

Advancements in Polymer Composites: A Lightweight Solution for High-Strength Structures

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Abstract- In this review, we discuss the current state of the art of graphene nanoplatelets (GNPs) in the field of lightweight materials in aerospace, automotive, and automotive industries. The research is focused on enhancing the mechanical and thermal properties of polymer composites, focusing on the use of high-performance polymers (HPPs) as reinforcements. These materials are characterized by a wide range of physical, chemical, and electrical properties. Graphene-based nanocomposite materials are found to be able to improve the mechanical, electrical, and thermal properties of the composites. This review study focuses on the development of lightweight composites for aerospace and automotive applications.

Index Terms- High-performance polymers (HPP), Hybrid aluminum matrix composites (HAMCs), Graphene, Graphene nanoplatelet (GNP), Lightweight structures

1 INTRODUCTION

Polymer composite materials have been created as a better and lightweight substitute for traditional metals-based structures, especially in the manufacturing of automobiles, airplanes, construction, and medical devices [1]. Polymer composites lay down essential solutions for decent solutions as their high stone ratio, durability, and versatility. Polymer composites, which are materials made from a polymer matrix with reinforced fibers or other fillers, have made remarkable progress in mechanical properties, making them suitable for high-strength structural applications [2]. Polymer composites, especially those reinforced with fibers, have proven to be a breakthrough solution, combining a distinct combination of mechanical properties, durability, and versatility. General properties of polymer composites such as high specific stiffness and strength, corrosion resistance, and low temperature.

Fulfilling the increasing demands for strut performance in aerospace, structures, etc., has

motivated the development of new innovative lightweight materials, especially polymer-based composite materials.[3], [4]. The rebuttal comprises specific advantages, like significant mass reduction and improvements in mission performance with cost benefits in maintenance, manufacturing, and research and development. synergetic effects of HPPs and graphene are explored for further improvement of polymer composites in terms of their versatile range from mechanical to electrical and thermal properties. [3].

One important domain of research and development in aerospace technology will concern process innovations for producing advanced matrix materials, reinforcing fibers, and manufacturing techniques in polymer composites, with the goal of enhancing their performance as well as economy.[3], [4]. The development of polymer composites to the need for materials that could withstand extreme conditions while minimizing weight was paramount. Fiber-reinforced polymers (FRPs) created a significant milestone for the conventional strength-weight ratio of materials[5], [6]. Modern developments in manufacturing techniques-such as additive manufacturing or 3D printing-have increased further the realm of polymer composites, with the shell to produce complex geometries and tailor properties, rendering them suitable for most application areas [5], [6].

Polymer composites originally appeared in the hands of the engineers and industrial scientists between the two world wars when the former took on the latter in the pipeline to commercialization. Interestingly, recent technology has found these composites competing on the mainstream industrial side as the thrust is to have materials that can survive the most demanding conditions of service and yet be light [1], [7]. The addition of nanomaterials, like carbon nanotubes and graphene, into polymer matrices has further developed

and tuned the mechanical properties of these composites [7]. Nanocomposite polymer materials hold a promise of enhanced mechanical qualities coupled with reduced weight achieved through nanomaterial incorporation into polymer composites. They are polymeric materials reinforced with nanoscale fillers, termed polymer nanocomposites (PNCs), offering unique characteristics borne out of their interaction with the matrix material (Fu et al., 2019). This unique property allows classifying materials along the types of matrix and reinforcing filling materials like 2D layered, 1D fibrous, and 0D spherically [8]. The incorporation of nanofillers can significantly improve mechanical, thermal, and barrier properties of the resultant composites [8], [9].

One of the major advantages of polymer composites is tailoring them for specific applications. Engineers can optimize the properties of the material for stringent requirements of various industries by selecting the type and orientation of the reinforcing fibres and the polymer matrix [7]. This customization is particularly significant within the aerospace sector, where weight reductions or the fuel efficiency translate directly into improved performance [7].

Based on the condition that single polymer composites mechanical behavior is a consequence of fiber types, matrix substance, and processing techniques. High-strength fibers, such as carbon, aramid, and glass, are added as fillers in polymer matrices to enhance tensile strength or stiffness [5]. The selection of matrix material, whether thermosetting or thermoplastic, is critical in deciding the thermal and chemical stability and overall durability of the composite material.[5], [6].

The introduction of nanomaterials into polymer composites provides further possibilities for achieving improved mechanical properties without compromising lightweight characteristics [10]. Nanocomposites an emerging class of materials consisting of a polymer matrix reinforced with nanoscale fillers are known to possess special properties due to the interaction of the matrix with the filler [10].

The most relevant classification of these materials is on the basis of matrix and filler type: polymer matrix nanocomposites (PMNC), metal matrix nanocomposites (MMNC), and ceramic matrix nanocomposites (CMNC) [10]. The developed PMNCs have drawn particular attention due to their

good thermal, mechanical, and fire-retardant characteristics [10].

Recent research has shown that it is essential to strengthen the interface between fibers and matrix for optimizing the mechanical properties of polymer composites [5], [6]. Surface-treatment advancements and hybrid composites are a start towards the development of better interfacial adhesion and performance enhancement [5], [6].

The establishment of eco-friendly composites has gained momentum in the world as sustainability is gaining importance globally. Sustainable fiber-reinforced polymer (FRP) composites, produced from renewable and bio-degradable sources, have shown promise as an alternative to conventional composites [11]. They are not only environmentally friendly but also display mechanical properties comparable to those of traditional glass or carbon FRP composites [11].

Roars resource, light and cheap natural reinforcement are the jute, flax and hemp. But there is an indirect compromise between the performance of the composite and biodegradability, which is not easy [11].

The concept of life cycle engineering (LCE) is crucial for determining environmental impacts in the lightweight structures [5]. Lightweight structures should be better than the regular structures with regard to environmental impact per functional unit. This is claimed by that because introduction of new materials into a product and all new manufacturing processes usually increases environmental impacts on the raw materials and fabrication stages [5].

Natural fiber-reinforced composites are generally inferior to synthetic fibers in mechanical properties, which is one of the barriers toward their widespread application [11]. Recycling and end-of-life management of lightweight structures are also considerable problems concerning composite materials [12]. Lightweight polymer composites contribute to sustainability initiatives by reducing energy consumption during manufacturing and operation [7]. Given the massive environmental impacts from industries, lightweight materials are viewed as a strategic shift for achieving sustainability goals [7]. Advancements in polymer composites have been a significant leap forward in the material science field, opening up possibilities for the future in developing high-strength yet lightweight structures

that will meet the rigorous requirements of modern engineering challenges. The potential for polymer composites to revolutionize a variety of industries remains vast and exciting as research continues to uncover new possibilities [7]. Future research should develop new materials and manufacturing processes that would increase the performance of lightweight composites while their environmental burden would be reduced (Herrmann et al., 2018). Overcoming these obstacles may be possible with the incorporation of cutting-edge technologies like additive manufacturing and nanotechnology (Sen, 2020).

2 LIGHTWEIGHT MATERIALS

Lightweight structural materials are applicable for most industrial processes. They even allow the construction and manufacture of the current lightweight technologies and structures. [13]. Blanco et al. (2021) say that aerospace and automobile industries have great application of such advanced structural lightweight materials mainly for lightweight component parts of vehicles and aircraft, making them easy on the energy usage and meeting high functional demands [13]. The review focused on light structural materials and multi-materials that could be applied with some manufacturing techniques. The materials that were reviewed are aluminium alloys, titanium alloys, fiber-reinforced plastics, high-performance polymers, and graphene. There are also other materials, such as advanced high-strength steel, ceramic matrix composites, and processing techniques, in this section. Moreover, this material covers historical background and importance and gives formulation, characteristics, and applications of all the materials discussed in the material.

2.1 Novel Matrix Material

Novel matrix materials broaden the horizon of the applications of composites. The matrix material can be reinforced to make polymer composite. According to the researchers, polymer matrix composites could be the solution for the aerospace industry's need for lightweight, high-strength structures [14]. These materials, combined with the excellent properties of polymeric materials, such as epoxy resins and reinforcing fibers, such as carbon, glass, or Kevlar, create composite structures that are strong and stiff [14].

It also presents some crucial facts about the new matrix material. Epoxy resins were the most widely

used aerospace polymer matrix materials for a long time due to their excellent mechanical properties and endurance, but now they are being pushed into research on other matrix materials because of the growing demand for greener and cheaper alternatives [15], [16]. For instance, thermoplastic polymers like polyamides and polyimides have demonstrated promise as cost-effective, recyclable alternatives to thermoset epoxy resins [17].

Some important characteristics offered by these types of emerging matrix materials include better recyclability, much lower processing temperatures, and significantly more damage-tolerant behavior. The new matrix materials open a range of advantages over conventional epoxy-forming matrices, such as superior recyclability, lower processing temperatures, and more damage-enduring behavior, which is particularly relevant to aerospace applications [14]. The scope for the composite material is expanding every year, resulting in the advancement of composites in their processing and manufacturing.

2.2 Titanium alloys

Titanium is a metal used in virtually every aircraft due to its high specific strength (weight-to-strength ratio) at high-temperature performance and ability to withstand corrosion and fracture [18]. The commercially available forms of titanium are commercially pure and alloyed. The alloys are broadly categorized into three groups: alpha, alpha-beta, and beta [19].

The paper mentioned, as well as alpha-beta titanium alloys, will not be put to effective use unless they meet the performance required at the forthcoming century. This would be possible only with more understanding of how such alloys fracture and deform under conditions of cyclic stress [20]. The commercially pure titanium consists of titanium and what are known as impurity elements like iron, nitrogen, hydrogen, and oxygen. With regards to the commercially pure titanium materials, they have several grades, with stronger ones having more O and Fe as compared to weaker elements [19], [21].

It explains that 'titanium alloys have superlative qualities over other metals due to their high specific strength, high stiffness, remarkable fatigue-resisting capacity, very good fracture toughness, extremely high heat resistance, cryogenic embrittlement resistance, and low thermal expansion [20]. It is promising to replace steel and aluminum alloys as engine materials

and airframe structures. Unfortunately, these very promising prospects have been constrained by the exorbitant costs—about eight times more than that of commercial aluminum alloys—as well as the poor manufacturability of titanium alloys [20].

2.3 Aluminium alloys

Aluminum (Al) is the third most prevalent metal in the earth's crust. Characteristics of aluminum are its formability, attraction, particular strength, light weight, and resistance to corrosion. Some alloys of aluminum, such as AA7075, are known to have better strength than that of structural steel, while pure aluminum has a low strength in nature and several different aluminum compounds. Most of the aluminum alloys at lower temperatures retain both strength and ductility, and in some cases, increase them quite noticeably [22]. The summary of the advancements made in recently joining Al alloys, along with references for the industry and research work done in this area and on the weldability of heat-treatable aluminum alloys, found these alloys could be joined effectively using low-heat-input arc welding techniques such as cold metal transfer arc welding or pulsed arc welding [23]. In addition, the same research also proved that friction stir welding (FSW) is promisingly superior to fusion welding when it comes to joining Al alloys. For instance, FSW does not necessarily lead to a loss in joint area strength in solid-solution-hardened Al alloys. Lithium is among the lightest alloying constituents present in aluminum alloys. Aluminum alloys gain strength and reduce weight when lithium (Li) is added. Specific strength (strength/density) and stiffness are significantly increased by applications of synergistic properties combinations. Beryllium (Be) and Lithium (Li) are the two elements that may reduce density while significantly raising the Young's modulus of aluminum alloys [24].

Noble et al. found that lithium could be dissolved in aluminum even up to 14% (4 weight percent) with proper heat treatment, able to get Young's modulus of up to 86 GPa, which is also 30% more than pure Al [24].

Stiffening agents such as ceramic particles or fibers are incorporated for improving the tensile strength, hardness, and fatigue performance of Al-MMCs; thus, they could be applied in high-stress applications such as in aerospace and automotive industries. Mechanical performance of these composites depends on the characteristics, dimensions, and volume content of the

reinforcement and also on processing methods applied, e.g., powder metallurgy or stir casting. As found in the paper, it was revealed that the Al-MMCs would have better heat conductive properties, thus providing potential effectiveness in the heat management of the cellular structure, especially in electronics and engine parts [25].

The research work is focused on assessment of the density and elastic modulus of aluminum alloys (2024 + LiX). According to findings, for every 1% increase in additional lithium, there is about a 6% increase in the modulus of elasticity, while for every 1% increase in additional lithium, there is a 3% drop in alloy density [26]. The same study confirmed that Al-Li alloys are processed in a more environmentally friendly way than any other conventional process. They are able to do such preferentially immense attribute features as strength-to-weight ratio, high capability of fabrication, good workability, ductility, very good thermal conductivity, and corrosion resistance, and also have an attractive and natural finish [23].

This research analyzes hybrid aluminum matrix composites (HAMCs) made of SiC, Al₂O₃, and sugarcane bagasse ash (SCBA) agro-wastes for possible enhancement in mechanical and tribological properties. Results show that these reinforcements can improve wear resistance and orient the properties to specific applications, especially within the narrow environments they operate [27]. Take the mechanical property concern based on observations in previous studies led the authors also to conclude that the literature is limited in use of SCBA and graphite (Gr) with respect to tri- and tetra-hybrid reinforcements, which needs further investigation into their microstructure and performance. It also points to the need for optimization of powder metallurgy processing parameters for the manufacture of components that possess enhanced mechanical properties such as low porosity and high corrosion resistance. Overall, these findings lean towards positive indications for future research on lightweight and high-strength materials [27].

The momentous qualities of aluminum lattice composites (AMCs) incorporate tall quality and modulus of versatility, ductility, solid wear and erosion resistance, tall crawl temperature, great weariness execution, and a low coefficient of development. They are broadly utilized in mechanical technology, high-speed apparatus, turning shafts, car motors, and braking frameworks within the car and aviation

sectors. The microstructure of the strengthening network has to be uniform, with ceramic particles scattered consistently all through [13].

2.4 Fiber Reinforced Polymers

Fiber-reinforced Polymer (FRP) are light and very stiff as compared to the steel-based materials, they make the application much better, more efficient, and more durable in terms of energy costs and fuel economy as far as the rail vehicles are concerned. Fiber orientation in fiber-reinforced composites attains its peak importance at the load direction and is therefore of utmost importance because fiber orientation must be optimally aligned with the load direction. This particular design quality is highly esteemed in the strength-upgrading parts of these sections, like a bogie frame and sleeper section [28]. Replacing conventional wood sleeper crossties with polymer matrix composites has been justified as the latter does not suffer from environmental degradation and also incurs low maintenance costs. The change, therefore, helps in keeping the railway elements intact for a longer duration. The introduction of FRP composites will drastically reduce production costs and maintenance overheads and also assist in fulfilling the rising appetite for high technology in railway vehicles. The paper concludes that, in order to enhance the research and applicability areas of FRP composites, specifically in the railway sector, more efforts must be diverted toward the use of existing FRP composites or else newly dedicated for further adsorption with new applications [28].

The present manufacturing techniques of aerospace lightweight fiber-reinforced polymer (FRP) composites are advancing in smartness as well as efficiency. This review has several manufacturing processes, including but not limited to autoclave, resin transfer molding, additive manufacturing, and so on. It also brought their merits and demerits into shedding light [20].

The paper focused on the use of big data, machine learning, and digital twins to put conditions on the management of manufacturing processes to make them fully automated and cheap [20]. On that, these are focused on intelligent composite structures that are self-sensing and self-healing co-evolutions, drastically increasing aircraft performance and safety. These findings also provide avenues for further studies in this field that seek to address the challenges faced in the development of advanced manufacturing technologies for the FRP composites [20]. High-performance fiber-

reinforced composite materials are attaining more importance in almost every aspect of life than they used to in the past by enhancing the performance of existing traditional materials. These possess a high strength-to-weight ratio, improved toughness, and resistance to corrosion and impact, making them applicable in mechanical and aerospace as well as automotive and biomedical fields [29]. The results demonstrate that quantitative high-performance fibers, such as carbon and aramid fibers, are crucial for enhancing composites' mechanical performance. For instance, carbon fibers offer great stiffness and thermal stability, whereas aramid fibers offer high strength at low weight and strong resistance to impact or abrasion. Given that composite materials can replace metals and metal alloys in some crucial applications, the research highlights the need of selecting the appropriate fiber type and composite processing techniques for improved functional qualities of composite materials. Most significantly, the findings support the necessity of developing and bringing to market such advanced materials in order to meet the growing market's demand [29].

3 HIGH PERFORMANCE POLYMER

High-performance polymer composites are important components in the aerospace, automotive, and construction sectors, with outstanding properties such as high strength-weight ratios, corrosion resistance, and design flexibility. High-performance polymers are high-strength, high-density, and low-density materials that are an excellent choice for a wide range of structural applications in the automotive, aerospace, and construction industries [30], [31]. HPP is different from conventional polymers in terms of mechanical properties and the ability to adapt performance to specific application requirements. The increased use of polymer composites can be attributed to the high resistance and weight ratio, corrosion resistance, and design flexibility[32]. These advanced materials offer lightweight but robust solutions for a wide range of high-performance applications in multiple sectors [15]. The unique properties of polymers, such as tailoring to specific requirements, corrosion resistance and environmental degradation, and the potential to reduce weight, have become increasingly common in various industries requiring high-performance, durable, and lightweight materials [15], [16], [17]. Recent research into high-performance polymer composites has focused on the development of new innovative reinforcement fibers, matrix materials, and manufacturing processes to further enhance the overall

performance, cost-effectiveness, and sustainability of these cutting-edge materials. The choice of reinforced fibers is an essential factor in determining the mechanical, thermal, and physical properties of polymer composites [33].

4 NANOMATERIALS

The persistent pursuit of innovative materials that can meet the growing demand for lightweight but robust structures has driven the rapid development of polymer composites. When incorporated into a polymer matrix, nanomaterials significantly increase the overall strength, rigidity, and durability of the composite (Lua and Jin, 2019). For example, the addition of nanoparticles such as silicon carbonate to nylon 12 has been shown to greatly improve the mechanical properties and increase the strength and thermal resistance of the material, allowing it to be used in more extensive engineering applications (Cantoni et al., 2014; Lua and Jin, 2019). This mechanical and thermal performance improvement is due to the high-performance properties of nanofillers integrated into a polymer matrix with synergy (Lua and Jin, 2019). The concept of nanocomposite technology has been underpinned in recent years, and researchers are exploring the use of various nanomaterials as reinforcements in polymer composites. Polymer composites reinforced with nanomaterials have shown considerable improvements in mechanical, thermal, and physical properties compared to traditional polymer materials (Lua and Jin, 2019; Sharma et al., 2020).

New developments in composite materials have led to the development of nanocomposites that incorporate nanoscale reinforcements such as carbon nanotubes, graphene, or ceramic nanoparticles. These nanomaterials demonstrate the mechanical, thermal, and electrical characteristics of polymer composite materials and are suitable for various applications, including aerospace, transportation, etc [35], [36]. Carbon nanotubes and graphene nanomaterials are used as fillers to improve the mechanical properties of polymer matrices such as strength and stiffness [6].

The potential of carbon nanotubes and graphene-based nanomaterials as high-performance electrodes for supercapacitors to generate and deliver the necessary amount of power. The combination of these two materials gives the advantages of developing an appropriate energy storage solution. The performance of nanomaterials such as CNT/graphene composites is evaluated in different configurations of

electrochemical cells with high-voltage electrolytes. It highlights the performance of these materials in ILs and organic electrolytes that do not combine with ion liquids, supporting the use of ion liquids to improve performance [37]. Nanomaterial-based composites have shown promising results in addressing the limitations of traditional composite materials such as reduced resistance, stiffness, and durability [35], [38].

4.1 Graphene

Graphene's contribution to the mechanical, electrical, and thermal properties of fiber-reinforced polymers is the primary advancement. It works excellently in high-end industrial settings [39]. The introduction and movement from research to industrial-scale manufacture of graphene fiber-reinforced polymer pose supply chain concerns. Smart materials are fiber-reinforced polymer materials that are capable of sensing and responding to structural changes almost instantaneously, which would, for end users, mean reduced maintenance and improved operation security [39]. Within this study was developed a nanocomposite comprising ultrafine 1D LiMn₂O₄ nanorods embedded into 2D graphene oxide sheets via simple hydrothermal processing followed by solid-state reaction, yielding nanorods with diameters ranging from 10 to 50 nm.

Nanocomposites such as these have exhibited a high specific charge capacity of about 130 mAh g⁻¹ at a rate of 0.05 C. Lithium ion release occurred within the voltage range of 3.5 to 4.3 V with respect to Li/Li⁺ [40]. The material showed almost 98% Coulombic efficiency after 100 cycles, indicative of excellent charge-discharge stability. Approximately 87% of the initial charge capacity is retained, proving encouraging for application as long-term batteries. The structural study indicated that the composite's D band is more intense than its G band, indicative of increased disorder in the sp² hybridized carbon atoms due to the interaction with LiMn₂O₄ [40].). It was possible to produce graphene by combustion synthesis, where the properties of the product can be fine-tuned by varying the diluent amount of MgO since it is the parameter that controls the combustion temperature and, consequently, the morphology and crystallinity of the final graphene. The synthesized graphene substrate has a very high theoretical monolayer capacity of 125.2 mg/g for the dye methyl orange (MO). The adsorption data fit well to the Langmuir isotherm model, implying that the adsorption is predominantly monolayer in nature. The research clearly stated that, in water treatment using

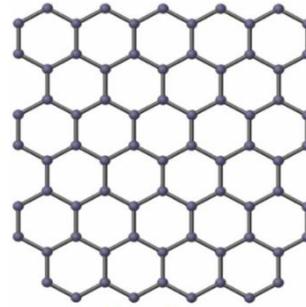
graphene, the method of synthesis by combustion is more effective than that which was used before in water treatment without any possibility of contaminants remaining in the water [41].

Two-dimensional novel materials development will be a promising opportunity for future technology enhancements pertaining to the generation of ultrashort pulses. This development will bring forth further avenues into economic development concerning medical diagnostics and precision engineering. Systematic investigative approaches are thus required in this field to achieve a higher efficiency and a wider range of operation for fiber-coupled laser devices [42].

A controlled vacuum filtration process followed by spark plasma sintering (SPS) permitted the fabrication of very specific types of highly oriented GNP/Cu composites, particularly graphene nanoplatelet (GNP)/Cu composites. The vacuum GNP/Cu composite containing 35 vol% GNPs presented a thermal conductivity (TC) of 525 W/mK, which is 1.5 times greater than that of the pure copper matrix and 99% higher than that of a similar volume fraction of the GNP in a nonvacuum GNP/Cu composite [43]. This tremendous gain in TC was because of the formation of a large-scale GNP network, which was not only highly ordered in its form but also extended to a length that minimized the thermal resistances at the GNP-Cu junction. Quantitative analysis was further carried out to evaluate the degree of orientation of the GNPs, which showed that the V-GNP/Cu composites indeed possessed a higher orientation degree than the NV-GNP/Cu composites. This study demonstrated that the jacket thermal conductivity of the composites could be better improved with this achieved high degree of order (>0.72) plus the minimization of the interfacial thermal resistance. The results indicate that the construction of a moderately dense in-plane graphene network [43].

Graphene powder or suspensions are consumed in hundreds of thousands of square meters of chemical vapor deposition (CVD) graphene over copper substrates as well. It's a great, strong base on which the industrial applications of graphene can be further enhanced; however, this lot of products is in the "infancy" of commercialization, which means there is hope that much more work will be required in relation to potential uses of graphene not needing avant-garde technologies. A complete graphene materials industrial chain is needed. Preparation methods are of great influence on graphene properties and

applications. It establishes the necessary close linkages between production and application sectors in optimizing performance and market visibility. [44].



Graphene

Figure 1 Graphene and graphene oxide

Graphene nanoplatelets have been found to have a reinforcement effect for a uniform grade of magnesium alloy—the ZK60 model. Mg alloy with 0.3 wt.% GNP has shown almost 50% enhancement in yield strength, yielding an efficiency of 250. This clearly indicates that one can use graphene nanoplatelets to greatly enhance the mechanical characteristics of magnesium alloys; they also played a role in grain refinement at the stage of solidification. This is because graphite nanoparticles act as nucleating sites so that small grains are formed within the matrix [45]. It has also been recorded that the grain size decreased from 92 to some minimum value in the composites filled by graphene nanoplatelets, which is an important factor in the enhancement of mechanical properties. The work presents the notion that the interfacial combination in question is very important with regard to graphene nanoplatelets and magnesium matrix. The existence of good interfacial bonding is crucial so that the stress could then get effectively transferred from the matrix to the reinforcement and that the performance of the composite material can improve [45].

Graphene-polypyrrole nanocomposite materials are found to exhibit negative permittivity in a wide frequency range from 1 up to 1000 MHz. The phenomenon results from free electrons in the material and negative permittivity values in the order of about -1.226×10^5 when adding 10 wt% GNs; it could be made possible by electron plasma resonance because of that. The dielectric loss tangent is much better. High GNs loading can lower dielectric loss tangent value to less than 0.32. This indicates increased energy storage and reduced energy loss in the nanocomposites and thus opens their applications wide [46]. It provides evidence on linking the conductivity of the

nanocomposites to their dielectric properties. The dielectric loss tangent is found to be dependent upon the amount of GNs loaded in the polymer, which led these dual-component systems to exhibit negative permittivity. Applications that would have benefited from these unique electric properties and low dielectric loss levels include invisibility cloaks and perfect lenses [46].

Forthcoming research is mainly expected to develop new micromechanical models and subsequently validate these models with the performance of graphene composites. The primary objective is to drive penetrating market sales with the inclusion of research gaps, particularly relevant for products at high volume, for graphene fiber-reinforced polymers. This paper is important to tackle these limits to move on toward using graphene fiber-reinforced polymers in high-performance applications. [39].

4.2 Carbon Nanotubes

Carbon nanotube reinforcements have redone oxygen polymer composites for the high-strength, low-weight constructions in numerous industries [47]. Carbon nanotubes have become substantial reinforcements for polymer composites with excellent mechanical, electrical, and also thermal properties [47], [48].

The incorporation of carbon nanotubes into the polymer matrices has been hot season research. Thus, it will be possible to develop super-strong and super-stiff composites from polymer material [47]. The molecular engineering of the polymer-carbon nanotube interphase is the most important factor in unlocking the full potential of these composite materials [48]. Advances in geometric modeling and finite element analysis now offer deeper comprehension regarding the role of reinforcement materials like Kevlar and carbon fibers in enhancing the mechanical and structural performance of polymer composites [49]. Additionally, some of the recent works have introduced further investigation of shape memory polymer applications for energy dissipation enhancement of fiber-reinforced polymer composites to overcome the inherent brittleness deficits [50]. Their high strength-to-weight ratio, corrosion resistance, and durability have led to increasing use in aerospace, military, transportation, and construction applications of fiber-reinforced polymer composites [50]. The strength of today's state-of-the-art carbon fiber composites continues to be less than 10% of their theoretical value. However, the current research has discovered that the polymer-carbon nanotube

interphase, which is defined as the area where the carbon components interact with the organic environment, including carbon nanotubes, will have a great impact on the mechanical properties of the nanocomposite materials [48]. The molecular engineering of the polymer-CNT interphase is a potential avenue for increasing the mechanical properties of these composites, incidental to the full realization of the promise of carbon nanotubes. Strategies such as pristine or flattened CNTs could be used to improve the binding energy between the polymer and the CNTs, as the CNTs' long length-to-diameter ratio and high surface energy do give rise to strong van der Waals forces and load transfer improvements [51]. It has been recently indicated that conventional fiber-reinforced polymer composites, such as carbon-fiber-reinforced polymer, glass-fiber-reinforced polymer, and aramid-fiber-reinforced polymer, typically show a fairly linear stress-strain behavior up to the point of failure. Subsequently, the termination of such a material property leads to brittleness [52]. We saw great improvement indeed concerning recycling and remanufacturing, which can be regarded as imperative for ensuring sustainable as well as wide acceptance of these materials [52].

The high aspect ratio and rapid broad specific surface, which create strong van der Waals forces between individual nanotubes, lead to an inherent tendency of carbon nanotubes to aggregate (Al Abir et al., 2023; Chen et al., 2018; Pramanik et al., 2018; Zhang et al., 2019). Some of the alternative strategies that have been investigated for the aforementioned problems include in situ polymerization, which consists of synthesizing the polymer in the presence of the carbon nanotubes (CNTs) to allow a more intimate integration between the two components. Different surface modification techniques, both covalent and non-covalent, have also been explored by researchers for the functionalization of carbon nanotubes so as to enhance their dispersion within the polymer matrix [48], [55], [56]. The covalent aspect involves grafting polymers or other organic moieties on the surface of the CNTs, which can greatly enhance the interfacial interactions and load transfer between the CNTs and the polymer matrix [48], [55]. Apart from carbon nanotube incorporation, researchers have also been exploring hybrid reinforcements such as a combination of carbon fibers and carbon nanofilaments as an alternative route to improve the mechanical properties of polymer composites [57]. This may provide a strong

Table 1 Polymer Nanocomposites classifications [59]

CATEGORY	TYPES	DESCRIPTION	EXAMPLES
Morphology	Exfoliated	Individual nanofillers dispersed within the polymer matrix	Graphene-polymer nanocomposites
	Co-continuous	Interpenetrating network of polymer and nanofillers	Polymer-CNT nanocomposites
	0D (Nanoparticles)	Spherical or near-spherical nanofillers	Metal nanoparticles, silica NMs
Nano-filler Dimension	1D (Nanofibers)	Elongated, fiber-like nanofillers	Carbon nanotubes, cellulose nanofibers
	2D (Nanosheets)	Plate-like nanofillers	Graphene, clay platelets
	Glassy	Amorphous polymer matrix with a glass transition temperature (T _g)	Polystyrene-nanoclay composites
Thermal Response	Rubbery	Elastomeric polymer matrix with low T _g	Rubber-nanocarbon black composites
	Semi-crystalline	Partially crystalline polymer matrix with melting point (T _m) and T _g	Polypropylene-talc nanocomposites
	Thermoplastic	Can be melted and re-shaped	Polyethylene-nanoclay composites
Class of Polymers Utilized	Thermosetting	Undergo irreversible curing reaction	Epoxy-graphene nanocomposites
	Biodegradable	Degrade by microorganisms	Polylactic acid-cellulose nanofiber
	Conducting	Have inherent electrical conductivity	Polyaniline-nanotube composites
	Simple Mixing	Mixing directly NMs with Resin	Can be applied for all NMs
Blending methods	In situ polymerization	Nanofillers are formed within the polymer matrix during synthesis	Can be applied for all NMs
	Melt extrusion	Disperses nanofillers into molten polymer	Can be applied for all NMs
	Solution dispersion	Nanofillers are dispersed in a polymer solution before solidification	Can be applied for all NM

mechanical integration where carbon nanofilaments serve as brackets between the individual carbon fibers, allowing better load transfer and thus better improving the mechanical properties of the composite material through direct growth of carbon nanofilaments on the surface of carbon fibers [57]. Moreover, the direct growth of carbon nanofilaments on carbon fibers through a technique like "graphitic structures by design" can be shown as a promising approach. The novelty in this research domain is a new method for increasing the recyclability of composite materials, with particular reference to thermoset types, i.e., engineering the polymer-reinforcement interface at the molecular level [48]. Because of properties such as high stiffness, strength, and low weight, polymer composites have been developed as a viable option for different high-strength structural applications. [15]. Improving dispersion of CNTs in polymer matrixes and enhancing interfacial interaction between polymer and CNT will be two of the primary challenges in developing polymer/CNT composites.

5 Synergistic effects of HPPs and Graphene

By adding additional materials, such as fibers and fillers, to polymer matrices, composite structures can be constructed that have improved mechanical, thermal, and functional properties compared to individual components, called synergistic effects [58].

5.1 Enhanced Mechanical Properties

Combining graphene with HPPs such as PEEK (Polyether Ether Ketone) and Kevlar significantly improves tension, friction and impact resistance. This improvement is due to the excellent load capacity and high aspect ratio of graphite, which allows better stress distribution throughout the composite material. The presence of graphite not only strengthens the polymer matrix, but also helps prevent cracking, which improves the durability and longevity of composite [60].

5.2 Improved Thermal Conductivity

The high thermal conductivity of graphene, combined with HPPs, can reach up to 5000 W/mK, resulting in composites with superior thermal dissipation characteristics. This is particularly useful in applications where overheating is the cause of failure, such as electronics and aerospace components requiring efficient thermal management. The incorporation of graphene promotes improved thermal channels within the polymer matrix, thereby

improving the overall thermal performance of the composite. [60]

5.3 Electrical Conductivity

The addition of graphene to HPPs can add electrical conductivity to otherwise insulated polymers. This transformation is essential for the protection of flexible electronics, sensors and electromagnetic interference (EMI). The conductive pathways of the graphene within the polymer matrix enable efficient charge transport and these composites are suitable for advanced electronic applications [60].

5.4 Barrier Properties

Graphene increases the barrier properties of HPPs and increases resistance to gas and moisture permeation. This improvement is essential for packaging materials and protective coatings, which are crucial to maintaining the integrity of the content. The addition of graphene creates a more difficult path for molecules to penetrate, thus reducing the permeation rate and improving the overall barrier performance of composites [60], [61].

5.5 Lightweight and High Strength

The synergistic effect of the combination of graphite and HPP produces lightweight and strong materials. This feature is particularly beneficial in automotive and aerospace industries where reducing weight without compromising strength is vital to improving fuel efficiency and performance. The high strength-weight ratio of the graphene reinforced composite allows the design of lighter components capable of withstanding high stresses. [60], [62].

6 TECHNOLOGIES IN LIGHTWEIGHT STRUCTURES

Limitations encountered in the production of supercapacitors, such as liquid collection, carbon nanotubes/graphene electrode compression, and reduction of supercapacitor resistance, are summarized. For example, chemical vaporisation (CVD) and exfoliation techniques have been used to increase the production of CNT and graphite and their role in industrial production. The role of cleaning methods focuses on eliminating heavy metals and oxygen-containing groups affecting the performance of supercapacitors. Lastly, although the development and application of carbon nanotubes and graphite nanocomposites is underway, more engineering and

optimization work is needed to make them useful for the market's supercapacitor products. [37].

Table 2 Summary of overview on New Composite Materials for High-Strength and Lightweight manufacturing

Material	What was done	Outcomes
Graphene Nanoplatelet/Epoxy Nanocomposites	Developed a method for enhancing the mechanical properties of epoxy composites by utilizing functionalized graphene nanoplatelets.	Potential for structural applications that are both high-strength and lightweight.
High Strength Bio Composite for Lightweight Serial Robot Mechanisms	Produced bio-composite prototypes with a variety of compositions and calculated their mechanical properties.	The potential for lightweight serial robot mechanisms is shown by new material.
Sandwich panels reinforced with short fiber with additive Manufacturing	The developed sandwich panels reinforced with short carbon fiber using direct-write additive manufacturing.	Development of mechanically strong and lightweight AM composite components.
Lightweight Anisotropic Composite	Chitosan and hydroxyapatite nanocrystals were combined to create a composite aerogel for thermal insulation and characteristics that prevent flames.	Bio-based composite aerogel for environmentally friendly heating materials.
Nanoparticle reinforced composites	Compression, extrusion, injection, hand layup, resin transfer molding	Composites with nanoparticle filler have better storage and energy efficiency.

7 APPLICATIONS OF LIGHTWEIGHT STRUCTURES

The use of recycled carbon fiber in the manufacture of fiber reinforced plastic composites (CFRPs) through 3D printing can be advantageous, as it reduces both the environmental and economic costs of additive processes, compared to the first use of fiber. The selection of raw materials is a decisive factor in predicting the long-term resistance of CFRPs. The examination revealed that the use of appropriate materials could improve the mechanical performance of the end product [7]. There is a significant lack of understanding of how long CFRP 3D printed components will last. Further research should extend beyond the ductility and flexural properties to other physical mechanical properties. The continuous fiber placement method faces challenges due to the need to develop new algorithms to promote the correct fiber placement, which is the key to improving the strength of CFRP printed in 3D. The manuscript describes problems that affect CFRP sheets, such as fiber failure and microcracks, which may damage their long-term performance. It was proposed that recycled fibers can produce more affordable and power-efficient products, and this should be the focus of future weaving [7].

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importance for their use in the aerospace industry, as well as the fact that they can be used in some very high weight reductions in structural applications in future [63].

Table 3 Common Nanofillers in Polymer Nanocomposites and their applications in Industry[59]

NMs	Industry	Application
Ag	Electronics, Healthcare	Biosensors, conductive films, and antimicrobial coatings
Al ₂ O ₃	Automotive, Construction, Aerospace	Building materials, wear-resistant parts, and flame retardants
BaTiO ₃	Electronics, Energy	Capacitors, piezoelectric devices, and energy storage devices
CNTs	Electronics, Automotive, Aerospace	Reinforcing agents for composites, conductive materials, lightweight structures
Graphene	Electronics, Energy, Composites	Transparent electrodes, conductive fillers, and composite reinforcing
SiO ₂	Healthcare, Electronics, Construction	Drug delivery vehicles, coatings that resist scratches, and flame retardants
TiO ₂	Paints & Coatings, Energy, Construction	Photocatalysts for self-cleaning surfaces, pigments, UV protection in coatings
ZrO ₂	Ceramics, Energy, Biomedical	Solid fuel cell electrolytes, biocompatible dental ceramics, and implants
CNFs	Packaging, Automotive, Biomedical	Tissue engineering scaffolds, biodegradable composites, and lightweight materials

8 INNOVATION

In addition to these aspects of matrix materials, the selection of a fibre reinforcement is also very

important for obtaining the desired mechanical properties in polymer composite structures. So far, continuous fibres such as carbon, glass, and Kevlar have been extensively used as a reinforcement. However, the aerospace industry has started to explore



Figure 2 Application of polymer nanocomposites for aerospace applications [66]

novel hybrid fibre architectures with the aim of specific mechanical property optimization for their applications. [14], [16]. Graphene is a nanoscale-carbon with very good features that are suitable for aerospace design. Epoxy has been widely used for that purpose. Epoxy resin is a high-performance thermosetting polymer because of its good mechanical properties. High-performance epoxy resin is being used for structural composites in space industries. Like any other nanofillers, type of epoxy resin also influences the final properties of the resulting nanocomposite. So, the structure of the epoxy resin and the type of crosslinking agent for cure (with the nanofiller type/contents) will also influence the characteristics of the material. The melt method may result in poor dispersion of the graphene nanoparticle and so affect the material properties. High-performance epoxy nanocomposites for enhanced flame resistance, thermal stability, strengthened properties, conductance, a non-flammable aspect, radiation shields, and many other high-performance characteristics [64], [65].

The researchers have also extended their study to the use of bio-based and biodegradable polymers like polylactic acid and polyhydroxyalkanoates as matrix materials. This has been explored to replace petroleum-based polymers that have been associated with environmental concerns [14], [15].

9 CONCLUSIONS

The growth of polymer composites in this world has changed the entire design of lightweight, high-

performance structural applications, allowing engineers and architects to do even more in their aerospace, transportation, civil infrastructure, and beyond. As these innovative materials become even more adapted to the requirements of varying sectors, they will be commonly used.

It has actually encouraged innovations for making designs and developments of high-strength lightweight structures which are expected to be applied into various industries. Lightweight structures obtained extra dimensions with the emergence of polymeric materials and nanocomposites, which are characterized by certain properties and have a broad variety of applications. Research on technologies for manufacturing has shown us how important advanced machining methods and additive manufacturing are to lightweight aircraft structures. These technologies further allow complex parts to be made, and now even entire airplane constructs can be formed in a paradigm shift in the aerospace manufacturing industry, due to precision, efficiency, and design flexibility. A full appraisal was made of two important properties of aerospace materials- structural integrity and durability-considering the ramifications relating to difficult conditions of weather, corrosion, and fatigue. State-of-the-art methods were discovered to counter these scenarios so that lightweight aircraft structures could ensure long-term dependability--from modeling techniques to the use of intelligent materials and nanocomposites. Those developments foreshadowed in our review include smart-and-adaptive reach assets, improved materials synthesis, and multifunctional capabilities investigation. However, these cheap new lightweight materials will continue to shape the future destiny of aerospace engineering only if scalability, production costs, and environmental sustainability issues are resolved.

In the end, this review study delves into the past, present, and future of light materials in aircraft engineering. It documents how their presence has made great differences in the field, considering performance improvement, fuel efficiency, and even overall structural integrity-the indeed be highlighted from historical milestones and state-of-the-art inventions. While it continues to search for lightweight materials, the aerospace industry redefines the paradigm for future air and spacecraft structures as increasingly strong, more sustainable, and lighter than ever before.

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