Review Article

Aayush Bhat, Sejal Budholiya, Sakthivel Aravind Raj*, Mohamed Thariq Hameed Sultan*, David Hui, Ain Umaira Md Shah, and Syafiqah Nur Azrie Safri

Review on nanocomposites based on aerospace applications

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Abstract: Advanced materials were used and are being implemented in structural, mechanical, and high-end applications. Contemporary materials are used and being implemented in structural, mechanical, and high-end applications. Composites have several major capabilities, some of them being able to resist fatigue, corrosion-resistance, and production of lightweight components with almost no compromise to the reliability, etc. Nanocomposites are a branch of materials within composites, known for their greater mechanical properties than regular composite materials. The use of nanocomposites in the aerospace industry currently faces a research gap, mainly identifying the future scope for application. Most successes in the aerospace industry are because of the use of suitable nanocomposites. This review article highlights the various nanocomposite materials and their properties, manufacturing methods, and their application, with key emphasis on exploiting their advanced and immense mechanical properties in the aerospace industry. Aerospace structures have used around 120,000 materials; herein, nanocomposites such as MgB_2, multi-walled carbon nanotubes, and acrylonitrile butadiene styrene/montmorillonite nanocomposites are discussed, and these highlight properties such as mechanical strength, durability, flame retardancy, chemical resistance, and thermal stability in the aerospace application for lightweight spacecraft structures, coatings against the harsh climate of the space environment, and development of microelectronic subsystems.

Keywords: nanocomposites, aerospace, materials, manufacturing, applications

*** Corresponding author: Sakthivel Aravind Raj,** Department of Manufacturing Engineering, School of Mechanical Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu, 632014, India, e-mail: aravindsakthivel@hotmail.com
*** Corresponding author: Mohamed Thariq Hameed Sultan,** Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor Darul Ehsan, Malaysia; Laboratory of Biocomposite Technology, Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor Darul Ehsan, Malaysia; Aerospace Malaysia Innovation Centre (944751-A), Prime Minister's Department, MIGHT Partnership Hub, Jalan Impact, 63000 Cyberjaya, Selangor Darul Ehsan, Malaysia, e-mail: thariq@upm.edu.my
Aayush Bhat, Sejal Budholiya: Department of Manufacturing Engineering, School of Mechanical Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu, 632014, India
David Hui: Department of Mechanical Engineering, University of New Orleans, Louisiana, United States of America
Ain Umaira Md Shah: Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor Darul Ehsan, Malaysia
Syafiqah Nur Azrie Safri: Laboratory of Biocomposite Technology, Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor Darul Ehsan, Malaysia

1 Introduction

The space environment is distinguished by extreme temperatures, vacuum, micrometeoroids, space debris, and large variations because of sunspot activity. The design and construction of spacecraft and aerospace systems are largely dependent on these parameters. The surfaces exposed to these systems degrade because of the presence of atomic oxygen (AO). Materials that can sustain differences in hundreds of degrees and reduced material erosion yield factor are considered for aerospace applications [1]. Aerospace structures require materials with high strength and stiffness to retain mechanical properties because of high phase temperatures [2]. Initially, it was achieved using composites with a mixture of graphene, with epoxy resin as curing agent, which comprises of various materials with respect to expected outcomes in application areas such as an increase in strength of the base material, increase in temperature resistance, and improvement of tribology behavior of the material. Advanced composites were used in lightweight aircraft structures, fatigue damage, and corrosion resistance [9]. Sensors mounted on light weight carbon and glass fiber composites enabled structural health monitoring (SHM) of aircrafts, which helped understand the wave propagation induced by different loading criteria [16]. An improvement in the tensile load carrying capabilities of woven glass fibers were observed by prestressing them before and during the curing stage of the laminate. Prestressing was found to have improved fiber packing density and reduced crimping, causing significant improvement in performance. Prestressing also led to the fibers being oriented straighter, leading to a better load transfer from the matrix to the fiber [40,41]. A simulation study revealed that the residual stresses induced in the prestressed fiber depended on the elastic modulus of both the matrix and the fiber [48]. Despite these properties of composites, they lacked damage tolerance because of temperature elevations, and it paved the way for nanocomposites [2,3]. The earliest mention of nanocomposite technology was given by Bower in 1940. It consisted of the suspension of nanoparticles into a reinforcement metal matrix material, a combination of Al/SiC and Al/BN. It is a quintessential technology emphasizing lightweight, durability, and inexpensiveness because of abundance in nature. As opposed to copolymers, nanocomposites displayed a higher pyroelectric coefficient (~35% higher). The need for the service life highlights materials with high damage tolerance and reduced density [5]. In aerospace structures, the extreme temperatures and its effects play a major role, mainly in the tribology behavior. The wear and friction resistance were reduced because of the addition of alumina particles. Therefore, the combination of nanocomposite materials such as polytetrafluoroethylene with alumina were used to optimize existing advanced structures [7]. Nanocomposite materials consist of the carbon nanobeads, carbon nanotubes (CNT), multi-walled carbon nanotubes (MWCNT), diamond-like carbon, carbon nanorods, carbon nanocones, and carbon nanofibers. These materials surpass conventional engineering materials in superior properties [8]. The categories of nanocomposite materials that aim at solving pre-existing problems in the aerospace industry include CNTs, MWCNT, and polymer-clay nanocomposites [10,105].

Molybdenum disilicide nanoparticles dispersed in an aluminum matrix were found to exhibit good wear resistance, which is a deciding factor in ensuring that the parts of an aerospace system do not start degrading under long-term usage [14]. High strength materials such as titanium have also been used in nanocomposite systems for high-end aerospace properties. Titanium nanopowders were used as a matrix system reinforced with graphene oxide (GO), which provided a high hardness, which is a primary objective in several structural aerospace components [39]. Laser sintering enabled a fast and flexible technique of dispersing the GO in the matrix. Over the past few years, space exploration gained momentum that lay the foundation for multifunctional materials. The polymer nanocomposites with CNT sheet reinforcement displayed a significant reduction in vibration damping factors. Because of its improved mechanical, electrical, and thermal properties, the MWCNT can be used in aerospace applications [12]. One of the key properties of nanocomposites includes functioning at elevated and sub-zero temperatures, which made them suitable for the extreme conditions of outer space and the lower earth orbit [22]. CNT is the most common type of nanocomposite technology used in aerospace applications. It consists of connector chains formed by deformation and adhesion techniques, and the integration of high-density polyethylene (HDPE) with recycled polyethylene terephthalate (PET) in CNT resulted in maximum load pressure of 24.9 MPa which was useful for advanced structure design [27]. The fabrication of coatings such as Al, Cu/Al, and Cr/Al on advanced structures enhanced the adhesion and thermal resistance [73]. The scope for sustainable development using nanocomposites has fuelled its growth in the aerospace industry [31]. Subsequently, nanocomposites were incorporated in engineering construction which gave enhanced properties for tubular columns in steel structures [77]. The inclusion of nanocomposites in various subsystems in the aerospace industry, mainly the self-healing properties of nanocomposite polymers portray a positive outlook of the nanotechnology industry [72]. The intertwined nature of sustainable impacts and consistent improvement in technology make nanocomposites an ideal technology for aerospace applications. Nanocomposites can be integrated into complex aerospace geometries and reduce the waste generation in manufacturing techniques. This can be used for the design of lightweight and low maintenance fuselage and structures [106]. This review focuses on the following aspects: (i) nanocomposite materials and their properties; (ii) manufacturing methods used for nanocomposite materials; and (iii) growth in aerospace applications, and future scope. The unique combinations of nanocomposites make them ideal for a corrosive environment similar to that of a space environment. The reinforcement and matrix serve to optimize the structure, microelectronics, and impact studies.

2 Material review

Cantor *et al.* studied the different materials used in CNT, with the highest pressure tolerance by the twisted chains of $CdCl_2$, along with the KI chains that adorn the entire

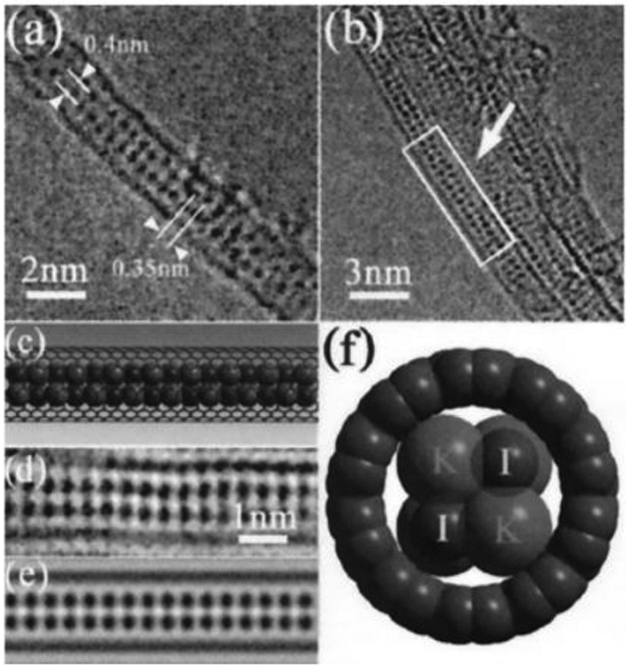

Figure 1: (a and b) High-resolution transmission electron microscopy (TEM) of KI crystal chain; (c–e) model of the atom structure; (f) projection [3].

surface of the atoms. Figure 1 shows the CNT walled structure with a KI crystal chain because of the position of the atoms, and it was used in automotive panels that undergo variation in pressure [3].

Mallick and Zhou [4] investigated the fatigue behavior of polyamide-6 (PA6) nanocomposite and polypropylene (PP) nanocomposite; the stress–strain relationship depicted a nonlinear relationship below the yield strain. Because of the agglomerated nanoparticles, the PP nanocomposite showed a higher ratio of maximum yield strength and fatigue strength. The utilization of zinc oxide nanocomposites with polyvinyl alcohol (PVA) was discussed.

The space environment caused major changes in the microstructure of spacecraft structures. Microstructure studies of two multilayer nanocomposite films, $A1/A1_2O_3$ and Ti/TiN, were performed to understand the influence of microstructural changes caused by nano-indentation on their properties [6]. TEM analysis revealed that the response of the system toward indentation was primarily influenced by the thickness of the metallic layer. A tribological study also revealed a brief reduction in friction caused by the presence of the nanostructured layer of metal. These could potentially be used in satellite structures for prevention against space debris. The material was formed with a combination of 5, 9, 13, and 16% of PVA and ZnO. Aerospace systems were inclusive of damping applications, but the poor thermal properties of viscoelastic and elastomeric were improved using the debonding mechanism of CNTs, with the combination of carbon nanopaper sheets integrated into the matrix [12]. Nanocomposites eliminated factors such as material erosion because of AO, destruction of the surface by micrometeorites, and a reduction in self-contamination because of solar radiation. Because of the pyrolysis mechanism, the energy from the environment vaporized from the ablative materials along with the gas; furthermore, this resulted in the production of char layer which was used as a thermal coating for missiles. Zhang *et al.* further applied graphene and indium-doped tin oxide (ITO) that was used for the prevention against lightning, which was a dielectric medium and reduced conductivity of the composite fuselage [20–22]. Dwivedi *et al.* studied the high-temperature nanocomposite polymers; polyetherimide (PEI) was the matrix for polymeric nanocomposites (PNC) that resulted in improved damage tolerance [26]. These highlighted the use of CNT in fuselage structures. To enhance the protection against photo-degradability, TiO_2 was used with a hybrid clay-like composite that functioned as bio nanocomposites because of segmental low-density polyethylene (LDPE) motions. These provided flame retardancy for re-entry vehicles and structures. It prevented the damage because of AO [28]. Algarin *et al.* used statistical methods to compare the incorporation of NbB_2 and ZrB_2 with aluminum, and converted pellets into wires with improved electrical properties [34]. Farahani *et al.* used two different approaches to integrate nanofillers in nanocomposites to improve electrical properties which are used in protecting aircraft against electromagnetic interference. Figure 2 shows the methods to incorporate nanofillers in nanocomposites [37].

Boostani *et al.* studied powder metallurgy which was used for the fabrication of SiC nanoparticles and graphene nanosheets, the accumulation of which served as thermally active compounds for aerospace applications. Conventional strengthening mechanisms were surpassed by metal matrix nanocomposites because of outstanding mechanical properties such as enhanced tensile elongation mainly for aluminum metal matrix reinforced by ceramic nanoparticles. Furthermore, the addition of nano-ZrO_2 particles reduced the degradation by AO for metal nanocomposites [36–38]. Uddin *et al.* focused on flame retardant nanocomposite coatings suitable for aircraft applications [66]. The Hummers method was used to synthesize the GO, and it was bonded using the layup process followed by the vacuum bagging process. The results of the burn test showed that without the nanocomposite inclusion, the burn length lasted longer. These methods aim at

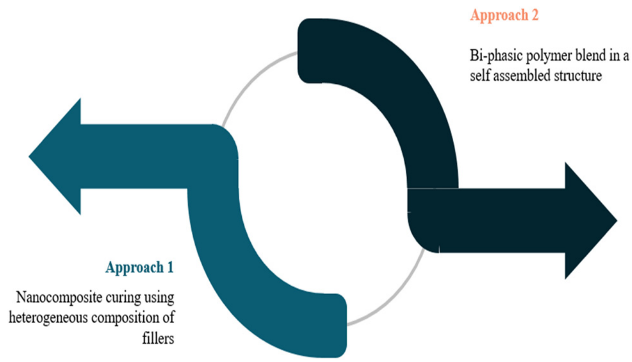

Figure 2: Different processes of combining nanofillers [37].

optimizing existing techniques for the formation of MWCNTs. Wear and hardness studies were performed on copper-alumina nanocomposites [38]. The study concluded that the wear resistance improved by increasing the amount of alumina, with delamination being a possible wear mechanism. The experimentation also concluded that nanocomposites have higher hardness than micro-composites; however, for the same composition, micro-composites were found to have greater resistance to wear. Polymer nanocomposites mixed with acrylonitrile butadiene styrene (ABS) pellets and organically modified montmorillonite (OMMT) powder increased the tensile strength from 49.64 to 64.36 MPa, along with the linear shrinkage [44]. Various filler materials were used in the aerospace industry, and these included calcium carbonate, opacilite, Microdol H600, and Polestar 200P. The mechanical and acoustic analysis showed calcium carbonate as the most optimum material for aerodynamic applications [45]. The strength of Al and Al–Mg wires was improved by introducing pellets of aluminum nanocomposite containing MgB_2 nanoparticles into the melt [33]. Li *et al.* combined the reduced weight and radiation prevention techniques of materials and optimized MWCNT embedded in a polymethyl methacrylate (PMMA) matrix. It emphasized on spacesuit applications because of a 2.4% reduction in neutron generation and 18% reduction in weight [46]. Shin *et al.* experimentally proved the characterization of reinforced AL2024/MWCNT, prolonging the fatigue life and cycle endurance over 2.5×10^6 under 600 MPa applied stress [53]. Tensile strength tests revealed that the inoculated wires possessed greater ultimate tensile strength, in comparison with pure aluminum wires and Al–Mg wires. Purohit *et al.* investigated the tribology of $Al–Al_2O_3$ nanocomposite using the stir casting process, and the wear rate was significantly reduced (~66%) because of the addition of reinforcement [67]. The rapid growth of additive manufacturing (AM) methods revolutionized the aerospace industry, yet the use of fused deposition modeling (FDM) was limited because of reduced strength. The shape memory polymer (SMP) was fabricated using glass pellet copolymers, and it involved the combination of SMP pellets in a dimethylformamide (DMF) solvent, which was combined with the carbon black (CB) and underwent sonication. The fabrication of the nanocomposites was performed using solvent casting with DMF evaporation. SMP nanocomposites have improved toughness capabilities because of the presence of conductive CB, which optimize the electrical stimulus. These could be used in aerospace applications with optimized structures for fabrication of cube-satellites [59]. The ZnO matrix consisted of Co_3O_4 and $ZnCo_2O_4$ phases. The contribution of Co ions remained minimal for the overall magnetism of the nCoO/(1−n)ZnO nanocomposites which reduced interference in the magnetic regions. Markova *et al.* highlighted the importance of intermetallic synthesis of nanoparticles such as Co–Sn, Ni–Sn, and Co–Ni to enhance the material properties, and coatings were used for MWCNT with surface interactions [60]. The ZnO doped nanomaterials were studied, which focused on the magnetometric methods [61]. Because of its combination of non-toxic electrical and thermal properties, polyethylene was used onboard in the International Space Station (ISS) for protection against space radiations, which could result in life-threatening diseases. However, because of its inability to retain excellent mechanical properties, nanocomposites with medium density were proposed. The microstructures were significantly altered because of hydrogen bonding and covalently cross-linked polyimide, and MWCNT is combined with acid and amine which improves thermal and electrical properties [65]. The results of the numerical analysis proved that GO could be used as a reinforcement for multifunctional composites in the space environment. Furthermore, GO along with clay nanocomposites functioned as a heat shield to ensure dissipation of heat [66]. Gao *et al.* used transition metal disulfide that displayed a dense columnar microstructure, which reduced friction and reduced Al content [70]. Venkatesan *et al.* investigated a hybrid composite of glass fiber and CNT. Upon experimentation, it is noted that the coefficient of friction decreases because of an increase in load [69]. Emission of IR and solar absorption was observed during spaceflights, and the combination of polymer resins in an aluminum–titanium–magnesium matrix gave an alternative for the passive thermal coatings. Liu and Wilkinson studied the effects of an aerospace-grade epoxy resin on the fracture characteristics; three methods were used for the formation of the percolated network with as-received MWCNT which had lesser interaction with the resin matrix [71].

The functionally gradient CNTs (FG-CNT) displayed a decrease in buckling load because of the interphase matrix and an increased volume of CNT at the top and bottom surfaces. The equivalent solid fiber which was the FG-CNT in the interphase region enhanced the rigidity of the boundary edges and increased the buckling load at the maximum transverse deflection. Magnetometry was used to study the synthesized TiO_2 and carbon graphitic nanocomposites [76]. Srivastava and Kumar used non-linear engineering methods to study the interphase between Mg matrix and CNT [77]. Gautier *et al.* explored ceramic coatings for aircraft components, AlSiTiN, and AlSiCrN that reduced wear and tear [80]. Addition of epoxy enhanced fire retardancy techniques, by the graphene nanomaterial inclusion as resin, with 3–5% inclusion of graphene [81] Power generation applications were synthesized using the n-type $Bi_2Te_{2.7}Se_{0.3}$, and the addition of selenium dopant resulted in power enhancement in wearable technology [82]. Matei *et al.* highlighted the use of a polymer matrix with nanocomposite materials. Properties such as reduced weight, radiation protection, and coatings are beneficial for space applications. The combination of fillers [ZnO, Y_2O_3] with the nanocomposite materials showed a variety of microstructures and vibration absorption tendencies [83]. The combination of $Yb_2Si_2O_7/Yb_2SiO_5/SiC$ had a self-crack healing material that reacted with SiO_2 to form the reinforcement, and the heat treatment process was used to alter the microstructure that increased strengthening properties [84]. The Ni–Sn and Co–Sn displayed higher surface area than graphite-based and Co–Ni-based nanoparticles. The *in situ* borohydride reduction technique enabled the enhancement of electrical and magnetic properties for intermetallic nanocomposites, which aim to be used in battery systems. Shape memory alloys that change shape because of the presence of soft segments served as the optimum materials for spacecraft during orbit because of the high transition temperatures [87]. The magnetic susceptibility *versus* temperature was compared in temperature ranges less than 20, 20–100, and more than 100 K. These were used to study the static and dynamic responses in structures, for high and sub-zero temperatures. In the Raman spectroscopy technique, CNT composites were integrated into the aerospace composite structures. The development and combination of MWCNT were incorporated with polydimethylsiloxane (PDMS) [89]. Kaiser *et al.* highlighted the importance of high-performance nanostructured materials, the aerospace-grade thermoset materials along with 977-3 epoxy resin and 525-4 BMI resin [90]. Laurenzi *et al.* highlighted the numerical analysis that displayed the arrangement of the atoms in nanomaterial structures. NASA developed a system of studying radiation impact on nanocomposites which investigated the density and energy impact, and the iteration was performed on Kapton, aluminum, PPS where filler performances were analyzed. After the addition of GO fillers, the properties such as loading and shielding from radiation were enhanced [91]. The impact damage caused by micrometeoroid orbital debris (MMOD) was reduced by CNTs and graphite nanoplatelets (GNPs) suspended in an epoxy matrix, and the placement of sensors determined the depth, location, and impact damage because of MMOD. The sensors were fabricated with CNTs, piezoresistivity, and GNPs [92]. Guo *et al.* studied the bond-slip performance between glass fiber reinforced polymer (GFRP) and concrete nano-$CaCO_3$. The bond strength decreased with the increase in nano-$CaCO_3$ and it increased with the GFRP thickness. The aggregate mixture of coarse and fine particles improved the overall compressive strength of the GFRP tube [93]. Platnieks *et al.* characterized the use of sustainable polymers and graphene platelets [94]. The polyurethane (PU) followed a two-step polymer route, and a ratio of 55/45 of the hard material to the soft material was used. Subsequently, the radially grown CNTs had an overall effect on the interfacial stresses, and the multiscale modeling network with the aid of FEA was used to improve the mechanical properties. These were used to overcome the damage mechanisms and improve the shear stress, with the CNT enhanced interphase region. The regions depicted were an amalgamation of layers, polymeric coating along with epoxy resin suspended with the graphene layers, as shown in Figure 3 [95].

With the growth of interphase materials, Laurenzi *et al.* highlighted the need for rapid development in materials that are protected against space radiations [97]. It shifted the electrical conductivity with the increase in crystallinity from 0.5 to 1.0% for the GN phase. The growth of future space exploration was aided by sustainable technologies such as solar power [109]. Figure 4 shows the luminescent solar concentrators with nanocomposite technology, it served as a coating to absorb the solar rays and converted it into energy [101].

An exfoliated nanocomposite structure was fabricated and analyzed using X-ray diffraction [102]. A PA6-OMMT nanocomposite system was fabricated *via in situ* polymerization, and the OMMT interlayer distance was greatly enhanced with the layer exfoliation. The system was found to have good thermal and mechanical properties. A uniform distribution of nanoparticles in the matrix plays a vital role in determining the overall strength of the composite. A homogenous sample of MWCNTs dispersed in epoxy resin was prepared *via* an improved ultrasonic dual mixing

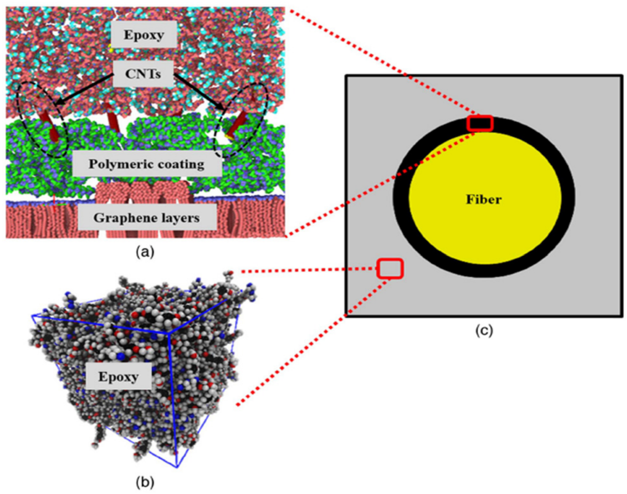

Figure 3: (a) CNT interphase region; (b) epoxy layer; (c) polymer (outer area), fiber (the inner circle), and interphase region (solid line around the fiber) [95].

process [103]. Strong MWCNT–epoxy interphase majorly impacts the properties of the final component. A uniform dispersion revealed a significant improvement in the physical properties of the composite, such as tensile strength and toughness for a minor increase in the quantity of the nanoparticles. The biosynthesis method was used to form the nanocomposite films, the combination of the ZnO/PVA NCs [30]. The electrochemical techniques increased the ZnO content and microstructural analysis confirmed the loading of ZnO which increased the overall efficiency of nanocomposite films [104]. Sanjeev *et al.* provided substantial solutions with the utilization of biopolymers in nanocomposite technology. One of the key properties displayed was the low mass density with electromagnetic shielding. These overcame barriers faced in the aerospace industries, being valuable additions as coatings and materials, and these displayed significant improvements in the mechanical properties, durability, and material characterization which transformed the aerospace industry [110].

3 Manufacturing techniques

Table 1 gives a basic summary of discussed manufacturing techniques in the following section.

Nylon-based nanocomposites were fabricated in 2008, wherein the polymer solution was produced in an organic solvent, followed by the addition of nanoparticles of clay and ultimately vaporizing the solvent [10]. The technique, called solution-induced intercalation, was implemented to fabricate a batch of nylon-6 polymer/clay-based nanocomposite systems. Co-deposition was implemented to suspend nanoparticles of Al_2O_3 in a nickel plating solution [11]. A high-speed plating technique was executed to embed the nanoparticles into the metal matrix and was a cost-effective technique to produce turbine blades for jet engines. Sheet-based nanocomposites were manufactured *via* vacuum-assisted resin transfer molding (VARTM) [12]. The technique involved the application of a suitable resin into a sealed vacuum bag consisting of pre-laid composite fabrics (here, mats of glass fiber and carbon nanopaper sheet in the desired orientations), under vacuum. The final part was tested for its damping properties and was found to have structural applications for its high damping characteristics.

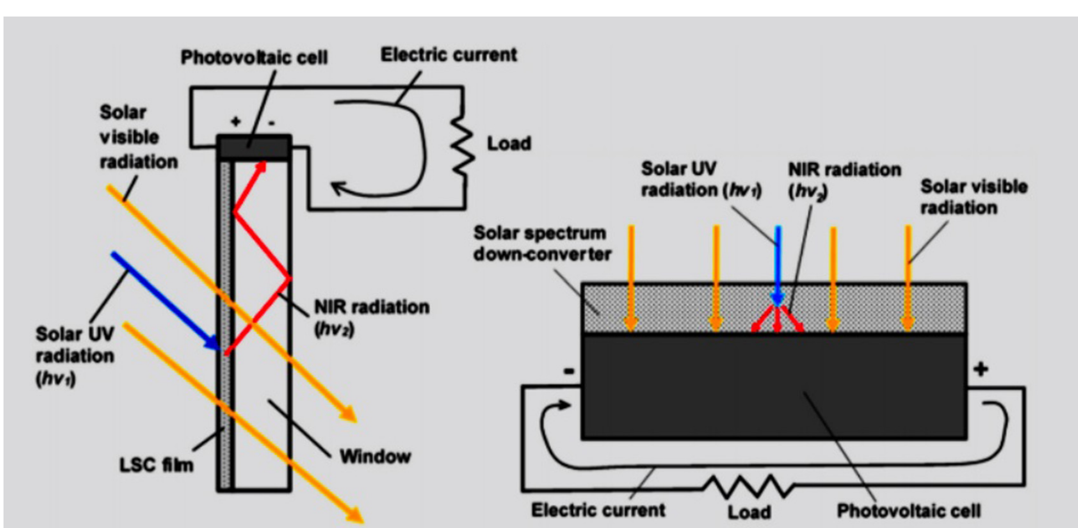

Figure 4: The nanocomposite coating converts near infra-red (NIR) radiation into energy and converts and powers the photovoltaic cell [101].

Table 1: Summary of all discussed manufacturing techniques

S. no.	Manufacturing technique	Brief description
1.	Solution-induced intercalation [10]	Matrix produced in a solvent, nanoparticles added, and the solvent is evaporated
2.	Co-deposition [11]	High-speed plating used to embed nanoparticles into the matrix
3.	Vacuum-assisted resin transfer molding (VARTM) [12]	Composite fiber (carbon or glass fabric) dispersion with matrix, under vacuum
4.	Single screw extrusion [19]	Matrix and reinforcement mixed at high temperatures to form a melt, which is extruded as raw material for other fabrication techniques like injection molding
5.	Spray coating [20]	Pre-mixing of nanoparticles and matrix, followed by spray coating it onto the substrate
6.	Cross-accumulative roll bonding (CARB) [24]	Furnace treatment of matrix and reinforcement, followed by forming, cutting, and bonding the plates using rollers
7.	Melt compounding [25]	Blowing nanoparticles into the matrix at high temperatures
8.	Vibrational casting [26]	Vibration and heat provided simultaneously to better disperse nanoparticles in the matrix
9.	Ball mill fragmentation [34]	Nanoparticles treated in a ball mill, and then extruded out in the form of wires
10.	Melt extrusion [35]	Matrix taken in the form of pellets, mixed with nanoparticles while simultaneously heating and wrapping it around a rotating mandrel
11.	Drop casting [37]	Nanoparticles and epoxy systems blended together in a magnetic mixer, followed by drop-by-drop casting onto the glass slide
12.	Powder metallurgy [38]	Nanoparticles prepared *via* ball milling and injected into the matrix
13.	FDM [44]	Twin screw extruder used to mix the particles with the matrix, extruded as filaments and used as raw material for an FDM system
14.	Compression molding [46]	Melt mixing used to mix the particles and matrix, which was pressed under temperature and pressure
15.	Hot filament chemical vapor deposition (HFCVD) process [47]	Using a tungsten filament as a heating source, the substrate was heated and cooled, followed by deposition of particles on it
16.	Ultrasonic cavitation [51]	Matrix melted in a furnace, nanoparticles added and stirred, and cavitation is used to degass the material and improve microstructure
17.	Flux-assisted liquid state processing [52]	Matrix ingots heated at high temperatures followed by addition of nanoparticles and a flux to improve the particle-matrix blend
18.	Selective laser melting (SLM) [54]	Matrix and nanoparticles blended in a tumbler mixer, and the particles obtained are sintered together to form the nanocomposite
19.	Magnetic field induced alignment [62]	Nanoparticles oriented in a matrix using a low magnetic field
20.	Stir casting [63]	Blend of matrix and reinforcement stirred continuously till mixed well, and poured into a mold
21.	High frequency induction heat sintering [64]	Thermally exfoliated particles were consolidated under temperature and pressure, and sintered
22.	Thin film bonding [66]	Modified hummers method used to fabricate the film, bonded to a vacuum bagged laminate using an adhesive
23.	Dip coating [68]	The material solution prepared by mixing the particles and polymer under ultrasonication, with the cleaned substrate dipped repeatedly into it till coated completely
24.	Pultrusion [69]	The raw material blend prepared by mixing the matrix and nanoparticles, and pulled through a mold to achieve the required shape of the tube
25.	Ultrasonication [78]	Excitation of the suspension setup of the nanoparticles
26.	Vacuum sintering [79]	Powdered particles milled and pressed, and sintered for compaction
27.	Physical vapor deposition (PVD) [80]	Powdered nanoparticles sputtered into atoms and deposited onto the substrate
28.	Melt blending [94]	Dried matrix pellets blended with particles at high temperatures
29.	Spark plasma sintering [32,99]	Powdered particles prepared first using high energy ball milling (HEBM), followed by sintering and cooling
30.	Electrospray deposition (ESD) [100]	Fabric sprayed by a mixture of nanoparticles and a resin, with the resin cured after the completion of the spraying process

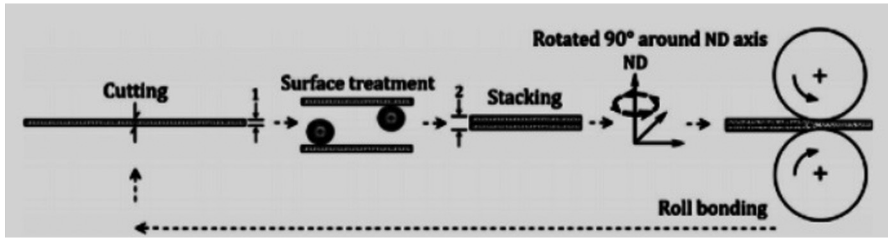

Figure 5: CARB process for fabricating Al–SiC nanocomposites [24].

The implementation of a single screw extruder to manufacture PET/HDPE nanocomposites was researched [19]. The barrel temperature ranged from 200 to 250°C, and the melt released from the extruder was used as the raw material in an injection molding system to form specimens for tensile and flexural tests. Nanocomposite coatings were prepared to be coated on carbon fiber reinforced plastics (CFRP) to analyze the improvement in resistance to lightning strikes, post coating [20]. Calculated quantities of graphene and ITO were added to an epoxy system and were stirred *via* a magnetic bar, followed by spray coating it onto the CFRP. Cross-accumulative roll bonding (CARB) was implemented to fabricate A356 aluminum alloy matrix and SiC nanocomposite [24]. The technique involved furnace treatment of the aluminum alloy followed by the addition of a predetermined quantity of SiC particles. The material was then cast and cut into rectangular samples and annealed. Two cleaned strips of samples were stacked and joined at the ends, followed by roll bonding. Figure 5 depicts the material preparation phase followed by roll bonding.

Melt compounding was approached as a technique to manufacture an LDPE/nano TiO_2-based bio nanocomposite system [25]. The technique involved the addition of TiO_2 nanoparticles as a compatibilizer to an LDPE matrix. The process implements a single screw extruder to blow the nanoparticles prepared onto the surface of the molten polymer at around 175°C. Dwivedi *et al.* [26] investigated the effectiveness of a Vibrational Casting apparatus to process a nanocomposite system consisting of PEI/Cloisite (30B). The system managed to provide vibration and heat simultaneously to melt and stir a mixture of PEI and *N*,*N*-dimethylacetamide (DMA), to which the Cloisite was then added. The DMA was evaporated before the molding cycle as required. The process was quite efficient by virtue of recyclability and recovery of solvent, with the final part possessing good thermal and mechanical properties. Figure 6 indicates the vibrational casting apparatus, consisting of a DC motor and RPM regulator, heating coils, and temperature controller. The technique shows a positive response toward manufacturing aerospace components.

A nanocomposite system composed of aluminum and NbB_2, and ZrB_2 nanoparticles were manufactured *via* ball mill fragmentation [34]. The technique involved the addition of aluminum powder to the nanocomposite particles in a ball mill, where the raw materials were sintered at high temperatures. The material was then used to draw aluminum wires, post-cold forming. The manufacturing technique could hold potential with regard to aerospace applications, especially because of the use of aluminum. A nanocomposite system consisting of a PP matrix, with reinforcement fibers filled with nanoclay, was manufactured using melt extrusion [35]. The process incorporated the implementation of a single screw extruder which was used for heating PP pellets, along with nanoclay particles and a compatibilizer. The fibers were drawn at the end of the heating and mixing process and were wound around a rotating mandrel. Drop casting was executed to prepare a polymer/MWCNTs-based nanocomposite system [37]. Polyethersulfone (PES), which is a high-grade aerospace-based polymer, was mixed with the first resin of an epoxy resin system which was blended in a magnetic mixer at a high temperature. MWCNTs were added to the blended mixture, with constant stirring. The second

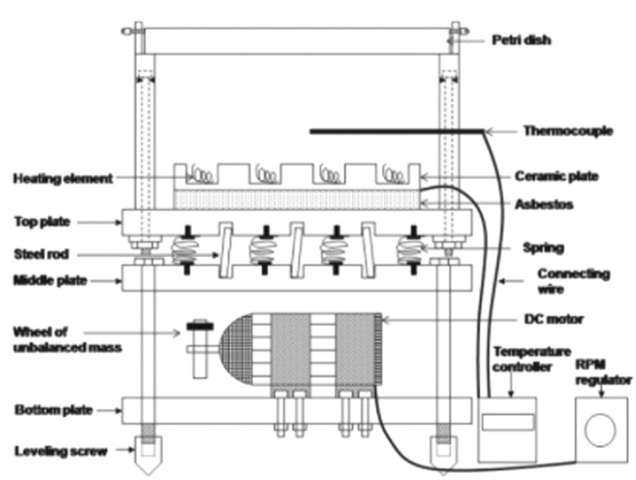

Figure 6: The vibrational casting system developed to process PEI/Cloisite 30B nanocomposites [26].

epoxy resin was subsequently added to the mixture, which was followed by casting the mixture, drop-by-drop onto the glass slide. A graphene nanosheet/SiC-based nanocomposite system was fabricated *via* powder metallurgy [38]. The particle system was prepared by ball milling a calculated amount of graphene nanosheets and SiC, followed by the addition of aluminum powder. The particulate system was then injected into molten A357 aluminum alloy. The WO_2 nanoparticles were deposited onto the substrate. FDM was performed to prepare a sample of ABS/OMMT nanocomposites to test its mechanical and thermal properties [44]. The sample was prepared by first mixing a predetermined ratio of montmorillonite with ABS pellets in a homogenizer, with subsequent mixing in a twin screw extruder. The extrusion led to the formation of filaments of the mixed nanocomposite particles, which were then broken down into pellets for material input into the FDM system. The pellets were melted and then extruded through the nozzle of an FDM printer. A nanocomposite system was fabricated for proton shielding using compression molding [46]. PMMA powders were melt-mixed with MWCNTs, which were then compression molded with PMMA pellets into sheets. A tungsten oxide (WO_2)-glass fiber mat nanocomposite was prepared by hot filament chemical vapor deposition process (HFCVD) process [47]. The technique involved the use of a tungsten filament as the heating source, in a chamber made of stainless steel which was pumped with gaseous argon. The substrate was heated to a required temperature and post-reaction, was cooled down with simultaneous argon gas flow. Ultrasonic cavitation was implemented to prepare A356 alloy matrix and Al_2O_3 nanoparticle composites [51]. The A356 alloy was melted in a furnace, followed by addition of the nanoparticles *via* ultrasonic stirring technology (UST) which enabled a uniform distribution of the particles in the alloy. Scanning electron microscopy also detected the formation of a fine globular microstructure instead of a dendritic one. An aluminum matrix, TiB_2 reinforced nanocomposite system was manufactured using flux-assisted liquid state processing [52]. Aluminum ingots were melted at high temperatures to form the melt, to which TiB_2 nanoparticles along with a flux (here $KAlF_4$) were added and followed by constant stirring. Addition of the flux improved the blending capability of the nanoparticles with the aluminum melt. The process seemed to be capable of industrial production, provided the flux was completely removed from the final nanocomposite. The utilization of aluminum makes the process more likely to be used in avionics. Selective laser melting (SLM) was adopted as a manufacturing technique to fabricate a nanocomposite system consisting of IN718 (a nickel superalloy) as the matrix with TiO_2 as the reinforcement [54]. Before the SLM process, the matrix and the reinforcement were blended in a tumbler mixer to form a raw material system. This raw material was then used as the powdered particles during the SLM process, as observed in Figure 7. With the powder hopper depositing the nanoparticles layer by layer, the lens is used to focus the laser beam to melt powder particles in a layer and the build platform moving downward with each melted layer. IN718 is a versatile material, which when manufactured using AM improves quality and reduces production time, thus having a good perspective in aerospace applications.

A manufacturing technique to prepare a novel nanocomposite system was researched by Huang *et al.* [62]. The process, called magnetic field induced alignment, involved tethering Fe_3O_4 nanoparticles onto the surface of MWCNTs. These particles were then oriented in epoxy resin using a low magnetic field. The process required neither heating at high temperatures nor inert gas protection. Mechanical testing proved the technique to be quite efficient in aligning the MWCNTs in the matrix, thus forming a highly oriented nanocomposite. Aluminum metal matrix nanocomposites (AMMNCs) were manufactured using stir casting [63]. $AlSi_9Cu_3$ alloy was melted at high temperatures, followed by addition of nanoparticles of Al_2O_3 which behaved as the reinforcement. The mixture was stirred till the particles were well blended with it, and the melt was then poured into the mold. The implementation of aluminum reinforcement further establishes a potential for administering this technique in aerospace technology. A promising material for aerospace engine components is an alumina/graphene nanoplatelet system, manufactured using high frequency induction heat sintering [64]. To start off, the graphene platelets were thermally exfoliated and were dipped into nanoparticles of alumina. The sample was then consolidated under

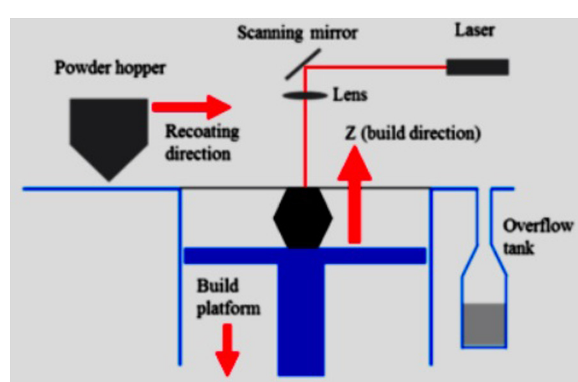

Figure 7: SLM schematic used to fabricate the IN718/TiO_2 nanocomposite system [54].

high temperature and pressure, under vacuum. The temperature of sintering was controlled throughout the procedure. Thermal stability of a GO/laminated composite panel system was assessed by thin-film bonding [66]. The thin film of GO was fabricated *via* modified hummers method, and the laminated panel was fabricated using prepreg vacuum bagging. The bonding surface of the panel was roughened using sand paper to achieve a better bond surface. A suitable adhesive was chosen to bond the surface of the panel to the film, followed by vacuum bagging to ensure consolidation. Another thermal coating for a spacecraft was developed using dip coating [68]. Aluminum alloy was chosen as the substrate, which was de-greased by ultrasonication and cleaned in an alkaline solution. The nanocomposite coating system was prepared by dispersing MWCNTs into a polymer solution under ultrasonication, followed by dispersion in PVA. The substrate was then dipped into the solution, dried, and the process repeated till coated completely. Pultrusion was implemented as a technique to fabricate composite rods using a glass tube mold [69]. The technique involved mixing epoxy resin with a hardener, coupled with the addition of CNTs to this matrix blend. Dry glass fibers were then coated with the matrix and were then pulled through the mold, thus giving them the desired tube shapes. A well-dispersed nanocomposite system consisting of GO and MWCNTs were prepared using ultrasonication [78]. During ultrasonication, the material setup is agitated at high frequencies and the suspension was surrounded by an ice-water bath to prevent excessive heating. Vacuum sintering was implemented to manufacture a nanocomposite system consisting of copper powder and TiB_2 nanoparticles [79]. The two constituents were fixed, mixed together, and were subjected to ball milling, followed by cold isostatic pressing for sample compaction. Post pressing, vacuum sintering in a sintering furnace was performed to sinter the particles together. A final step was to further densify the particles *via* hot extrusion. Physical vapor deposition (PVD) was used to deposit two ceramic coatings, AlSiTiN and AlSiCrN, on the surface of a high-speed steel (HSS) sample to assess the wear resistance provided by the coatings [80]. Spray coating technique was used as a method to manufacture Mylar substrates coated with MWCNTs/epoxy nanocomposites [85]. Epoxy and MWCNTs were sonicated followed by the addition of the curing agent. The mixture was then spray coated onto the mylar substrate. Nanocomposites have a wide range of applications in the aeronautical industry. Solvent exchange and sol–gel techniques were implemented to manufacture a SiO_2 aerogel/TiO_2 nanocomposite system [88]. The aerogel was first manufactured using solvent extraction, followed by the implementation of the sol–gel technique coupled with ultrasonic assistance to manufacture the aerogel-TiO_2 system. It was found that the technique helped the individual constituents of the system to retain their structural characteristics. A nanocomposite system consisting of polybutylene succinate (PBS) and graphene nanoplatelets was fabricated *via* melt blending [94]. The PBS pellets were first dried out in an oven and were then mixed with graphene to be blended at high temperatures. The films of required thicknesses were then fabricated *via* compression molding. Spark plasma sintering (SPS) was adopted as a technique to manufacture an aluminum matrix composite reinforced with graphene nanoparticles [32,99]. The aluminum matrix and GO powders were first prepared using high energy ball milling (HEBM), followed by SPS of the particles and cooling, both in vacuum. The sintering technique holds good prominence in terms of manufacturing aluminum parts for aerospace applications, with the parts manufactured possessing high densities. Electrospray deposition (ESD) was implemented as a method of manufacturing woven carbon fiber (CF), with MWCNTs deposited on its surface [100]. The woven CF was mounted initially on a steel roller, which was then coated with a sonicated MWCNTs and photosensitive resin mixture using a syringe pump. A UV curing lamp was used to cure the resin post spraying. Electro-sprayed CF could be prominent when it comes to fabricating high-end avionic components with improved flexural strengths in comparison with just woven CF–epoxy composite systems. Recent advances in manufacturing techniques have shown great potential in developing high grade nanocomposites. AM techniques enable production of parts with complex material properties and geometries. Powder bed fusion techniques such as SLM help sinter a mixture of powdered particles of matrix and reinforcement to form the required nanocomposite. On the contrary, material extrusion techniques such as FDM use screw extruders to deposit layers of mixed matrix and reinforcement particles on the build platform, and the material hardens on solidification. Such techniques can significantly improve the in-space manufacturing technologies and help develop structural nanocomposites.

4 Applications in the aerospace industry

Nanocomposites have a wide range of applications in the aerospace industry. The temperature and corrosion resistance of an Al_2O_3 nanoparticle/nickel matrix nanocomposites were assessed [11]. Turbine blades of a jet engine coated with the nanocomposite were found to have low grain growth at soaring temperatures and were therefore used as overlay coatings in several aerospace applications. A durable nanocomposite coating for aerospace applications was developed [13]. Conductive CNTs were dispersed in a PU matrix, with a slight increase in the wt% of CNTs causing a crucial improvement in thermal diffusivity. The coating was found to have lower surface resistivity and great flexibility for de-icing applications in the aerospace industry. 10-Dihydro-9-oxa-10-phosphaphenanthrene-10-oxide-based phosphorus tetraglycidyl epoxy nanocomposites were assessed and found to have flame retardant properties, ideal for aerospace applications [15]. Surface erosion caused as a result of ultraviolet radiation was assessed by implementing a nanocomposite system comprising silica nanoparticles in a polymer matrix [17]. The ISS revolves around the earth in the lower earth orbit and is subject to extreme amounts of ultraviolet radiation, which can have erosive consequences. The silica particles were found to reduce the erosive yield of the polymer epoxy caused by the AO and were considered as reliable alternatives to other polymer-based systems. Nanosilica–ethylene propylene diene monomer (EPDM) rubber nanocomposite was used as a thermally resistant material to protect the structural parts of a space vehicle during lift-off [18]. Physical testing revealed the nanocomposite to possess good thermal expansion coefficient and low erosion rate. Nanocomposites were approached as the material to provide protection against lightning, as an alternative to aluminum and copper which tend to undergo galvanic corrosion under certain environmental conditions [20]. An ITO doped graphene and indium coating were developed, with experimental analysis indicating that the nanocomposite coating possessed good electrical conductivity. Figure 8 depicts the impact that a lightning strike can have on a composite reinforced with fibers, in the absence of an electrically conducting outer layer of aluminum.

The use of nanocomposites to replace conventional polymer-based composite materials in a solid rocket motor (SRM) was researched [21]. Thermoplastic PU elastomer nanocomposites (TPUNs) were implemented to replace conventional Kevlar-reinforced EPDM in SRMs to enhance thermal protection. Experimental investigation proved the TPUNs to possess higher compressive strengths in comparison with Kevlar-based EPDM. The material seemed to have a good impact on how well the components were protected from the high temperatures. An aircraft fuselage must be made of conductive material to ensure that lightning strikes can have an uninterrupted flow, without causing any damage to the interior of the aircraft. A shape charge suppression study was performed to assess the charge accumulation in a nanocomposite system composed of SiO_2 nanoparticles and LDPE [23]. It was found that the SiO_2 nanoparticles help suppress the accumulation of charges in the LDPE matrix, but were found to be efficient only at uniform temperatures. The sol–gel materials were studied and analyzed for various shape polymers, and these can be used in high temperature aerospace applications [28]. Nanoclay enabled delay in degradation of dielectric properties by reducing the moisture absorption capabilities, thus helping radomes maintain radar transparency. The addition of nanoclay particles enhances the performance of epoxy matrix in aircraft radomes [29]. The main impacts of weightlessness were intertwined with manufacturing, structure, and mechanical properties. The impact of nanocomposites was analyzed for low-earth orbit applications [36]. It was found that the surface of a structure developed using a ZrO_2/polyimide composite was wrecked because of the AO. However, the addition of nanoparticles of ZrO_2 to polyimide was found to decrease the coefficient of friction, with reduced wear rate. The overall mass of the structure also reduced owing to the light-weight nanoparticles. The nanocomposite system was believed to be prospective tribological material in spacecraft applications. The impact of the addition of nanoparticles of SiC and Al_2O_3 to metal matrix composites (MMCs) to improve the fatigue strength of aerospace components was examined [42]. It was observed that an increase in the percentage of the nanoparticles led to an increase in the fatigue strength of the composite, with the distribution of the grains and their size massively impacting the improved fatigue behavior. The increase in drag and surface contamination of turbine blades of

Figure 8: The damage caused by lightning on an FRP [20].

an aircraft because of insect residue was offset by the use of nanocomposites [43]. A superhydrophobic coating composed of alternating layers of the per-fluoroalkyl methacrylic copolymer (PMC) and SiC nanoparticles was prepared, which was able to resist the accumulation of residues, owing to its hydrophobicity and low surface roughness. The impact of nanocomposites for radiation protection in space-based applications was experimentally analyzed in comparison with conventional lightweight aluminum reinforced composite matrix [46]. MWCNTs were immersed in a PMMA matrix, which proved to possess greater resistance to radiation. The nanocomposite system was significantly lighter than the conventional composite, with enhanced thermal stability, thus showing good potential to be implemented in space-based technology. Nanocomposite films were used to analyze their performance against long-term UV exposure [49]. Graphene-based nanocomposite films were developed and were found to show that with an increase in exposure to UV light, the hydrophobicity of the films increased and showed potential for implementation in enduring space missions. Stretchable sensors were developed using nanocomposites for SHM of morphing aircraft [50]. Strain sensors were developed from PDMS-MWCNTs-based nanocomposite, were found to possess good linearity, and can be used to monitor the occurrences of cracks in aircraft morphing technologies. The high glass transition temperatures (T_g) and flame retardancy of nanocomposite materials were studied for aerospace applications [58]. Functional MWCNTs reinforced polyimide nanocomposites were manufactured and analyzed for thermal behavior. An improvement in T_g of the nanocomposite polymers was found in comparison with pure polyimide, with improved flame retardancy, thereby making them a suitable candidate for aerospace applications. The necessity of heat-resistant components is paramount, especially in spacecraft engines [64]. An alumina ceramic-graphene nanoplatelet-based composed system was tested against monolithic alumina, was found to have high densities and fracture toughness, and was capable of functioning at high temperatures, thus fulfilling the requirement to be used as a material to manufacture specific components of an aircraft engine. The resistance to wear against the harsh conditions of space was analyzed in vacuum [70]. A nanocomposite tungsten disulfide (WS_2)-Al film was fabricated to test its tribological properties against a pure WS_2 film. It was observed that the nanocomposite film possessed greater hardness than the pure film, with brittleness increasing with an increase in the content of aluminum. The nanocomposite was found to have greater wear resistance, with a significant increase in wear life. Because of the harsh space environment, nanocomposite films were used that reduced the surface roughness and prevented the effect of space debris. Materials such as Al, Cu/Al, and Cr/Al were used to compare the adhesive strength. The best adhesion was displayed by polyamide/Cr/Al sample, which was 3.1 GPa. It prevented the surface roughness of more than 20 orders of magnitude [73]. The MWCNTs-EPDM nanocomposite was implemented for its thermal stability [74]. The addition of the nanoparticles to EPDM caused an improvement in the ablative performance of the composite *via* an increase in the char residue. The nanocomposite showed the potential to be developed for thermal stability in SRMs. Structures such as wings, fuselages, rocket motor castings, engine nacelles, and cowls, horizontal and vertical stabilizers, and pressure bulkheads were fabricated using composite materials. These required both mechanical and electrical properties for the resistance against high-impact damaged properties. The percolation theory evaluated the electrical properties of MWCNTs in epoxy resin. The increase in MWCNT content increased the conductivity. The thermogravimetric analysis revealed an increase in the thermal stability increasing the MWCNT content. These components were developed using carbon–fiber-reinforced composites with MWCNT/nanocomposite epoxy resin [75]. The wear resistance of the landing gear of an aircraft was improved by implementing nanocomposite coatings on the structurally stressed components [80]. AlSiCrN, a nanocomposite, was coated on the surface of a HSS substrate and was observed to improve the wear resistance of the substrate, with no significant dependence on the impact speed. Metal to metal bonding of alloys of aluminum in aircraft components was investigated using epoxy-based nanocomposites [81]. Epoxy was found to possess poor thermal stability, a property that improved significantly after the addition of graphene nanoparticles to the epoxy. An improvement in T_g was observed, along with improved mechanical properties in comparison with a pure epoxy system. Aircraft gas turbine blades manufactured from ytterbium disilicate-SiC-based nanocomposites were manufactured and analyzed for self-healing characteristics [84]. It was found that the nanoparticles were effective in sealing the cracks formed in the blades, by virtue of oxidation of the SiC to SiO_2, which enabled the volume expansion of the formed liquid glass into the crack. The system was effective in improving the bending strength of the component as well. A bioinspired flapping-wing design for a micro air vehicle was manufactured using a CNT reinforced PP nanocomposite [86]. It was experimentally analyzed that the natural frequency of the synthetically developed wing was quite close to the characteristic frequency of the wing of a dragonfly, with the manufactured wing being achieving stiffness and Young's modulus not far from that of the veins of the actual wing.

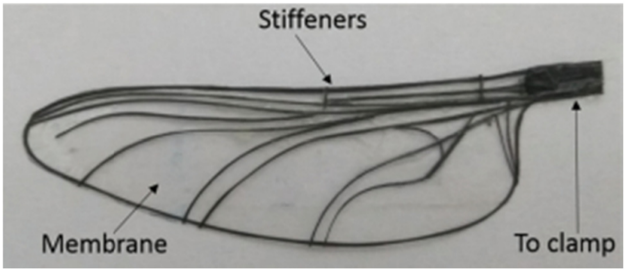

Figure 9: A dragonfly inspired nanocomposite wing structure [86].

Figure 9 demonstrates the synthetic wing structure, with similar morphology as compared to an actual dragonfly wing.

The ability of nanocomposites to endure the severe conditions of space, with enhancement in thermal and mechanical properties of a monolithic system, in comparison with the conventional polyethylene layers were investigated [91]. A polyethylene matrix reinforced with nanoplatelets of GO was tested numerically for resistance against solar radiation, with the GO platelets being excellent reinforcements against radiation, even at low wt% of nanoparticles. Habitat development on other planets is subject to a variety of criteria, one of which is impact damage by space debris [92]. A CNT/graphene nanoplatelet–epoxy matrix nanocomposite sensor was developed to investigate its performance against impact by MMOD. The sensor was found to be capable of detecting damage because of MMOD impact, with a resolution greater than that of capacitive sensors. The capability of certain nanocomposites to keep aerospace components ice-free was investigated [96]. An ultra-flexible carbon nanowire (CNW)/PDMS nanocomposite was etched onto the surface of a biomimetic nanocomposite. It was observed experimentally that the adhesion of the nanocomposite with the substrate increased with an increase in the surface roughness of the substrate. The CNW/PDMS-based nanocomposite was found to possess icephobicity, which holds potential anti-freezing applications in the aerospace industry. An enhancement in radiation insulation by implementing nanocomposites was numerically analyzed [97]. Carbon-filled nanocomposites, specifically GO-based nanocomposites, were found to be the most optimum radiation insulant materials when compared to polyethylene and boron carbide particle reinforced composites. The thermal insulation required for an SRM was investigated by implementing an EPDM filled nanosilica matrix reinforced with Kevlar fiber [98]. Studies regarding the thermal and mechanical stability of the nanocomposite revealed an improvement in fire resistance, lower heat conduction, and good mechanical stability. These properties confirmed that the nanocomposite system could be implemented as a reliable casing for an SRM. The addition of polyamidoamine with traditional rubber improved the damping performance that can potentially be used as elastomers for mechanical subsystems. Lu *et al.* highlighted the tensile strength and elongation at break increased from 1.95 to 6.45 MPa [108].

5 Conclusion and future scope

Nanocomposites have effectively contributed to groundbreaking successes in aerospace. The advancement of nanocomposite materials resulted in improved fatigue strength, lightweight components, and radiation control because of coatings onboard the ISS. Several manufacturing techniques were used to develop and process nanocomposite parts, with newer techniques being analyzed and developed consistently. Every technique has its merits and considering the complexity of steps to be followed, and the intricacy of the machinery, the choice of the technique can have a major influence on the quality of the nanocomposite. Graphene has displayed superior mechanical properties, and the molecular dynamics simulation showed that the graphene enabled an increase in stability of strength and reduced fatigue stress. These display excellent properties that could potentially revolutionize the aerospace industry [57]. Nanocomposites have shown tremendous growth in the field of aerospace technology, with high-end applications demanding the employment of highly structural materials, which nanocomposites seem to fulfill well. The implementation of these materials has significantly improved the structural capabilities of specific components and has met with the stringent material and manufacturing demands of the aerospace industry. MWCNTs play a major role in fabricating microelectronics for aerospace applications. The combination of diamine monomer 2,4-bis(4-aminophenyl amino)-6-chloroquinazoline and f-MWCNT displayed unique flame retardancy and dielectric constant that could exploit their use in an aerospace application [58]. The hardness and fracture resistance were increased because of the increase in MWCNTs, and it could be enhanced by 76% for improving hardness in aerospace applications. The integration of AM technologies, multifunctional structures, advanced nanocomposites, and structures paved the way for optimized integrated spacecraft structures [55,56]. The future of nanocomposites looks promising when space-based missions are called upon, such as instances of radiation insulation requirements in space and MMOD damage resistance [92,97,107].

Space technology and its ever-increasing challenges require materials with enduring properties, making it easier to choose nanocomposites over conventional alloys.

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