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Review

Graphene Nanocomposites in Space Sector—Fundamentals and Advancements

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Abstract: Graphene is one of the most significant carbon nanomaterials, with a one-atom-thick two-dimensional nanostructure. Like other nanocarbons, graphene has been used as a polymer reinforcement. This review explores the impact of graphene and graphene-based nanocomposites on aerospace applications. The fabrication and indispensable features of graphene-derived nanocomposites have been considered. Numerous polymers and nanocomposites have been employed for aerospace systems such as reinforced thermosetting/thermoplastic polymers and epoxy/graphene nanocomposites. Moreover, graphene-modified carbon-fiber-based composites have been discussed for the space sector. Aerospace nanocomposites with graphene have been investigated for superior processability, structural features, morphology, heat stability, mechanical properties, flame resistance, electrical/thermal conductivity, radiation protection, and adhesion applications. Subsequently, epoxy and graphene-derived nanocomposites have been explored for heat/mechanically stable aerospace engineering structures, radiation-shielding materials, adhesives, coatings, etc.

Keywords: graphene; epoxy; nanocomposite; fabrication; aerospace; mechanical; thermal

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1. Introduction

Polymer composites/nanocomposites have found potential for aerospace-related technological and engineering areas [1]. In the aeronautical field, fiber-based composite structures were initially applied in space structures [2]. Later research focused on the significance of polymers and nanofiller/additive-based nanocomposites in this sector [3,4]. Accordingly, using nanofillers (instead of macrofillers) remarkably enhanced the durability, fatigue resistance, strength, and toughness properties of aeronautical materials [5]. Moreover, using lightweight nanocomposites in aerospace vehicles has advantages of reducing fuel consumption and improved performance compared to heavy metal space structures [6,7]. Most importantly, carbon nanoparticles such as graphene, carbon nanotubes, and nanodiamond nanofillers have been used to form aerospace nanocomposites [8]. Among carbon nanoparticles, graphene is recognized as an important carbon nanostructure [9]. It has carbon atoms arranged in a honeycomb lattice structure. A graphene nanosheet is one-atom-thick with exceptional structural and physical properties. Polymer/graphene nanocomposites offer fine processability, resilience, frivolity, mechanical stability, thermal conductivity, and electrical conductivity properties [10]. Owing to the remarkable features of graphene and polymer/graphene nanocomposites, their potential applications have been discovered for aerospace [11].

In essence, this advanced review focused on the design, features, and potential of graphene and derived nanomaterials for aerospace. Incidentally, various combinations of polymer/graphene and epoxy/graphene nanocomposites, related fabrication approaches, and possible utilizations were considered. Some previous literature reports were observed on the design and performance of polymer/graphene nanocomposites; however, the reported literature is not updated enough to portray the true current state of polymer/graphene materials and graphene-modified carbon fiber composites for aerospace [12]. Likewise, the previous literature does not depict the main progress in this field during recent years. In this regard, future developments in functional polymer/graphene nanocomposite are not possible for aerospace-related researchers without gaining prior knowledge of the recent relevant literature. Significant literature reports on aerospace-related polymer/graphene nanocomposites have been found between 2015 and 2023, which are now focused on in this overview [13]. To the best of our knowledge, such a specific review on aerospace-related polymer/graphene nanocomposites and graphene-modified carbon fiber composites has not been seen in the literature before with similarly well-arranged interpretations and outlines of the recent literature. Hence, this review portrays scientific developments and advancements in the field of polymer/graphene nanocomposites for aerospace. In a few words, this article offers a groundbreaking review on polymer/graphene nanomaterials in aerospace. Despite the remarkable properties and vast potential of polymer/graphene nanomaterials, devoted future research efforts are desirable to form high-performance nanocomposites to overcome the associated challenges.

2. Graphene

Graphene is a two-dimensional nanosheet made up of sp^2-hybridized carbon atoms [14]. Single-layer graphene was produced and recognized in 2004 by Andre Geim and Konstantin Novoselov [15], although it was theoretically explored by P. R. Wallace in 1947 and experimentally by Hanns-Peter Boehm and his coworkers in 1962. Graphene has been prepared through various approaches such as graphite exfoliation, graphite mechanical cleavage, chemical vapor deposition, laser techniques, and numerous other organic synthesis routes [16]. Graphene has revealed exceptional structural and physical features. First of all, graphene (a one-atom-thick nanosheet) is the thinnest known material [17]. Moreover, graphene has a high electron mobilization of ~200,000 $cm^2V^{-1}s^{-1}$. It also shows a high thermal conductivity of ~3000–5000 W/mK [18]. The significantly high Young's modulus of graphene has been observed as 1 TPa, i.e., 200 times stronger than steel [19]. Owing to van der Waals forces, graphene nanosheets possess a wrinkling tendency, and so can easily crumple [20]. To resolve the nanosheet wrinkling and dispersion issues, graphene has been modified to generate functional groups on the surface [21]. Consequently, graphene has been oxidized to form graphene oxide as a modified form with hydroxyl, epoxide, carbonyl, and carboxylic acid functionalities on the surface. Figure 1 portrays the general structures of graphene nanosheets, whereas Figure 2 displays the structures of graphene oxide. The majority of functional groups in graphene oxide have been found as epoxy and hydroxyl functionalities. Graphene has superior characteristics such as mechanical consistency, thermal stability, chemical stability, and electrical and thermal conductivity [22]. The properties of graphene have been further improved through incorporation in nanocomposites. Due to the unique structure and properties, graphene and graphene-derived nanomaterials have been applied in electronics [23–25], sensors [26], energy devices [27], membranes [28], etc. In addition, the impact of graphene has also been analyzed for aerospace purposes [29].

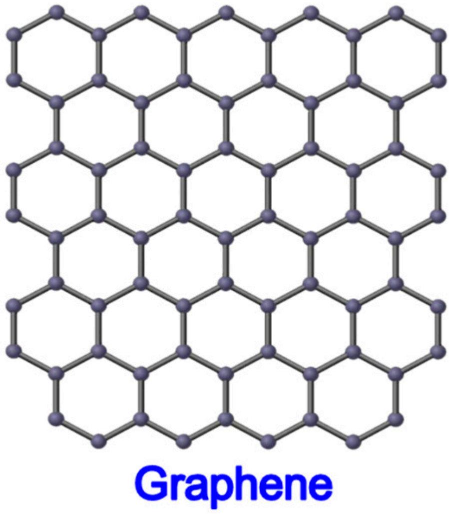

Figure 1. Graphene and graphene oxide.

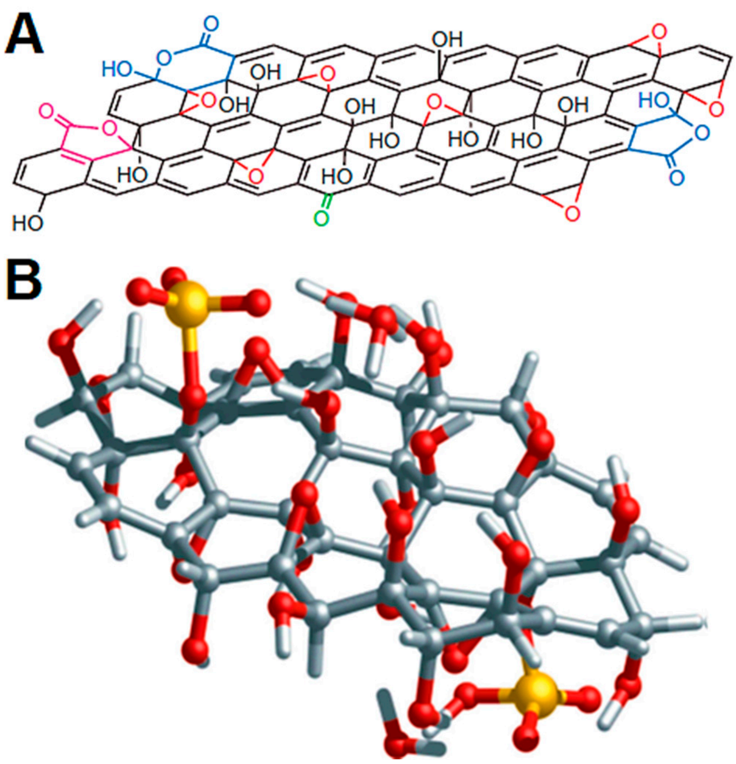

Figure 2. (**A**) Structural model of graphene oxide, taking into account five- and six-membered lactol rings (blue), ester of a tertiary alcohol (purple), hydroxyl (black), epoxy (red), and ketone (green) functionalities. The relative ratios are likely to be 115 (hydroxyl and epoxy): 3 (lactol O–C–O): 63 (graphitic sp2 carbon): 10 (lactol/ester/acid carbonyl): 9 (ketone carbonyl). Reprinted with permission from [30]. 2009, Nature. The model here only shows the chemical connectivity, and not the steric orientation, of these functionalities and (**B**) Structure of graphene oxide with epoxy and hydroxyl as dominant functional groups. Reprinted with permission from [31]. 2013, Wiley.

3. Composite/Nanocomposite Materials Regarding Aerospace

For technical and engineering industries, polymeric composites/nanocomposites have revealed several design and property advantages [32]. Before the application of composites, pristine polymers were used in aerospace structural parts [33,34]. Later, the development of composites and nanocomposites was focused on for aerospace purposes [35]. Compared with unfilled polymers, composite/nanocomposite materials showed better thermal and mechanical properties. In this regard, a number of thermoplastics, thermosets, and rubbery matrices have been applied in the space sector [36,37]. Composites/nanocomposites have the advantage of being lightweight in aerospace, relative to metal-based structures [38]. Using low-density materials also decreased the fuel ingestion of the spacecrafts [39,40]. Moreover, these materials have high strength, modulus, toughness, thermal stability, friction resistance, fatigue performance, and shear resistance characteristics [41–43]. Consequently, the structural durability and working life of aerospace structures have been improved [44–46]. Multifunctional composites/nanocomposites have been found to be valuable in increasing the capability of space structures in bearing shocks and jerks [47,48] and lightning strikes [49], in radiation shielding [50], and as high-temperature stable engine components [51]. In aerospace nanocomposites, carbon nanoparticles (carbon nanotubes, carbon nanofibers, etc.) and inorganic nanoparticles (metal, metal oxide, etc.) have been used as reinforcements [52,53]. In particular, widely used polymer/carbon nanotube nanocomposites have revealed reasonably high heat stability, flame defiance, thermal conductivity, strength, and mechanical stability for aerospace structures [54–56]. Nevertheless, research on aerospace-related composites/nanocomposites is continuously growing, in search of new high-performance structures [57].

4. Graphene in Polymeric Nanocomposites for Space Relevance

Graphene and related nanofillers have effectively increased the electrical conductivity, thermal conductivity, and mechanical features of nanocomposites [58–60]. For aerospace applications, nanocomposites have been investigated for physical property improvements and morphological profiles [61]. Various thermosetting and thermoplastic polymers have been used to form graphene-derived nanocomposites for aerospace structures [62]. Among thermosetting polymers, epoxy resins have been extensively used in aerospace-related applications [63]. Graphene and related nanofillers have been reinforced in epoxy matrices to enhance the essential conducting, thermal, and mechanical properties [64–66]. According to studies, up to 20 wt.% graphene nanofiller contents may increase the high thermal conductivity, toughness, and fatigue resistance properties of epoxy nanocomposites [67–69]. Moreover, graphene oxide nanofiller also improves the tensile strength, fatigue resistance, toughness, heat stability, and tribological properties of epoxy matrices [70,71]. Most importantly, epoxy nanocomposites with graphene and related nanofillers have been used in structural components, adhesives, coatings, etc., for aerospace vehicles [72].

Thermoplastic polymers such as polyethylene, polypropylene, poly(methyl methacrylate), poly(vinyl alcohol), and others have been applied in space applications [73]. Suner and coworkers [74] fabricated polyethylene and graphene-oxide-derived nanocomposites for enhanced mechanical stability. The addition of 0.5 wt.% nanofiller significantly improved the mechanical characteristics of the nanocomposites due to matrix–nanofiller compatibility [75]. Song et al. [76] reported on the polypropylene/graphene nanocomposites fabricated using the solution casting and melt method. The conditions and processes involved in the preparation of polypropylene/graphene nanocomposites are displayed in Figure 3. Graphene oxide was obtained from graphite flakes using the Hummers method [77]. Then, graphene oxide was processed through a solution as well as melt routes to form the nanocomposites. The mechanical properties of the polypropylene/graphene nanocomposites are displayed in Table 1. The inclusion of up to 1 wt.% nanofiller content was found to enhance the yield strength and tensile strength of the nanocomposites due to the mechanical interlocking of the polymer chains with the graphene nanostructure. Moreover, the enhanced mechanical properties were attributed to better graphene dispersion and load transfer between the matrix and the nanofiller [78]. Moreover, the increasing graphene loading was found to improve the crystallinity of the nanocomposite due to orderly nanofiller dispersion and interaction with the polymer matrix [79]. Nanocomposites have been found to be valuable for aerospace applications.

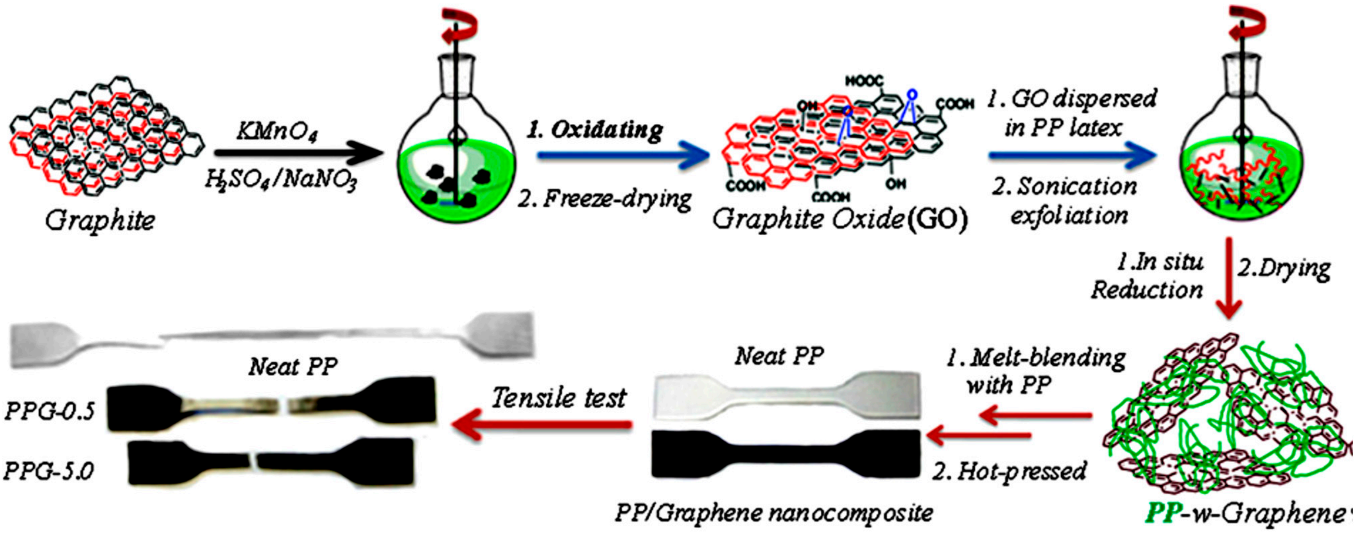

Figure 3. Schematic of polypropylene/graphene nanocomposite fabrication. PP = polypropylene; G = graphene; PPG = polypropylene/graphene. Reprinted with permission from [76]. 2011, Elsevier.

Table 1. Mechanical properties of polypropylene/graphene oxide nanocomposites with various loadings. PP = polypropylene; YS = yield strength; TS = tensile strength; %YS = percent increment of yield strength. Reprinted with permission from [76]. 2011, Elsevier.

Sample	YS (MPa)	TS (MPa)	YS (%)
Neat PP	22 ± 0.8	24 ± 0.8	-
PP + 0.1 wt.% nanofiller	30 ± 1.1	33 ± 1.4	36
PPG + 0.5 wt.% nanofiller	36 ± 1.2	36 ± 1.5	50
PP + 1.0 wt.% nanofiller	38 ± 1.7	37 ± 1.6	75

Huang and coresearchers [80] produced flame-retardant poly(methyl methacrylate) nanocomposites for aerospace. An in situ method was used to develop the nanocomposites [81]. Graphene and layered double hydroxide were added as intumescent flame retardants in the poly(methyl methacrylate) matrix to enhance the flame retardancy of the matrix. The poly(methyl methacrylate) matrix with the 1 wt.% graphene and 5 wt.% layered hydroxide considerably enhanced the nonflammability properties through improving the limiting oxygen index. Xu et al. [82] developed poly(vinyl alcohol)/graphene oxide nanocomposites via the vacuum filtration procedure. As compared to the Young's modulus of the neat poly(vinyl alcohol) matrix (2.1 MPa), the addition of 3 wt.% graphene oxide increased the property up to 4.8 GPa (by 128%). Moreover, including 3 wt.% nanofiller boosted the tensile strength by 110 MPa (70%), as compared to the neat polymer (65 MPa). The increase in the mechanical properties was credited to the interfacial interactions in the matrix–nanofiller, leading to relevance in aerospace. Hence, different polymers reinforced with graphene nanofillers have enhanced mechanical, thermal, and conducting profiles and are found to be useful as aerospace materials.

In the aerospace industry, high-performance matrices such as poly(ether ether ketone) (PEEK) [83,84], poly(ether ketone ketone) (PEKK) [85,86], polyetherimide [87], and polysulfone [88] have been found to be desirable due to high mechanical, thermal, and electrical properties. Puértolas et al. [89] fabricated PEEK/graphene nanocomposites using solvent-free melt-blending and injection-molding techniques. The 1–10 wt.% graphene nanofiller was included in PEEK matrix. The inclusion of graphene caused a 60% improvement in the hardness of the material. The coefficient of friction and the wear factor were decreased by 38% and 83%, respectively. Thus, graphene was found to be an important nanofiller to enhance the surface hardness and tribological properties of the PEEK matrix, desirable for aerospace uses. Alvaredo et al. [90] introduced graphene nanoplatelets in PEEK using the melt-blending technique. The 1–10 wt.% nanofiller was included in the PEEK matrix. The inclusion of graphene nanoplatelets enhanced the complex viscosity and rheological behavior of the nanocomposites and they were found to be effective for the space sector. Wang et al. [91] produced PEKK/graphene nanomaterials with enhanced electrical conductivity and mechanical performance, suitable for high-tech industrial relevance. Sun et al. [92] fabricated high-performance polyetherimide/graphene oxide nanocomposites. The inclusion of graphene oxide nanofiller improved the tensile strength and temperature-dependent tensile behaviors of the polyetherimide/graphene oxide nanocomposites. These materials have fine suitability for the space sector. Ionita et al. [93] developed polysulfone/graphene oxide nanocomposites using the phase inversion technique. The inclusion of 0.25–2 wt.% nanofiller was studied. The homogeneous nanofiller dispersion considerably improved the thermal stability of the nanocomposites. Janire Peña-Bahamonde et al. [94] also prepared polysulfone/graphene oxide nanocomposites through the solvent-free extrusion–injection technique. The addition of 3 wt.% nanofiller upsurged the dispersion, rheological properties, and toughness of the nanocomposites. These materials can be feasible candidates for aerospace applications.

5. Epoxy/Graphene Nanocomposites for Aerospace Applications

Epoxy composites reinforced with carbon or glass fibers have been widely used in the aerospace sector [95–97]. Carbon nanoparticles are a remarkable type of carbonaceous nanomaterial, also known as carbon nanoparticles. To attain improved structural, mechanical, and thermal properties in the epoxy composites, carbon nanoparticles such as carbon nanotubes, graphene, and graphene-derived nanofillers have been reinforced in epoxy resins [98]. In some attempts, fibers have been modified with graphene and used in aerospace materials [99,100]. Modified fillers have been applied to improve the fatigue resistance, fracture toughness, and other mechanical properties of epoxy matrices. Shiu and coworkers [101] fabricated epoxy/graphene nanocomposites with high mechanical robustness properties. Compared with the neat epoxy resins, the glass transition temperature of the epoxy/graphene was also found to be higher [102]. Shadlou et al. [103] also explored epoxy/graphene nanocomposites for enhanced tensile strength and Young's modulus for application in aerospace. A better mechanical performance was observed due to the fine dispersion and compatibility of the nanofiller in the epoxy resin. Bustero and coworkers [104] fabricated epoxy and graphene-nanoplatelet-derived nanocomposites for high-end aerospace applications. The nanocomposite was prepared through the facile hand lay-up technique (Figure 4) [105,106]. Initially, an epoxy resin layer was applied in the mold, which was then coated with the graphene nanoplatelet layer. After that, again, an epoxy resin layer was applied to form the layered nanocomposite, which was cured at 120 °C. The thermal stability of the epoxy and graphene nanoplatelet nanocomposites was analyzed using thermogravimetric analysis (Figure 5). The inclusion of graphene nanoplatelets enhanced the thermal stability of the epoxy resins. The highest improvement in the heat stability was observed with the inclusion of 30 wt.% nanofiller in the epoxy resin. The improvement in the thermal stability of the aerospace matrix was attributed to the reinforcement effect of the graphene nanofiller [107].

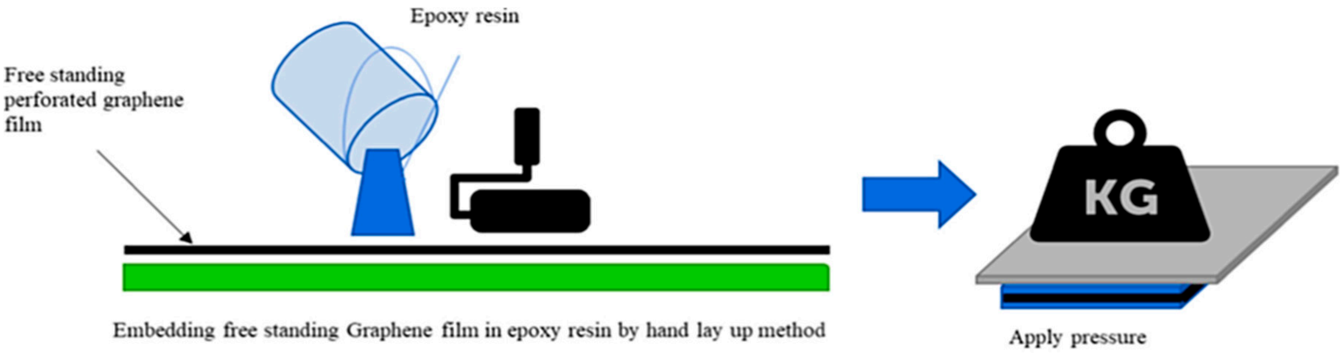

Figure 4. Fabrication process of epoxy/graphene nanocomposite. Reprinted with permission from [104]. 2020, Springer.

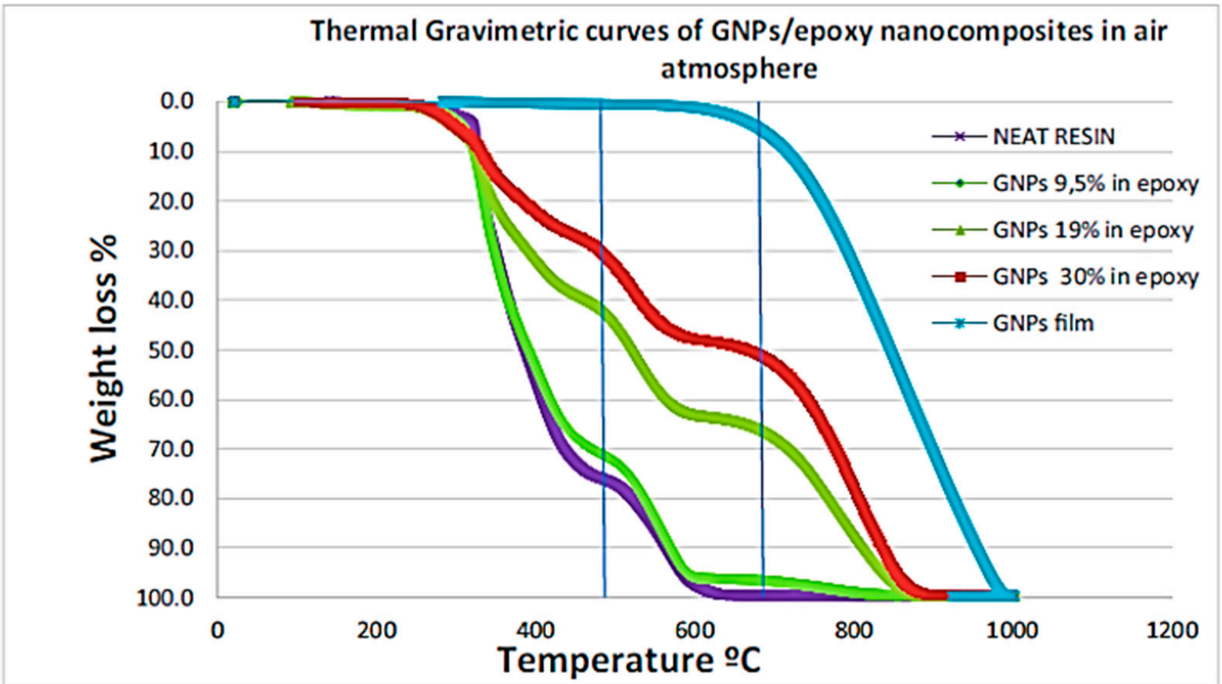

Figure 5. Thermogravimetric curves of graphene nanoplatelets/epoxy (GNPs/epoxy) nanocomposites in air. Reprinted with permission from [104]. 2020, Springer.

García-Martínez et al. [108] developed neat epoxy and epoxy/graphene nanocomposite coatings using the solution route. The coatings were applied on Al 2024-T3 samples and tested for surface properties. To study the hydrophobicity of the neat epoxy and epoxy/graphene nanocomposite coating, the water contact angle was analyzed (Table 2). The epoxy/graphene nanocomposite coating revealed a higher contact angle than the neat epoxy coating due to the enhanced barrier properties. Consequently, the graphene nanofiller enhanced the adhesion properties of the coatings without affecting the curing behavior.

Table 2. Water contact angle values for graphene-filled and unfilled epoxy resin. Reprinted with permission from [108]. 2021, MDPI.

Sample	Contact Angle (Degree)
Unfilled epoxy resin	60.4 ± 1
Epoxy resin/graphene	75.3 ± 1

Graphene oxide has been used as a reinforcement in epoxy matrices for aerospace [109]. The epoxy/graphene oxide nanocomposites possess light weight, high thermal stability, and high mechanical properties relative to neat epoxy resin [110]. In addition, graphene oxide has also been modified to reinforce epoxy resins [111]. Yousefi et al. [112] fabricated epoxy/reduced graphene oxide nanocomposites for the space sector. The epoxy/reduced graphene oxide nanocomposites showed high dielectric properties and a low percolation threshold value of 0.12 vol%. The electromagnetic interference (EMI)-shielding efficiency was found as 38 dB. EMI-shielding epoxy/reduced graphene oxide nanocomposites have found important use in the aerospace sector. Yousefi et al. [113] prepared a waterborne epoxy and reduced-graphene-oxide-based nanocomposite. The set-up for the formation of the reduced graphene oxide and uniformly dispersed nanocomposite is given in Figure 6. In the aligned epoxy and reduced-graphene-oxide-based nanocomposite, covalent bonding occurs between the epoxy and nanofiller. Moreover, π-π stacking interactions exist between bisphenol-A epoxy resin and reduced graphene oxide to enhance the matrix–nanofiller compatibility. The transmission electron microscopy images of the monolayer graphene oxide nanosheet and the epoxy/reduced graphene oxide nanocomposite are given in Figure 7.

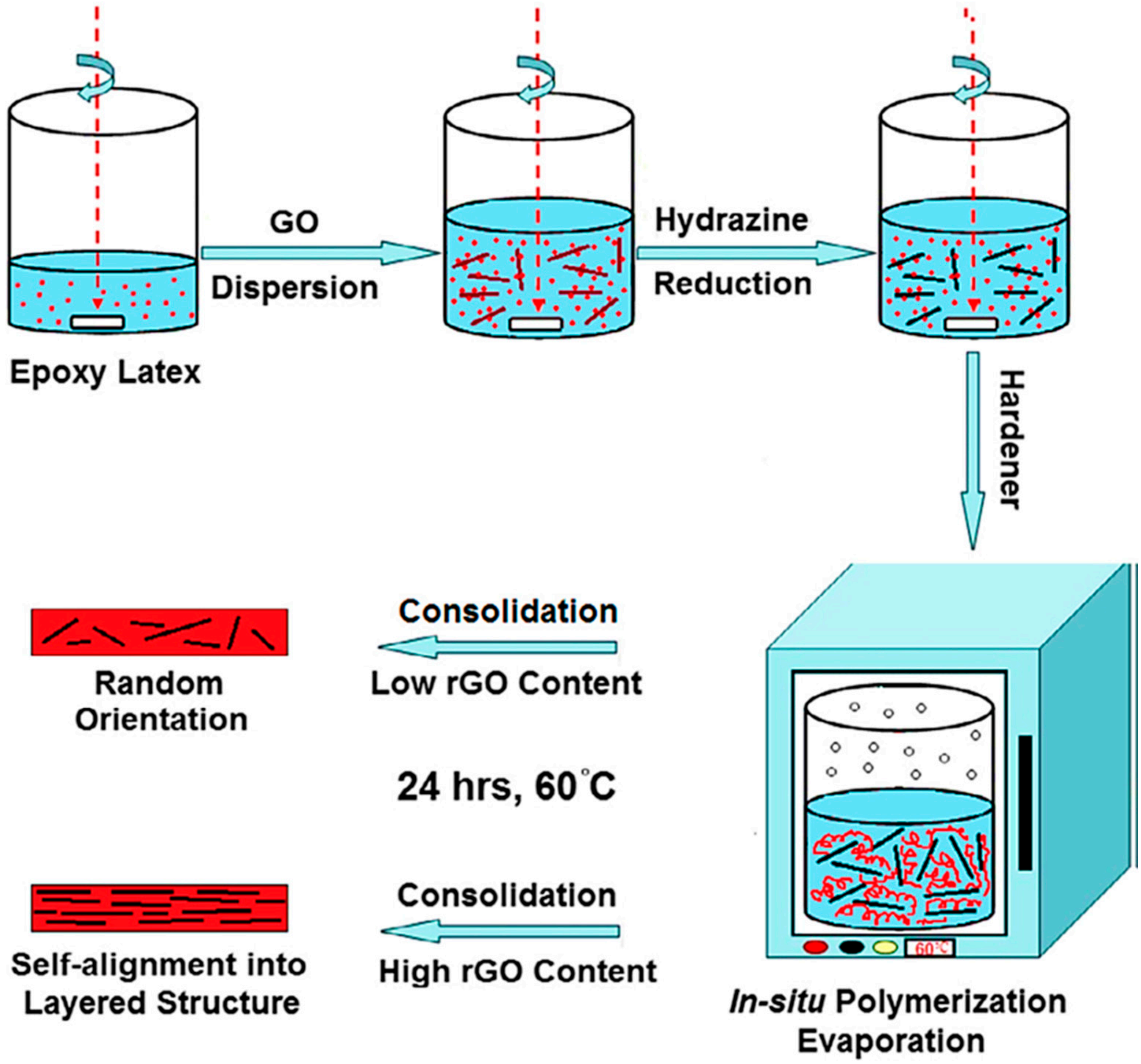

Figure 6. Schematic of nanocomposite preparation. Reprinted with permission from [113]. 2013, Elsevier.

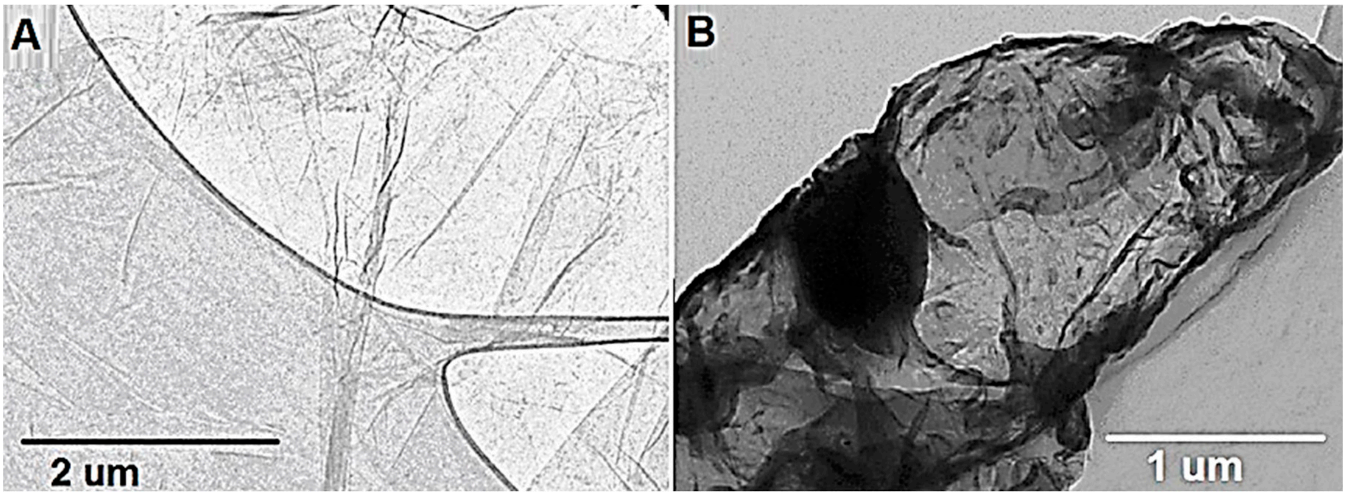

Figure 7. Transmission electron microscopy images of (**A**) monolayer graphene oxide nanosheets; and (**B**) epoxy and reduced graphene oxide nanocomposite. Reprinted with permission from [113]. 2013, Elsevier.

The reduced graphene oxide was produced from graphene oxide and used as a reinforcement in the epoxy resin. In reduced graphene oxide, the elimination of oxygen containing compounds may lead to a higher specific surface area compared with graphene oxide. Moreover, graphene oxide has strong hydrophilic behavior, while reduced graphene oxide has hydrophobic behavior. Consequently, graphene oxide has better dispersibility and colloidal properties compared with reduced graphene oxide. Accordingly, a single graphene oxide nanosheet was found as a homogeneous transparent layer in the micrograph. On the other hand, the reduced graphene oxide nanosheet seemed to be covered with the epoxy matrix. According to the mechanical property analysis, the inclusion of 1.5 wt.% reduced graphene oxide in the epoxy matrix enhanced the strength of the nanocomposite by 500%. The results pointed to fine interfacial adhesion between the epoxy matrix and reduced graphene oxide nanosheets.

Li et al. [114] prepared modified nanofillers of graphene oxide, i.e., 3-aminopropyltrimethoxysilane-functionalized graphene oxide (APTS-GO) and 3-glycidoxypropyltrimethoxysilane-functionalized graphene oxide (GPTS-GO). The APTS-GO and GPTS-GO were used as reinforcements in the epoxy matrix. Figure 8 presents the in situ solution routes to the formation of APTS-GO- and GPTS-GO-based epoxy nanocomposites. The silane coupling agents were capable of grafting to the graphene oxide surface and also developing covalent bonding with the epoxide groups. This led to the formation of well-compatible interface to enhance the mechanical properties of the nanocomposites [115]. Figure 9 shows the fracture surfaces of the APTS-GO- and GPTS-GO-based epoxy nanocomposites. The micrographs revealed the formation of twisting patterns for the APTS-GO and GPTS-GO nanocomposites. As compared with the neat epoxy, changes in morphology were observed for the nanocomposites which suggested energy absorption through the crack propagation mechanism [116]. Consequently, the addition of 0.2 wt.% functional nanofiller significantly improved the fracture toughness and fracture energy to 1.46 $MPam^{1/2}$ and 0.62 kJ/m^2, respectively. Epoxy/graphene nanocomposites have been used as effective adhesives for aluminum or metal substrates in aerospace engineering [117].

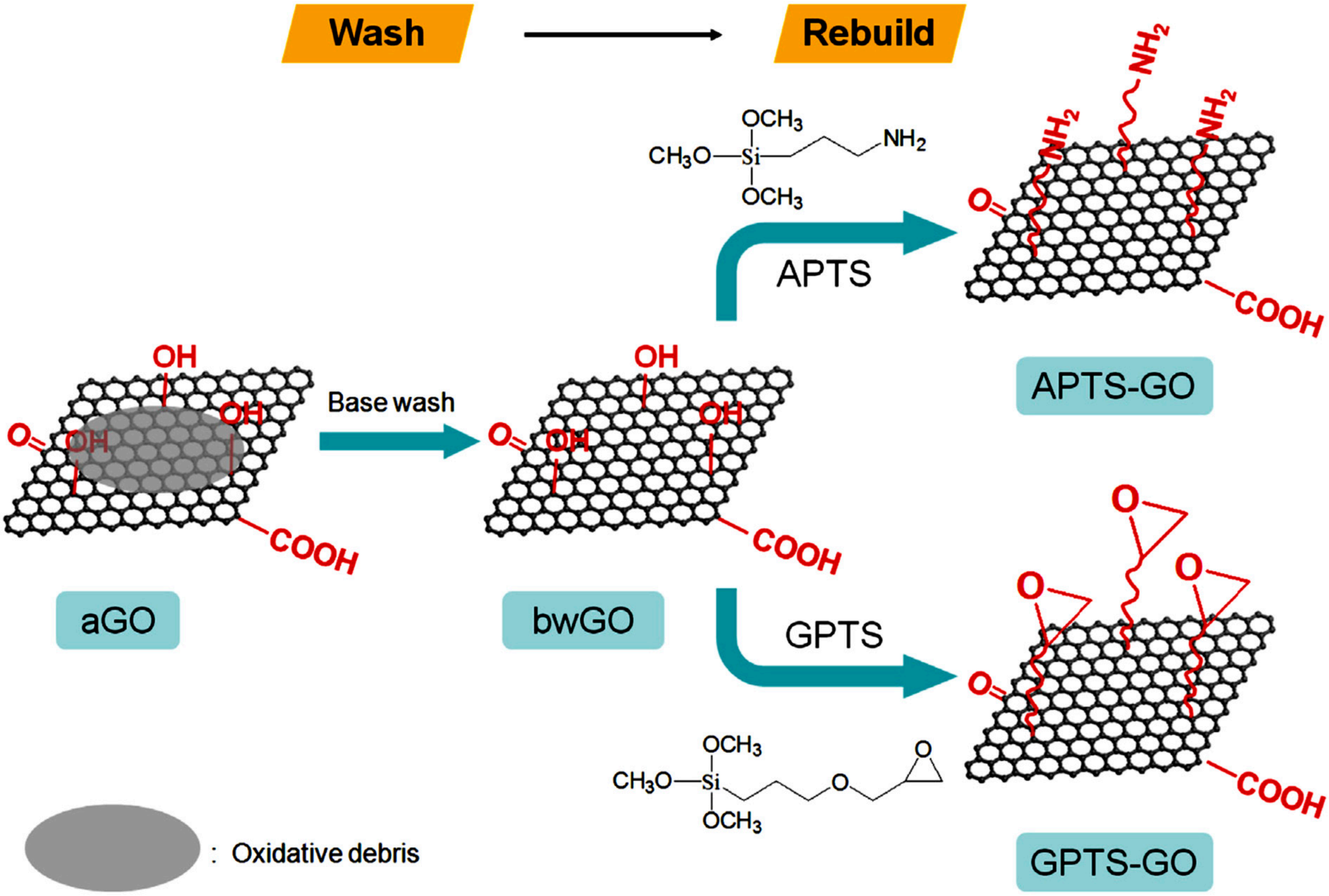

Figure 8. Schematic illustration of the "wash-and-rebuild" process. GO = graphene oxide; APTS = 3-aminopropyltrimethoxysilane; GPTS = 3-glycidoxypropyltrimethoxysilane; APTS-GO = 3-aminopropyltrimethoxysilane-functionalized GO; GPTS-GO = 3-glycidoxypropyltrimethoxysilane-functionalized GO. Reprinted with permission from [114]. 2013, Elsevier.

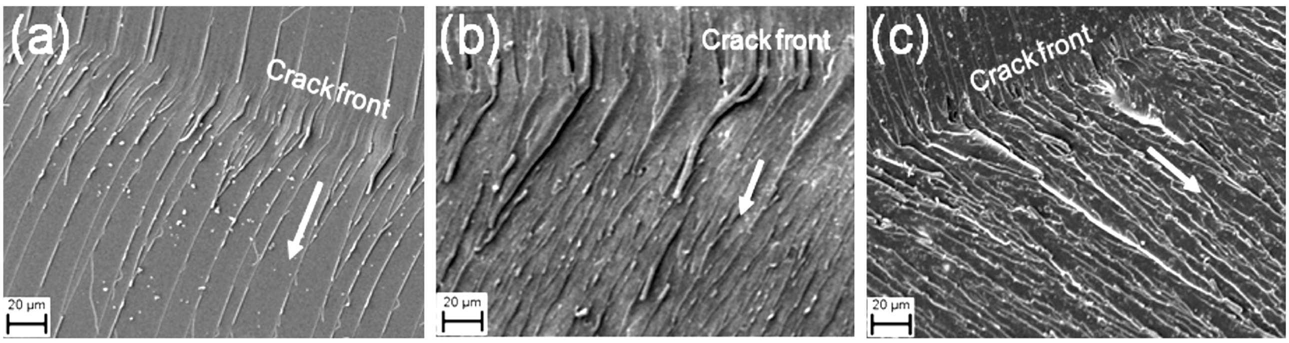

Figure 9. Fracture surfaces of specimens after fracture toughness testing (**a**) neat epoxy; (**b**) 0.2 wt.% APTS-GO/epoxy nanocomposites; and (**c**) 0.2 wt.% GPTS-GO/epoxy nanocomposites. The white arrows indicate the direction for crack propagation. APTS-GO/epoxy = 3-aminopropyltrimethoxysilane-functionalized graphene oxide/epoxide; GPTS-GO/epoxy = 3-glycidoxypropyltrimethoxysilane-functionalized graphene oxide/epoxy. Reprinted with permission from [114]. 2013, Elsevier.

Abdullah and coworkers [118] fabricated epoxy and graphene-oxide-derived nanocomposites through the direct mixing and curing technique. The 1.5 to 6 vol.% nanofiller loading improved the tensile strength and Young's modulus of the nanocomposites. The improvement in mechanical properties was credited to the interface formation between the epoxy and graphene oxide, which enhanced the mechanical properties [119]. Prolongo and coworkers [120] fabricated an epoxy/graphene nanoplatelet nanocomposite and an amine-functional graphene nanoplatelet nanocomposite. The nanomaterials were used as aerospace adhesives. The amine-functional graphene nanoplatelet had an ability to react with the epoxide groups of the epoxy resin to develop covalent linking. The covalently linked epoxy/graphene nanoplatelet nanocomposite was effectively used as an aerospace adhesive to recover the failure surfaces of joints (Figure 10). The nanocomposite showed fine adhesion to the aluminum surface, compared with the neat epoxy resin as well as the nonfunctional graphene nanoplatelet nanomaterial. Accordingly, the epoxy and graphene-nanofiller-derived nanocomposites revealed multifunctional applications in the aerospace sector [121].

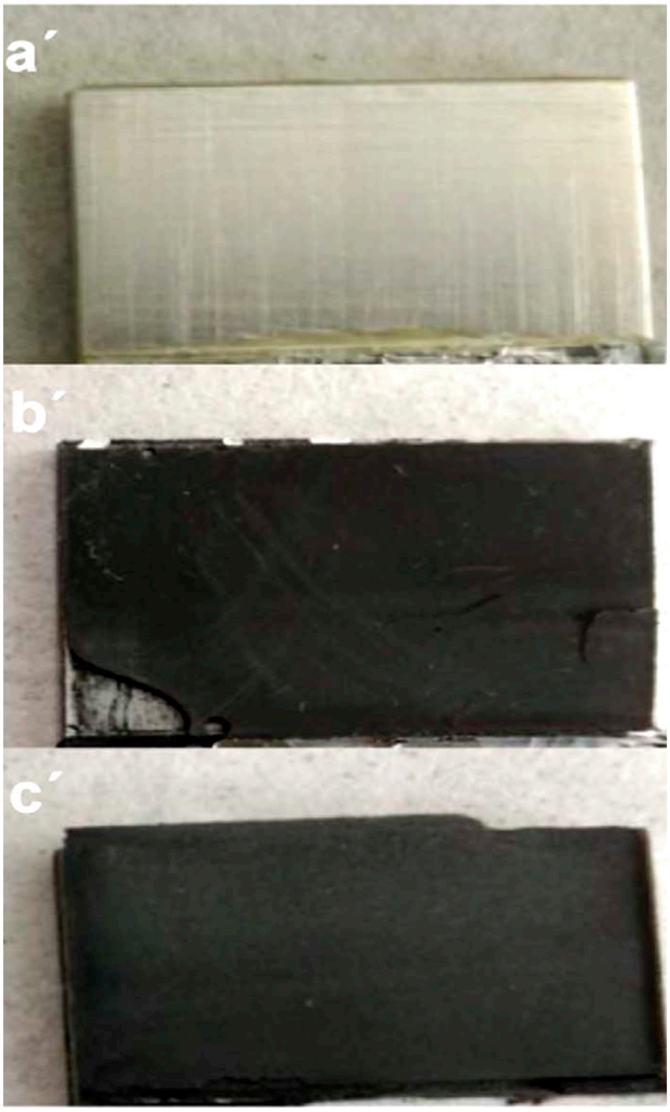

Figure 10. Failure surfaces of epoxy adhesives on aluminum joints: (**a′**) epoxy; (**b′**) 6 wt.% GNP-NH_2; (**c′**) and 6 wt.% GNP. GNP = graphene nanoplatelets; GNP-NH_2 = amine-functionalized graphene. Reprinted with permission from [120]. 2018, Elsevier.

As a consequence, various industrial aspects of using graphene nanomaterials in military space systems, space defense technology, and aerospace engineering have been discovered [122]. Versatile graphene-based fibrous systems have been developed for military space applications [123]. Graphene nanoplatelets have resulted in high electrical, thermal, and mechanical properties which enlarge the application of nanocomposites to space-related military relevance [124]. In this regard, carbon, jute, or glass fibers modified with graphene revealed a high EMI-shielding efficiency > 50 dB. Such materials have been found to be valuable for several military areas including vehicles and personal protective equipment. In space defense applications, high-performance, lightweight, graphene-derived nanomaterials revealed low fuel consumption and offered cost and weight savings [125]. Due to their unique properties, polymer/graphene nanocomposites have been successfully applied for the ballistic protection and lightweight personnel armor [126]. Because of the considerably high strength and Young's modulus of fiber/graphene-derived nanocomposites, relative to conventionally used metallic components, aerospace structures have shown improved longevity and aircrafts have shown improved fuel efficiency. Thus, graphene and its derivatives have found suitability in the materials used for aerospace engineering.

6. Polymers with Graphene-Modified Carbon Fiber for Aerospace

Carbon-fiber-reinforced polymer (CFRP) composites consisting of carbon fibers as reinforcements in the polymer matrices have been used in airplanes, automobiles, trains, ships, and wind turbines [127]. The increasing needs of cost efficiency and ecological strategies have led to the replacement of metallic structures with composite structures in these industries [128]. The mechanical properties of carbon fibers have been considered as key factors for the superior performance of CFRP [129]. Moreover, the high specific surface area, chemical inertness, and high interfacial strength of carbon fibers have been found essential to enhance the characteristics of CFRP [130–132]. The strong interfacial bonding facilitated the stress transfer from the matrix to the carbon fiber, leading to less fiber debonding and pull-out which improve the properties of CFRP [133]. Therefore, a suitably engineered matrix–fiber interface has been found essential to ensure the efficient load transfer the between matrix and the reinforcements to enhance the mechanical behavior of CFRP. For improved properties, carbon fiber modification has been used to improve the compatibility between the fiber and the matrix. The surface modification of carbon fiber has been performed through sizing [134,135], coating [136,137], chemical grafting [138,139], plasma treatments [140,141], and electrophoretic deposition [142,143].

An important surface modification method is the incorporation of secondary nanoscale fillers (e.g., graphene and carbon nanotubes) at the interface between the matrix and fiber [144]. In this regard, the roughening of the carbon fiber surface and direct growth of carbon nanotube has been considered [145]. However, using catalysts and thermally activated mechanochemical modification on the carbon fiber surface may reduce the strength properties [146]. Using graphene for the surface modification of carbon fiber has been found advantageous, since no catalyst is required for the growth of graphene [147]. Graphene and graphene derivatives such as graphene oxide, graphene nanoflakes, etc., have been used to modify carbon fibers [148]. Cui et al. [149] produced carbon fibers coated with graphene and TiAl-alloy-based composites. The powder metallurgy, melt spinning, and vacuum-melting techniques were used to form the aerospace-grade composites. The inclusion of graphene-modified carbon fiber in the TiAl alloy matrix enhanced the strength from 1801 to 2312 MPa. Compared with the neat matrix, the fracture strain of the composites was enhanced by 26.27% and density was decreased for aerospace uses. Zhang et al. [150] formed graphene-oxide-modified carbon fibers for epoxy composites. The carbon fibers were modified through sizing using 5 wt.% graphene oxide. The modified carbon fiber developed a matrix–filler interface to enhance the interfacial properties of epoxy/carbon fiber composites. Significant enhancements in the interfacial shear strength, interlaminar shear strength, and tensile properties of the graphene-oxide-modified carbon-fiber-based composites were attained, compared with the nonmodified CFRP. The enhanced mechanical performance was found useful for the aerospace industry. Karakassides et al. [151] used the one-step microwave plasma technique for the direct growth of graphene nanoflakes on the surface of carbon fiber. The inclusion of graphene-nanoflake-modified carbon fiber improved the tensile strength by 28% and interfacial shear strength by 101.5%, relative to nonmodified CFRP. The cost-effective and lightweight CFRP composites were applied in aerospace structures. Qiu et al. [152] used magnetic graphene-oxide-modified carbon fibers to improve the interfacial properties of CFRP. The Fe_3O_4 functional graphene oxide prevented nanoparticle aggregation and promoted the controlled sizing of the carbon fiber. The magnetic graphene-oxide-modified carbon fibers enhanced the interlaminar shear strength and interfacial shear strength by 56% and 467%, compared to the nonmodified CFRP. The materials were potentially applicable for aerospace structures. Thus, graphene-modified carbon fibers have the potential to improve the interfacial shear strength of epoxy composites by 100%, as demanded for aerospace applications [153]. The effect was observed due to the improved interlocking between the graphene and epoxy matrix. Moreover, graphene-modified carbon fibers have been used to improve the mechanical properties of thermoplastic matrices such as polypropylene and nylon [154]. Modified carbon fibers have enhanced matrix–nanofiller bonding, leading to significant improvements in the tensile and interfacial shear strength of the aerospace composites [155]. Moreover, thermoplastic polymer/graphene-modified carbon fiber composites have enhanced electromagnetic shielding effectiveness for aerospace applications [156].

7. Graphene Nanomaterials and Present Aerospace Industry

The aerospace industry is one of the foremost adopters of advanced composite materials [157]. Graphene is indeed a wonderful material for the aerospace sector. Graphene combines lightness, flexibility, and strength, making it an ideal material for aerospace. Many commercial-level applications of graphene nanomaterials have been discovered. Firstly, graphene, due to its mechanical strength and lightness, has been considered as an excellent candidate for solar sails which may lead to the exploration of star systems [158–160]. In future, sails weighing only a few pounds will be produced while preserving their structural integrity. Secondly, for space lifts, extremely resistant cables have been developed using graphene nanomaterials [161]. In future, such cables will be used to carry ounces of fuel, astronauts, satellites, pieces of space stations, etc., up to thousands of kilometers high. Thirdly, graphene has been used in microgravity to form cooling systems for satellites [162]. In this regard, Italian aerospace company Leonardo, the National Research Council, and the universities of Cambridge and Brussels have performed successful experiments (2017) [163]. Fourthly, the Graphene Flagship has emerged as the largest European research initiative [164,165]. The Graphene Flagship and the European Space Agency performed experiments on the use of graphene in zero-gravity conditions in 2017. The use of graphene was verified in the thermal devices in satellites through a parabolic flight in gravity-free conditions. Then, the European Space Agency (ESA) and Novespace (France) developed graphene-based coatings as heat exchangers and cooling systems in satellites [166].

The applications of graphene are definitely surprising and limitless in the aeronautical field [162]. Graphene has been used to create light and impact-resistant aircrafts and helicopters [167]. Owing to high electrical conductivity, graphene-based deicing systems have been integrated in the wings [168]. Due to the shielding capacity, graphene nanomaterials have been used to build wind farms to prevent disturbance towards radars. Engineers from the University of Central Lancashire (UK) in collaboration with the space industry developed a drone fully coated with graphene. The drone was presented at the Futures Day event at Farnborough Air Show 2018. In addition, graphene nanomaterials are receiving positive feedback in the aeronautical field. Aerospace experts are continuously working to create superlight and resistant space structures.

8. Forthcoming and Conclusions

Polymeric nanocomposites have found potential for different types of aerospace uses [169–171]. Graphene is an imperative nanocarbon with excellent characteristics, suitable for aerospace structures. In this regard, epoxy has been a frequently applied material. Epoxy resin is a high-performance thermosetting polymer with good mechanical properties. It has been widely used in structural composites for space industries. Like nanofillers, the type of epoxy resin also affects the final nanocomposite properties. Consequently, the structure of the epoxy resin and the crosslinking agent used for curing (in addition to the nanofiller type/contents) influence the material characteristics. The melt method may result in poor graphene nanoparticle dispersion, thus affecting the material properties. In particular, epoxy nanocomposites have been designed with superior flame resistance, thermal stability, strength, conductivity, nonflammability, radiation shielding, and other high-performance features [172,173]. Moreover, the choice of fabrication method used for epoxy/graphene also affects the nanocomposite properties. For epoxy/graphene-based nanocomposite coatings and adhesives, the solution, direct mixing, in situ, and melt methods have been used. The solution and in situ routes have resulted in homogeneous nanofiller dispersion, thus leading to better matrix–nanofiller interactions and enhanced physical properties. For the large-scale processing of epoxy/graphene-based structural composites, the lay-up technique has been preferred. This method also involves the dispersion of graphene in an appropriate solvent prior to layering. Furthermore, polymer/graphene nanocomposites must have the capability of bearing lightning strikes, friction, and jerks/shocks. Nanocomposites must have high durability and performance for aerospace structures [174,175]. Incidentally, functional graphene has been used as a filler in polymers to improve the properties desired in space such as high thermal stability, mechanical stability at elevated temperatures, corrosion protection, radiation shielding, etc. Furthermore, graphene-modified carbon fiber composites have been fabricated with significantly enhanced mechanical and radiation-shielding properties for aerospace applications. For space-related graphene nanocomposites and graphene carbon fiber composites, various efficient and reliable characterization techniques have been used. For thermal stability analysis, thermogravimetric analysis and differential scanning calorimetry have been used. The morphology analysis of the fracture surfaces of specimens has been performed with the help of high-resolution scanning/transmission electron microscopic techniques. A number of other characterization techniques for mechanical testing, damage/shock analysis, conductivity measurement, EMI shielding analysis, contact angle measurements, etc., have been applied to study the behavior of the nanomaterials.

The main challenges in designing polymer/graphene nanocomposites involve the uniform dispersion of graphene in the matrix and the scalable production of these materials. Both these challenges can be overcome by the choice of an appropriate processing technique. In this regard, facile and low-cost processing techniques have been preferred. Despite the challenges, polymer/graphene nanomaterials have tunable functional surfaces, a facile processing method, and superior physical properties compared to polymer/carbon nanotube nanocomposites for aerospace structures. Accordingly, homogeneous graphene dispersion has been found to be essential to enhance the foremost aerospace properties. In graphene-modified carbon-fiber-based composites, new fiber sizing and modification techniques need to be developed. The dispersion of graphene on the carbon fiber surface has been found to be essential to enhance the matrix–fiber bonding and the ensuing mechanical features. Subsequently, the resulting polymer/graphene nanocomposites and composites have potential in high-performance aerospace structures including next-generation airplanes, jets, missiles, and space shuttles. Thus, future research must focus on using modified epoxy and functional graphene nanofiller for commercial aerospace applications.

This up-to-date review discusses numerous polymer and graphene-derived nanocomposites within the aerospace field. In addition to thermoplastics, epoxy matrices have been reinforced with graphene nanofiller, resulting in high-performance nanocomposites for the aerospace industry. The main emphasis of this review is on the design and probability of polymer/graphene nanocomposites, especially epoxy/graphene nanocomposites, for aerospace applications. Moreover, a viewpoint on graphene-modified carbon fiber-based composites is presented. Homogeneous graphene dispersion has been found important to enhance space-related material properties. Graphene has also been used to modify the fibers for epoxy reinforcement. In this regard, numerous processing strategies have been used, as discussed in this article. Accordingly, the choice of processing method has been found to be important for enhancing the desired material properties. The resulting high-performance polymer/graphene nanocomposites have been found to be valuable for several space-related industries such as military space systems, space defense technology, and the engineering of aerospace structural parts.

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