🌐 *United International Journal of Engineering and Sciences* 🌐
(UIJES – A Peer-Reviewed Journal); ISSN:2582-5887 | Impact Factor:8.075(SJIF)
📓 *Volume 5 | Special Issue 1 | 2025 Edition*
National Level Conference on "Advanced Trends in Engineering Science & Technology" – Organized by RKCE

The Applications of Composite Materials Across Various Industries

Ch Prem Kumar, DV Nooka Raju Chitrada
Department of Mechanical Engineering, RK College of Engineering Kethanakonda, Vijayawada, Andhra Pradesh – 534201
Email: chintapremkumar313@gmail.com nookarajuchitrada@gmail.com

Abstract:

Emerging in the mid-20th century, composite materials have become a key research focus in modern technology. Their exceptional properties make them suitable for a wide range of industrial applications, including aerospace, automotive, construction, sports, and biomedical fields.

The growing demand for next-generation composites, incorporating synthetic or natural materials through advanced manufacturing processes, is emphasized. To develop environmentally friendly materials, the integration of natural components as reinforcements is crucial, ensuring complete biodegradability.

1. Introduction

The rapid growth in the usage and popularity of composite materials in engineering and material sciences is driven by their highly desirable combination of stiffness, toughness, lightweight properties, and corrosion resistance [1–4]. As the name suggests, a composite material is a combination of two or more constituent materials with significantly different physical or chemical properties. When combined, these materials create a final product with unique characteristics that surpass those of the individual components [5,6].

This enhancement makes composite materials superior compared to single materials. The concept of composite materials is well illustrated by naturally occurring examples, such as wood, which consists of fibrous cellulose chains embedded in a lignin polymer matrix [7,8]. Another example is bone, composed of inorganic hydroxyapatite crystals within an organic collagen matrix [9,10]. The classification and types of composite materials based on their constituents are discussed in subsequent sections.

Unlike mixtures and solid solutions, the components of composite materials do not blend, dissolve, or lose their individual identities. Instead, they combine and synergistically contribute their properties to enhance the final product [11,12]. Under microscopic examination, the distinct characteristics of each component within the composite structure remain identifiable [13].

A composite material consists of two primary elements: a **matrix** (also called the base or binder material) and a **reinforcement** (or filler material). The matrix surrounds and binds the reinforcement, which may exist in the form of fragments, particles, fibers, or whiskers of natural or synthetic materials [14–16]. The matrix typically serves as a relatively soft phase with properties such as ductility, formability, and thermal conductivity [17]. In contrast, the reinforcement phase is designed to be stronger and stiffer, often with lower thermal expansion, as it primarily carries the applied load.

Since the components of a composite material significantly influence its properties, a thorough study of their classification and distinct characteristics is essential [18–20]. Due to the extensive application of composites across various industries, researchers continue to develop advanced manufacturing techniques aimed at improving productivity and efficiency [2,21,22]. This study provides a deeper understanding of composite material classification, dominant properties, manufacturing techniques, and potential applications as superior alternatives to monolithic materials.

II. Applications

5.1. Automotive

Automotive braking systems experience extreme temperatures, often reaching thousands of degrees Celsius. Therefore, brake materials must exhibit exceptional thermal resistance and functional stability. Carbon fiber-reinforced silicon carbide (C-SiC) brake materials have emerged as competitive solutions for high-speed trains, heavy vehicles, and emergency brake systems in cranes. Fig. 1 illustrates an automotive carbon-ceramic brake and its braking system, demonstrating its high-performance capabilities.

Fig. 1 – Carbon fiber trunk lid of BMW E46 M3 CSL .

5.1.2. Electric Vehicles

An asymmetric supercapacitor device utilizing nickel cobalt oxide-reduced graphite oxide ($NiCo_2O_4$–rGO) composite material demonstrates superior stability during multistage charge-discharge cycles. This makes $NiCo_2O_4$–rGO a promising candidate for high-energy storage applications, such as batteries in electric vehicles.

For several years, research has focused on the characteristics of black phosphorus for applications in nanoelectronics, nanophotonics, and optoelectronics, specifically as an electrochemical energy storage material in lithium and sodium-ion batteries as well as supercapacitors. Black phosphorus exhibits remarkable electronic, photonic, and mechanical properties, including large specific surface area, anisotropy, tunability, and direct band gaps, making it an excellent material for energy storage applications.

5.1.3. Trunk Lid and Body Stiffener

Lightweight structures are crucial for meeting efficiency standards in the energy and transportation industries. Carbon fiber-reinforced plastics (CFRP) are an ideal substitute for electrical instruments due to their superior electrical properties. CFRP also functions as a supercapacitor for energy storage in automotive body parts, such as trunk lids and body stiffeners, thereby optimizing under-hood space. Figure 15 displays the carbon fiber trunk lid of the BMW E46 M3 CSL model.

5.1.4. Wireless Signal Transmission

Modern vehicles rely on numerous wired connections to transmit data from sensors and operate various devices. However, carbon fiber-reinforced composites eliminate the need for additional network cables, serving as an effective wireless transmission medium. A composite structure, consisting of conductive fiber layers separated by insulation, can function as a communication device when connected to transceivers. By applying voltage to either composite layer, it becomes possible to transmit power to electrical devices, reducing the need for separate wiring.

5.2. Aerospace

5.2.1. Aircraft Brakes

In high-temperature aircraft components such as exhaust nozzles, ceramic matrix composites (CMCs) are commonly used. Carbon fiber-reinforced silicon carbide (C-SiC) offers a high coefficient of friction, extended lifespan, and resistance to oxidation, making it an ideal material for aircraft braking systems, which must endure temperatures up to 1200°C .

5.2.2. Aircraft Structure

Aircraft structures must withstand extreme temperature variations while retaining mechanical strength and damage tolerance. Polymer matrix composites (PMCs) provide superior strength and stiffness, replacing traditional aluminum alloys in aerospace applications due to their lightweight properties and high durability.

5.2.3. Gas Turbine

To enhance combustion efficiency and reduce cooling gas requirements, integrally woven ceramic matrix composites (CMCs) are used in combustor liners. These multi-hole cooled CMCs improve turbine performance, leading to advancements in gas turbine technolog. Figure 16 illustrates the manufacturing process of a gas turbine.

5.2.4. Telescope Antenna

The Hubble Space Telescope utilizes a high-gain antenna constructed from 6061 aluminum matrix infused with P100 graphite fibers. This 3.6-meter-long antenna exhibits high stiffness and a low coefficient of thermal expansion, ensuring positional stability during space maneuvers.

5.2.5. Aircraft Seat and Carpet Fabric

Multilayer polymeric/TiO_2 composites feature double self-cleaning properties, enabling photo-oxidation and anti-sticking characteristics. Due to these unique attributes, such composites are utilized in the fabric of aircraft seats and carpets, enhancing hygiene and durability in aviation interiors.

Fig. 3 – Gas turbine manufacturing

Fig. 4 – Bearing shell

5.3. Mechanical

5.3.1. Heat Exchanger

In tropical and sub-tropical regions, where high temperature and humidity pose challenges, liquid-to-gas heat exchangers are utilized for cooling. Porous ceramic composites facilitate heat and mass transfer, effectively cooling return air streams. In winter, they can be used to humidify supply air.

5.3.2. Sliding Bearing

A novel motor sliding bearing incorporates low-to-moderate tin content and minimal nickel content, leading to improved adaptability and particle compatibility. These attributes make it ideal for high-speed sliding applications, such as main bearing shells or connecting rod bearing shell. Figure 18 illustrates bearing shells.

5.4. Bio-Medical

5.4.1. Skin Grafting

Chitosan composites, known for their bio-resorbability and porous structure, are used in wound healing applications. They facilitate cell adherence, proliferation, and migration, ensuring enhanced gas permeation, water absorption, and interaction with drugs. The chitosan-based biomaterial matrix is particularly effective for large dressing areas in severe skin damage or urgent recovery during skin grafting.

5.4.2. Orthopedic

Titanium implants, screws, wires, and plates are widely used due to their biocompatibility, mechanical strength, and bone integration. However, graphene and carbon nanotube (CNT) materials are emerging as alternatives due to their ability to absorb biomolecules and proteins, induce osteoblastic differentiation, and enhance osseointegration. These properties also support tissue growth, making them suitable for tissue engineering applications.

5.4.3. Haemodialysis

Cellulose acetate-carbon nanotube-graphene oxide (CA/CNT/GO) composite membranes exhibit high protein retention and are applied in tissue regeneration, water-oil purification, heavy metal ion removal, gas separation, and haemodialysi. Figure 17 represents a related apparatus.

5.5. Marine

5.5.1. Podded Propeller

Marine screw propellers experience high loading, vibration, pulsating forces, axial thrust, and centrifugal forces. Conventional propeller materials such as aluminum, stainless cast steel, aluminum bronze, and manganese bronze suffer from corrosion, cavitation, and galvanic cell formation, leading to high maintenance costs. Carbon fiber-reinforced plastic (CFRP) is preferred for its high strength-to-weight ratio, improved fatigue properties, corrosion resistance, and low maintenance requirements. Figure 5 showcases an Azimuth podded propeller used in submarines.

Fig. 5 – Azipod propeller.

Fig. 6 – Effect of Biofouling.

Fig. 7 – Hull of a ship.

5.5.2. Anti-Biofouling

Biofouling, the accumulation of micro- and macro-organisms on submerged surfaces, causes corrosion, structural alteration, increased weight, and drag, leading to higher fuel consumption (up to 40%). Nano-composite coatings applied via electrolytic deposition offer an effective solution, forming biofilm barriers that prevent microbial growth. Figure 6 displays an example of biofouling, where zebra mussels have compromised a marine instrument.

5.5.3. Hull

Marine hulls and structures incorporate polymeric cores and sandwich composite panels with glass or carbon fiber skins. These materials provide lightweight construction, fast production rates, high strength, and durability. Epoxy-based composites with CNTs are widely adopted in the marine industry. Figure 7 illustrates a ship hull.

5.5.4. Marine Structures

Metals, alloys, and composites degrade due to sea water aging. Hybrid composites (GCG_2C) exhibit lower water absorption and higher mechanical retention than plain glass-fiber-reinforced polymer composites (GFRP), with a flexural strength of 462 MPa. These properties make them ideal for ship frames and marine structures.

5.6. Chemical

5.6.1. Radiation-Proof Material

Basalt fibers, resistant to nuclear radiation, are used for transporting and storing radioactive materials. Basalt-based geo-composites serve as protective caps at nuclear waste disposal sites, ensuring long-term containment.

5.6.2. Piping

Compared to steel, basalt fiber-reinforced polymer (BFRP) pipes withstand pressures up to 1000 atm, making them ideal for transporting corrosive chemicals and shaft linings. Basalt-lined pipes (BLP) are commonly used for transporting mining chemicals, such as sodium and potassium chlorides, in abrasive slurry form.

5.6.3. Fuel Cells

Graphene-CNT-Copper nano-composites exhibit high hardness, wear resistance, and excellent electrical and thermal conductivity, making them suitable for heat sink materials and microelectronic devices. Additionally, metal nano-composites serve as electrode materials in fuel cells and hydrogen storage.

III. Conclusion

Composite materials have gained widespread recognition in research and manufacturing industries due to their unique properties, which surpass those of individual constituent materials. Researchers have continuously optimized composite compositions through extensive testing and phase change studies.

To enhance material efficiency, scientists have developed advanced manufacturing techniques that reduce production time and simplify complex fabrication processes. These innovations have resulted in high-performance composites with applications across aerospace, automotive, chemical, and sports industries.

Recently, bio-composites incorporating natural biodegradable materials have emerged as eco-friendly alternatives, offering unprecedented properties and market dominance.

References

[1] D. K. Hale, "The physical properties of composite materials," Journal of Materials Science, vol. 11, no. 11, pp. 2105–2141, 1976.
[2] R. M. Jones, Mechanics of Composite Materials. Boca Raton, FL, USA: CRC Press, 2014.
[3] D. X. Yan, P. G. Ren, H. Pang, Q. Fu, M. B. Yang, and Z. M. Li, "Efficient electromagnetic interference shielding of lightweight graphene/polystyrene composite," Journal of Materials Chemistry, vol. 22, no. 36, pp. 18772–18774, 2012.
[4] M. Sahmaran, V. C. Li, and C. Andrade, "Corrosion resistance performance of steel-reinforced engineered cementitious composite beams," ACI Materials Journal, vol. 105, no. 3, pp. 243–250, 2008.
[5] T. W. Clyne and D. Hull, An Introduction to Composite Materials, 3rd ed. Cambridge, U.K.: Cambridge Univ. Press, 2019.
[6] R. R. Naslain and M. R. Pomeroy, "Ceramic matrix composites: Matrices and processing," in Reference Module in Materials Science and Materials Engineering, 2016, doi: 10.1016/B978-0-12-803581-8.02317-1.
[7] D. Dai and M. Fan, "Wood fibers as reinforcements in natural fiber composites: structure, properties, processing and applications," in Natural Fiber Composites, 2016, pp. 3–65.
[8] H. Ehrlich, D. Janussen, P. Simon, V. V. Bazhenov, N. P. Shapkin, C. Erler, et al., "Nanostructural organization of naturally occurring composites—Part II: Silica-chitin-based biocomposites," Journal of Nanomaterials, vol. 2008, p. 54, 2008.
[9] D. Taylor, "Composites: Brittle fracture in fiber composite materials," in The Theory of Critical Distances, 2007, pp. 141–161.
[10] T. G. Yashas Gowda, M. R. Sanjay, K. Subrahmanya Bhat, P. Madhu, P. Senthamaraikannan, and B. Yogesha, "Polymer matrix-natural fiber composites: An overview," Cogent Engineering, vol. 5, no. 1, 2018, doi: 10.1080/23311916.2018.1446667.
[11] L. F. Nielsen, Composite Materials. Berlin, Germany: Springer, 2005, doi: 10.1007/978-3-540-27680-7.
[12] K. K. Chawla, Composite Materials: Science and Engineering. New York, NY, USA: Springer, 2012.
[13] F. A. Khalid, O. Beffort, U. E. Klotz, B. A. Keller, P. Gasser, and S. Vaucher, "Study of microstructure and interfaces in an aluminium–C60 composite material," Acta Materialia, vol. 51, no. 15, pp. 4575–4582, 2003.
[14] Q. H. Qin, "Introduction to the composite and its toughening mechanisms," in Toughening Mechanisms in Composite Materials, 2015, pp. 1–32.
[15] S. Tsai, Introduction to Composite Materials. New York, NY, USA: Routledge, 2018.
[16] E. J. Barbero, Introduction to Composite Materials Design. Boca Raton, FL, USA: CRC Press, 2017.
[17] D. Kumlutas, I. H. Tavman, and M. T. Coban, "Thermal conductivity of particle filled polyethylene composite materials," Composites Science and Technology, vol. 63, no. 1, pp. 113–117, 2003.
[18] S. S. Wicks, R. G. de Villoria, and B. L. Wardle, "Interlaminar and intralaminar reinforcement of composite laminates with aligned carbon nanotubes," Composites Science and Technology, vol. 70, no. 1, pp. 20–28, 2010.
[19] A. Pardo, M. C. Merino, S. Merino, F. Viejo, M. Carboneras, and R. Arrabal, "Influence of reinforcement proportion and matrix composition on pitting corrosion behaviour of cast aluminium matrix composites (A3xx.x/SiCp)," Corrosion Science, vol. 47, no. 7, pp. 1750–1764, 2005.
[20] R. Teti, "Machining of composite materials," CIRP Annals - Manufacturing Technology, vol. 51, no. 2, pp. 611–634, 2002.
[21] G. Lubin, Handbook of Composites. New York, NY, USA: Springer, 2013.
[22] N. Guo and M. C. Leu, "Additive manufacturing: Technology, applications and research needs," Frontiers of Mechanical Engineering, vol. 8, no. 3, pp. 215–243, 2013.