lic. No. 5892541079484).

in a deposition layer on the metal surface with 5–10 % porosity. The depositions are further processed in a subsequent step to achieve full density. To fabricate long fiber composites, the matrix material is sprayed onto reinforcing fibers.

According to Srivatsan and Lavernia [145], who evaluated and discussed several synthesis methods for creating MMCs using particle technology, spray deposition offers the best chance of creating high-quality MMCs. The recent use of cold spraying (CS) technology, a newly developed spray deposition variant, has been reported [146,147]. This method involves expanding pressurized gas through a diverging-converging nozzle to accelerate micron-sized particles to supersonic speed. In this process, metal matrix composites can be quickly deposited layer by layer because powder particles experience severe plastic deformation upon impact and bind to the substrate surface [148]. Throughout the entire process, the feedstock is in a solid form. Several factors, including deposition rate, spraying pressure, distance from the spray nozzle to the substrate, inert gas used and angle of spray, need to be monitored and controlled to ensure the desired results are achieved.

3.3. Ceramic composites manufacturing

Ceramic matrix composites (CMCs) are essential materials for high-temperature applications in harsh environments. Recent advancements have made CMCs suitable for use in industrial and aeronautical applications. Traditionally, ceramic parts are manufactured using techniques like hot pressing and sintering. However, new technologies and approaches are effective for the manufacturing of ceramic composites which are reinforced with a discontinuous phase. In this category of fabrication processes, a fluid is injected into the fiber structure to create the ceramic matrix. A variety of infiltration techniques can be employed for CMC fabrications, each with unique fluid types and conversion processes [149].

3.3.1. Polymer infiltration and pyrolysis (PIP)

PIP is a technique used to create CMCs, involving the infiltration of a low viscosity polymer into a ceramic structure that serves as reinforcement. The structure is then heated in an oxygen-free environment until the polymer breaks down and transforms into a ceramic. This process is known as the pyrolysis of polymers, which results in polymer-derived ceramics [150].

3.3.2. Chemical vapor infiltration (CVI)

Chemical vapor infiltration (CVI) is a method used for manufacturing ceramic matrix composites (CMCs) by heating a gaseous precursor to a high temperature until it is converted into a ceramic state [151,152]. The gaseous precursor enters the reinforcement structure (preform) either through a diffusion process or under an induced external pressure. As the precursor reaches the surface of the fiber, it dissociates and forms a ceramic layer. Typically, a carrier gas such as Ar, He, or H2 is used to deliver the vapor reagent to the preform during the CVI process.

3.3.3. Reactive melt infiltration (RMI)

In the RMI process, the liquid metal infiltrates a porous reinforcing preform and undergoes a chemical reaction with the surrounding material to form a ceramic matrix [153]. The liquid metal is usually injected under atmospheric pressure or in a vacuum, and capillary forces assist in the penetration of the melt into the porous structure. Once inside the preform, the liquid metal reacts with the preform material, leading to the formation of the ceramic matrix.

3.3.4. Slurry infiltration

This is the process of infiltrating a surface with a slurry made of tiny ceramic particles that, after drying and heat pressing, solidify into a ceramic matrix. The slurry infiltration method has been developed to the greatest extent for the production of glass-ceramic matrix composites. In this fabrication approach, a slurry containing tiny ceramic particles penetrates the porous reinforcement preform due to capillary forces [154]. After drying and heat pressing, the slurry fragment becomes the ceramic matrix. Glass-ceramic and fiber-reinforced glass composites are examples of materials made by slurry infiltration. The matrices that can be created through slurry infiltration are silicon nitride, alumina, silica and glass.

3.3.5. Sol-gel infiltration

This process involves infiltrating the preform with a sol preceramic precursor, which includes the mixing of chemicals in a solution, gelation, drying, and post-treatment at increased temperatures to create final products [155]. However, sol-gel solutions have a low ceramic content and experience considerable drying-induced shrinkage. To increase the matrix's densification, the cycle of infiltration and drying is repeated multiple times. Sol-gel infiltration is commonly used to create continuous reinforcement composites, but it can also be applied to produce composites with particle and short fiber reinforcing phases.

4. Applications

The use of composite materials is increasingly prevalent due to various factors, with the primary driver being the combination of strength and lightness in the end products they offer. Nowadays, it is rare to find any industry that does not benefit from the advantages of composite materials. Technology and its demands have significantly evolved over the past three decades, leading to new requirements and opportunities. Meeting these challenges necessitates advancements in novel materials and their corresponding production technologies. As a result, a variety of cutting-edge production methods and materials have been developed to meet these demands. The composites market can be broadly segmented into the following industry groups:

4.1. Aerospace

The thrust-to-weight ratio is a critical metric for assessing an aircraft's performance. Aerospace manufacturers have consistently strived to reduce this ratio by building lighter aircraft [156]. However, traditional metals used in airplane bodies are heavy, limiting the potential for significant improvements. To address this challenge and meet the aerospace industry's demands for improved performance, fuel efficiency, and reduced emissions, there has been a growing emphasis on developing advanced composites as high-performance structural materials. Initially, composites were primarily used in secondary components, but advancements in material knowledge and technology have led to their application in major aircraft structures, such as wings and fuselages. Fig. 12 illustrates the increasing utilization of composite materials in aviation, indicating their growing significance in the industry.

4.2. Automotive

The automotive industry is currently focused on finding lightweight, cost-effective, reliable and high-performance materials for various applications. Composite materials, especially hybrid composites involving aluminium, have emerged as viable solutions to meet these requirements [158]. By using composites, weight savings of 15 %–40 % can be achieved, depending on the type of reinforcement utilized. Composites also play a crucial role in helping the automotive sector meet international regulations concerning CO2 emissions. Currently, the use of composites materials is explored in electric vehicles for improved performance and efficiency. For examples, BMW's i3 employs carbon fiber-reinforced plastic in its passenger cell, reducing weight and enhancing range [159]. Other electric vehicle manufacturing companies use glass fiber-reinforced plastic in underbody panels and battery enclosures for better impact resistance and weight reduction [160]. In the context of automotive braking systems, temperatures can soar to thousands of degrees Celsius, making traditional monolithic metals unsuitable for braking components. As a solution, high-temperature composites like silicon carbide composites are utilized for heavy-duty braking applications. For other automotive components, such as engine and body parts, carbon epoxy composites are preferred due to their durability and lightweight properties. Natural fiber reinforced composites are also finding application in automotive door panels and interior elements.

According to industry analysis, the automotive polymer composites market was valued at USD 6.40 billion in 2016 and is projected to reach USD 11.62 billion by 2025 [161]. The adoption of composite materials is expected to have a significant impact on improving automotive performance, reducing weight, and meeting regulatory requirements. Fig. 13 provides an overview of the diverse uses of composite materials in the automotive industry.

4.3. Bio-medical

Composite materials have garnered significant attention in biomedical applications, encompassing bone fracture healing, joint replacement, tissue engineering and regenerative medicine [163,164]. Their widespread use in this field can be attributed to several advantages, including ease of processing, tunable properties suitable for specific applications, strong chemical resistance and

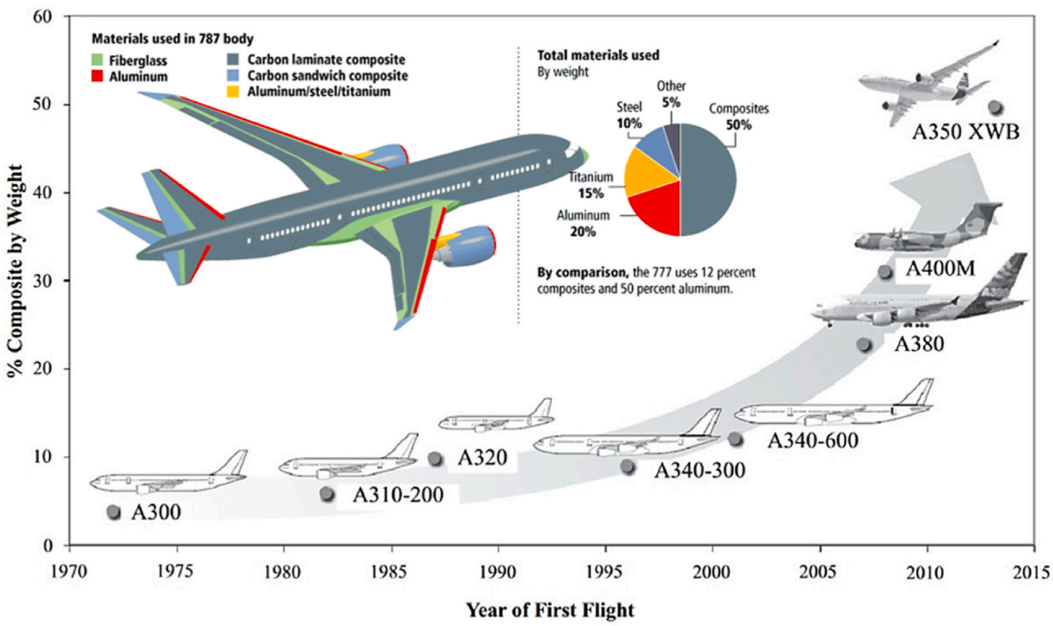

Fig. 12. Composite material utilization statistics in the Airbus passenger aircrafts over the years. Reproduced from Ref. [157] under CC BY4.0 license.

biocompatibility. Table 2 provides an overview of various composites employed in diverse biomedical applications, showcasing their versatility and potential in advancing medical treatments and therapies.

4.4. Construction

The rapid advancements in composite technology have provided civil engineers with valuable tools to enhance the functionality, safety and cost-effectiveness of structures to meet the growing demands of society. As governments worldwide invest significantly in upgrading public infrastructure, it is predicted that the construction composites market will exceed $65 billion by 2025 [179]. These composites find applications in load-bearing structures like beams, columns, roofs, multifunctional panels, and pedestrian bridges, contributing to improved construction practices and efficiency. In various engineering industries, composites are steadily replacing traditional materials. For instance, the use of 3D concrete printing often eliminates the need for steel reinforcements, leading to the adoption of engineered cementitious composites with exceptionally high tensile strain [180]. Additionally, researchers have explored the utilization of indigenous materials and agricultural byproducts as reinforcing elements in construction applications, offering sustainable and eco-friendly alternatives [181,182]. These ongoing research efforts contribute to the continued growth and diversification of composite applications in civil engineering and construction sectors.

4.5. Marine

In the marine environment, components and structures face significant stresses from wind, waves and tides. These structures must also withstand harsh conditions, including exposure to splash zones and saltwater submersion throughout their operational lives. Composite materials have emerged as an excellent choice for marine applications due to their corrosion resistance and combination of lightweight and robust properties. They are widely used in the construction of boat hulls, bulkheads and other components for both recreational and military boats and ships [183]. The adoption of composite technology has enabled manufacturers to improve the quality of marine products by creating rigid, lightweight structures that offer advantages in terms of both durability and sailing performance. Lower overall costs and the ability to utilize accelerated and automated manufacturing processes with composites have made the finished products more affordable and accessible to a larger market. As a result, composite materials have become a vital solution in enhancing marine structures and vessels, contributing to advancements in the marine industry.

4.6. Miscellaneous

4.6.1. Defence, security, & ballistics

Composite materials offer significant advantages in providing protection for people, vehicles and machinery due to their ability to absorb and distribute energy effectively. They also contribute to reducing the weight burden associated with protection systems. In the realm of ballistic applications, composite armor systems and ceramics are commonly used to deflect armored projectiles, employing materials with low breakage rates to protect against potential threats [184]. Various defence and security composite products demonstrate the wide range of applications for composites in protection. These include ballistic shield panels used for blast protection,

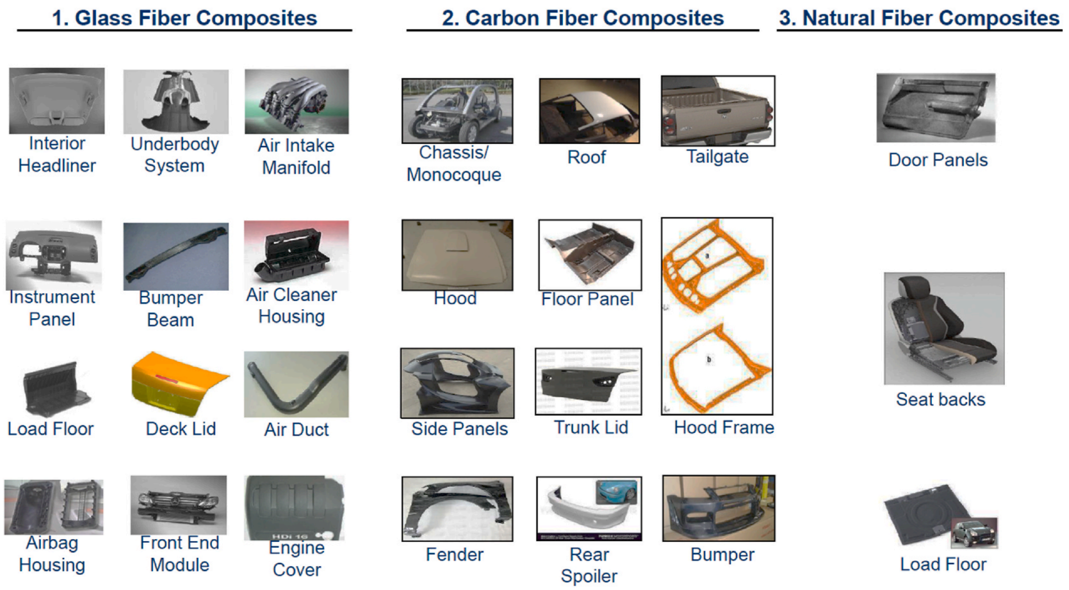

Fig. 13. Major Applications of Various Types of Composite Materials in auto motive sector for lightweight [162] (Reproduced with kind permission from Elsevier: Lic. No. 5892560146632).

Table 2
Examples of composite utilization in the biomedical sector.

Application	Composite materials	Source
Joint Replacement	Al2O3–Cr2O3-Based Ceramic Composite	[165]
	Al_2O_3/MWCNT/HDPE hybrid composite	[166]
Bone replacement and repair	ultra-high molecular weight polyethylene (UHMWPE)	[167,168]
	gelatin meth acrylamide (GelMA)/hydroxyapatite (HAp) composite	[169]
	TiO2-CaSiO3-HA Composites	[170]
Orthopedics and Dentistry	Alumina–Zirconia Composites	[171]
	GO/CF/PEEK composite coatings on Ti6Al4V (TC4) alloy	[172]
Tissue Engineering	Ionic-Liquid-Based Electroactive Polymer Composites	[173]
	polycaprolactone (PCL) and hydroxyapatite (HA)	[174]
	PCL/CSW/BT ternary composites.	[175]
Wound Dressing	lignin–chitosan–PVA composite hydrogel	[176]
	Aloe Vera extract-based composite nanofibers	[177]
	Halloysite nanotube (HNT) composites	[178]

hard armor plate vests equipped with ballistic hard armor plates capable of stopping armor-piercing rounds and helmets made from carbon and aramid fiber fabric prepregs to provide general head protection. With their ability to offer superior protection and optimize weight efficiency, composite materials play a vital role in enhancing the safety and security of individuals and equipment in various defence and security applications.

4.6.2. Oil and gas

The oil and gas industry faces numerous challenges, such as harsh conditions, corrosion susceptibility, high pressures and deep-sea environments. To overcome these issues, composite materials are becoming increasingly important. One of the most popular composite materials used in this industry is fiberglass, particularly in the manufacturing of composite pipes for transferring oil and gas from offshore drilling platforms to onshore plants. Fiberglass pipes are preferred in situations where the fluid being transported is high-pressure natural gas, as they offer excellent corrosion resistance and are less susceptible to deterioration compared to steel pipes.

Steel pipes used in oil and gas transportation are prone to corrosion and failure, especially in marine environments where hydroxides and chloride ions accelerate metal defects and cracking. To address these challenges, alternative materials like reinforced fiber composites are being explored. These composites have proven to be suitable alternatives due to their lightweight, high strength, stiffness, outstanding corrosion resistance and excellent performance under fatigue loading conditions. In composite materials used for interventions in tubular structures, thermosetting resins like polyurethanes, polyesters, phenolics, or epoxies are commonly used as matrix materials, while reinforcement materials include carbon, aramid, or E-glass fibers. The use of composite materials in the oil and gas industry is providing innovative solutions to enhance the durability, efficiency and safety of infrastructure and components in this critical sector.

5. Challenges, outlook and future trends

The challenges in advancing lightweight composite structures are multifaceted, with a primary concern being the development of cost-effective, scalable manufacturing techniques. Current fabrication processes, such as resin transfer molding, filament winding and advanced additive manufacturing, while effective, often remain resource-intensive and costly, limiting their widespread industrial adoption [185]. Additionally, recycling composite materials poses significant difficulties due to the heterogeneous nature of their constituents, making it challenging to separate and recover the matrix and reinforcement components without compromising material integrity. This presents environmental concerns, particularly regarding the sustainable lifecycle of composite materials and their disposal at the end of use.

Future research directions are expected to focus on overcoming these manufacturing and sustainability barriers by enhancing recycling technologies and improving the compatibility of composite components for easier disassembly and reuse. Furthermore, novel fiber and matrix combinations, particularly those involving bio-based or eco-friendly polymers, are being explored to improve mechanical performance while reducing environmental impact [cite]. The integration of nanomaterials, such as graphene or carbon nanotubes, into composite matrices also presents opportunities to achieve superior mechanical, thermal and electrical properties. Advancements in additive manufacturing techniques, including the use of 3D printing for complex composite geometries, are anticipated to revolutionize production efficiency and customization, making lightweight composites more viable for high-performance applications in aerospace, automotive and structural engineering [186]. The field must continue addressing challenges related to durability under extreme environmental conditions, such as temperature and load variations, to fully harness the potential of lightweight composites in future technological applications.

6. Conclusions

Composite materials have emerged as a revolutionary class of materials with immense potential and widespread applications across various industries. Throughout the discussions, it became evident that composite materials offer a remarkable combination of properties that cannot be achieved by individual constituents alone. This review paper provides a comprehensive and insightful analysis of composites materials, shedding light on their fundamental concepts, composition, classifications and their wide-ranging engineering applications. The paper delved into various types of composites, including polymer matrix composites, ceramic matrix composites and metal matrix composites, highlighting their specific advantages and applications. It also presents a detailed examination of diverse fabrication methods employed to create these materials, enabling researchers, engineers and industry professionals to capitalize on their benefits effectively. The recent advancements in lightweight composite materials have revolutionized various industries by offering an unparalleled combination of strength and weight reduction. Their lightweight, high strength, excellent corrosion resistance and adaptability have made them highly sought after in the fields of aerospace, automotive, construction, marine, defence and biomedical applications.

The future of lightweight composite materials offers vast potential and thus warrant further research. This research should focus on developing cost-effective and scalable manufacturing techniques, improving recycling methods, and exploring novel fiber and matrix combinations to enhance mechanical performance. There is also a need to address durability under extreme conditions, such as high temperatures and impact forces, while mitigating environmental concerns related to production and disposal. Advancing these areas will be essential for expanding the use of lightweight composites where performance and sustainability are critical.

CRediT authorship contribution statement

Resego Phiri: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sanjay Mavinkere Rangappa:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Suchart Siengchin:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Oluseyi Philip Oladijo:** Writing – review & editing, Validation, Methodology, Conceptualization. **Togay Ozbakkaloglu:** Writing – review & editing, Visualization, Validation, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:The paper's corresponding author, Sanjay Mavinkere Rangappa, works as an Associate Editor for Heliyon Materials Science. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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