Chapter 3

CNTs and BNNTs in Aerospace Enginnering

Murat Metehan Türkoğlu[1]

Abstract

The continuous efforts to enhance performance and efficiency in the aerospace industry necessitate the development of advanced materials with improved thermal stability and mechanical strength. In this section, the potential applications of Carbon (CNTs), Boron Nitride Nanotubes (BNNTs) in the aerospace sector are examined. In this context, their advantages in key areas such as thermal and mechanical properties and weight reduction of aircraft are analyzed. Composite materials like CNTs and BNNTs have the potential to significantly improve the strength-to-weight ratio of structural components of aircraft, thereby enhancing fuel efficiency and considerably reducing carbon emissions. This study discusses the advantages of nanocomposite structures such as CNTs and BNNTs in reshaping aerospace architecture in terms of energy efficiency and strength.

1. INTRODUCTION

Starke and Staley (1996) showed that the strength/weight ratio was important in material selection fort he first aircraft and they noted that nanocomposite materials were crucial for the aviation industry. Over time, due to the problems encountered in the aviation industry, it has been showed that composite materials have interesting additional properties. Throughout the 1990s, when aircraft fleets were examined, the need for composite materials with corrosion and damage resistance was indicated [1]. This evolution in requirements led to the development of advanced composite materials to address these challenges. With the static and dynamic strength calculations used in today's modern aircraft designs, the lifespan of aircraft has been extended to 70 years, and it has been reported that some bomber aircraft remain in the inventory for nearly 40 years due to their low

1 İstanbul Gelişim Üniversitesi Uçak Mühendisliği (İngilizce)-İstanbul Teknik Üniversitesi Savunma Teknolojileri Programı, mmturkoglu@gelisim.edu.tr, mmturkoglu@itu.edu.tr
ORCID ID 0000-0002-2857-866X

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frequency of use [2]. The prolonged service life of these aircraft illustrates the effectiveness of these material innovations. The use of composite materials allows fewer parts to be used at each stage. As the number of parts decreases, the number of spare parts and the budget allocated for them also decrease, which is very important for the continuity of the system [3]. For example, materials such as titanium have high corrosion resistance but are quite expensive [4]. Thus, the cost-effectiveness of composites over metals like titanium has also boosted their adoption. Carbon nanotubes usually have high aspect ratios, but their small lengths make them challenging to process. The difficulty of processing is demonstrated by the fact that, while Zheng et al. (2004) [5] has succeeded in synthesizing CNTs several centimeters long, mass production of long nanotubes is still not feasible, which is a significant barrier to their widespread application in aerospace. Further research by Kyoung et al. (2011) [6] produced micrometer-thick, free-standing CNTs using highly oriented multi-walled carbon nanotube airgel sheets, potentially enhancing the commercial manufacturability of CNT-based terahertz polarizers. Similarly, Okawa et al. (2007) reported on JAXA's development of a propulsion system using CNT field emission cathodes, highlighting the versatile applications of CNTs in both terrestrial and extraterrestrial technologies. [7] Unlike conventional filled polymers, Polymer Nanocomposites (PNCs) require relatively low dispersant loadings, making them an important candidate for aerospace applications .[8] Regarding aerospace applicability, thermal electrical and mechanical properties of PNCs were experimentally and theoretically investigated by Njuguna et al. and results were shown to be superior to other aerospace materials. [9] Moreover, Bellucci et al. (2005) focused on enhancing the mechanical properties of CNT-based nanocomposites by improving the synthesis methods and ensuring uniform dispersion of CNTs in epoxy resin matrices. Their research highlights the resistance to compression and stability against buckling. These findings underscore the significant potential of CNT composites in aerospace. [10] The challenges of dispersion and alignment in nanocomposites lead to randomly oriented PNCs, which are often used in low volumes because their morphology cannot be controlled. However, the modulus and electrical conductivity of carbon nanotube (CNT) composites aligned with controlled morphology are maximum along the CNT axis. It has been determined that aligned CNTs have higher strength and electrical conductivity [11] The development and integration of CNTs into spacecraft structures, notably for the Juno spacecraft, as detailed by Rawal et al. (2011), not only enhance electrostatic dissipation and shielding but also improve overall spacecraft performance in terms of mechanical properties, thermal and electrical conductivity, and fracture toughness. These advances underscore the broad applicability and potential of nanocomposites in high-stress environments. [12]

Recent developments and reduced production costs of BNNTs have reawakened interest in these nanomaterials in the aviation industry due to their transformative potential for aviation technology. Essentially, BNNTs are nanotubes made up of boron and nitrogen atoms arranged in a hexagonal lattice, forming robust covalent bonds, similar to CNTs. This structural similarity to CNTs provides a basis for comparison, yet it is their unique properties that distinguish BNNTs in aerospace applications. The unique molecular configuration of BNNTs provides numerous advantages to their application as a nanomaterial. For instance, BNNTs exhibit remarkable tensile strength, enabling them to be resistant to deformation and enduring mechanical stress. Moreover, the bond between boron and nitrogen demonstrates exceptional thermal stability, allowing it to maintain its structural integrity even under extremely elevated temperatures. Furthermore, BNNTs not only display chemically inert behavior but also, unlike CNTs, act as electrical insulation. This characteristic is due to boron nitride's large energy bandgap (5-6 eV), which makes BNNTs an excellent choice for electrical insulation applications such as aerospace and electronic components. Overall, further exploration of the application of BNNTs has uncovered their distinctive characteristics, including their improved tensile strength, thermal stability, chemical resistance, and corrosion resistance. These properties make the BNNT-based nanocomposites suitable for a range of aerospace uses, particularly in situations where materials need to endure extreme temperatures, harsh environments, and mechanical strains. Thibeault et al (2016) [13] demonstrated that hydrogen-containing BNNTs effectively protect against cosmic radiation and neutrons over a broad energy range. Additionally, Yamaguchi et al. (2012) [14] explored that nanohybrid BNNT/aluminum matrix composites could withstand at least nine times higher stresses compared to no-armed Al metal. It has been reported that this pioneering work could be a step towards the production of ultra-light and super-strong structural materials for aerospace applications. Zhang et al. (2009) [15] contribute to this area by developing heteronanotubes that combine carbon and boron nitride elements, potentially combining the best properties of CNTs and BNNTs. These heteronanotubes indicated that the stability of C-BN heteronanotubes (C-BNNTs) was comparable to carbon nanotubes, and they were found to be direct gap semiconductors with varying band gaps.

2. AEROSPACE APPLICATIONS

2.1. Fundamental problems in Aerospace Industry

Fundamental problems in use of structural aerospace are divided into categories as follows;

a) **The Cost and Repairability**

Applications of advanced materials in aviation and space have become an advanced industry. Global aircraft production is worth approximately US$200 billion annually [16] and accounts for approximately half of annual sales in aerospace and defense. In addition, the cost of raw material production is estimated to be 12 billion US dollars annually. [17] Material selection is critical for structural applications to define the aspects of the life cycle, ease of production, and service conditions. With the proper evaluation of material properties, safer, more durable, and cost-effective structures can be obtained through well-defined selection and optimization processes. Especially, in aerospace structures, the selection of materials is a prominent factor for designing structures that can carry loads without adding unnecessary weight. Lighter structures are better for aircraft because every extra kilogram added to structures plays a key role in earning less revenue from cargo, requiring more fuel to carry it. Although both higher strength-to-weight ratios, referred to as specific strength, and strength-to-cost ratios are desirable properties, higher specific strength increases the strength-to-cost ratio, which means materials with higher specific strength are more expensive. The main problem with costs is that no manufacturer will continue to produce large quantities because the materials may cause another problem while they are under development or the materials may encounter a new problem and therefore prices cannot fall to acceptable levels.

Table 1. Prices and physical properties of composite materials and metal alloys used in aircraft [18]

	Graphite Composite (aerospace grade)	Graphite Composite (commercial grade)	Fiberglass Composite	Aluminum 6061 T-6	Steel, Mild
Cost $/kg	$44-$550+	$10-$45	$3.5-6.5	$6.5	$0.65
Strength (MPa)	620-1400	350-620	140-240	240	410
Stiffness (GPa)	70-350	55-70	7-10	70	210
Density (kg/m^3)	1400	1400	1500	2800	8300

b) **The Preparation Phase for Technological Breakthroughs**

Although the history of composite materials dates back fifty years, the technology required for their mass production does not exist. For example, due to the high strength of composite material, it is extremely difficult to cut it to the appropriate size for a required application [19]. The time it takes to bring the materials used in the aviation industry to the market, the properties of nanomaterials, or the patent process can be evaluated as technical difficulties.

c) **Weight Budget**

In order to ensure that flights in the aerospace industry are safe, efficient and economical, care is taken to select the right structural materials for the design of aircraft and their components. Structural materials must be resistant to abrasion and puncture (hardness), have the ability to resist deformation (strength), have the ability to bend or twist without breaking (ductility), and have the ability to return to their original size. They must also have the properties of being flexible and good conductors of heat or electricity. Steel alloys, aluminum alloys, composite materials, plastics, rubber, fabrics and wooden materials are used in aircraft for reasons such as the amount of load, exposure to various environmental factors such as stress, excessive heat and fire, and the purpose of the aircraft (subsonic or supersonic).

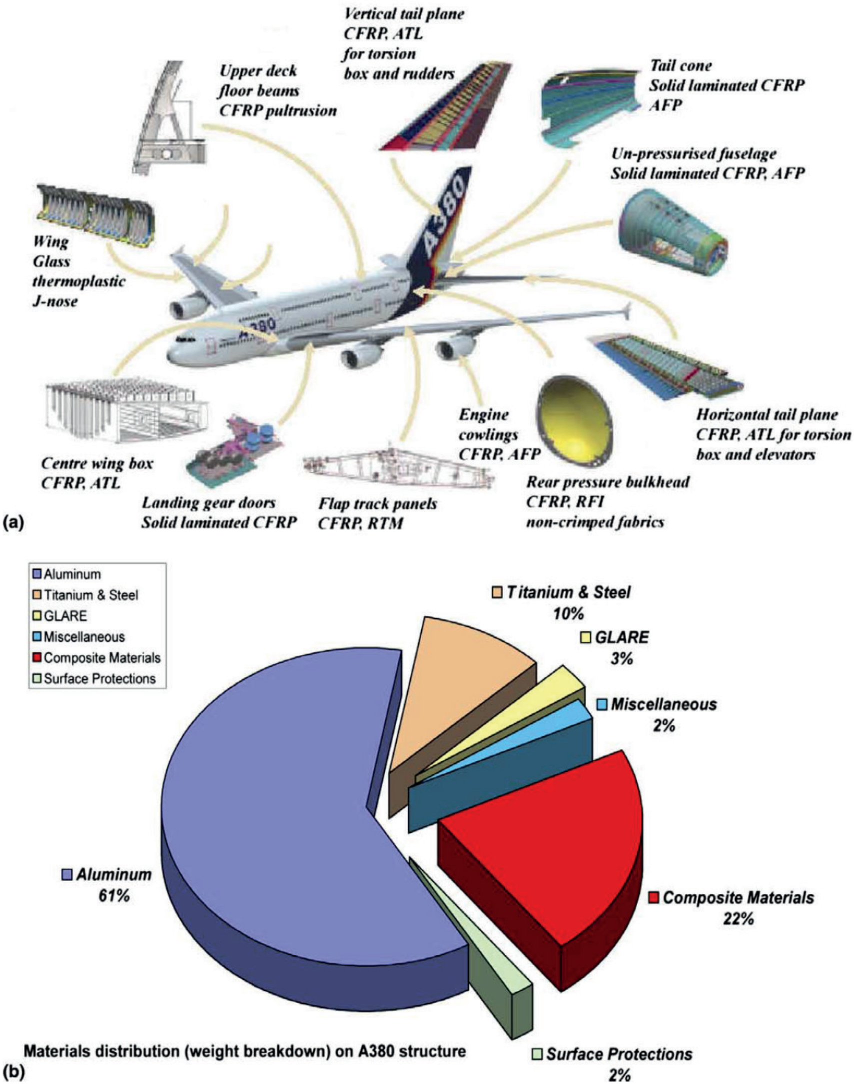

Figure 1. (a) Composite materials and thermoplastics used in the A380 and (b) their distribution on the architecture [20]

The strength coupled with the low density provides conceptual design objectives for aerospace structures hence, aluminum alloys (mainly aluminum-copper (2XXX series), and aluminum-zinc (7XXX series) have been widely used since the 1930s. However, aluminum alloys have major flaws. The absence of an strength limit and their susceptibility to corrosion restrict their areas of application. The vibrations produced by engines lead to crack formation and propagation, which is a major issue for aircraft structures. Steel alloys have higher strength compared to aluminum and can better withstand cyclic loads and fatigue below the endurance limit. On the other hand, steel is 2.5 times denser than aluminum, increasing the weight of the aircraft and leading to higher fuel consumption. Their specific strength is the same as aluminum. Titanium alloys, on the other hand, have a good fatigue strength/tensile strength ratio and corrosion resistance but are disadvantageous due to their high density. For such reasons, composite materials with strong fibers embedded in a matrix have emerged.

In modern aircraft such as the Boeing 787 Dreamliner, more than 50% composite materials are used. Due to their high strength-to-weight and stiffness-to-weight ratios, they provide a 10-15% weight savings in the manufacturer's empty mass (MEM), thus being extensively used in civil aircraft and between 15-25% in military aircraft.

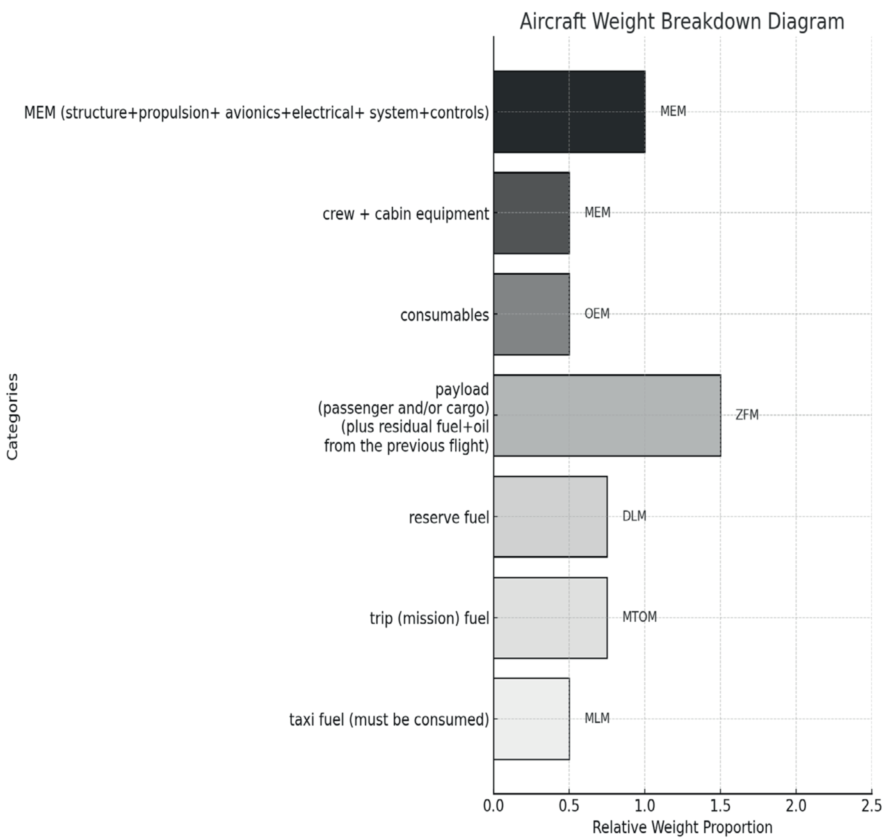

Figure 2. The aircraft weights diagram

Naturally, lightweight design is highly important for Airbus, which is planned to carry 35% more passengers (555 people) than the current aircraft with the highest passenger capacity. Thanks to the composite materials planned for use in Airbus, it is estimated that it will consume 20% less fuel per passenger.

d) **Sustainability and Service Life**

Sustainability is key issue in the aerospace industry. In this context, the Advisory Council for Aeronautical Research in Europe was established in Paris. Among the main goals that the institution plans to achieve by 2050 are a reduction of up to 75% in CO2 emissions, up to 90% in NOx emissions, and a 65% reduction in noise pollution. Therefore, researching new technologies is of utmost critical importance [21]

Table 2: Comparison of structures used in modern aircraft in terms of mass percentage. [22]

Material	Boeing 747	Boeing 777	Boeing 787	Difference
Aluminum alloys	81	70	20	↘
Steel alloys	13	11	10	↘
Titanium alloys	4	7	15	↖
Composites (various types)	1	11	50	↖

In order to quantify the danger, nanoparticles used in aircraft are defined as particles with a length/diameter greater than 3. This criterion has been established for the hazard assessment of natural and artificial mineral fibers. [23]

Turkish Air Forces Command launched the Özgür Project on 15 December 2010 for the modernization of F-16 aircraft that were not modernized within the scope of the CCIP project (Common Configuration Implementation Program, US Air Force was prepared for F-16 aircraft). Another aim of this study is to present practical concrete alternatives regarding modernization and evaluate their possible consequences. With the implementation of the Özgür project, new technologies will be adapted to aging warplanes but repair costs are expected to increase since old warplanes will be used. However, it is envisaged to become less dependent on foreign sources compared to producing new aircraft.

Gasses containing composite materials can cause risks. The fire-resistant composites in aircraft are shown in detail and their effects are discussed [24].

Air pollution in aircraft cabins was examined in the 1950s [25]. The effects of cabin air pollution on aircraft crews have been recorded [26]. Aerotoxic Syndrome, which describes exposure to pollutants, was introduced in 2000 [27].

e) **Airworthiness certification**

Authorities that monitor airworthiness evaluate the design of aviation materials according to qualification procedures. For example, patent processes progress faster due to the existing database of metals that has been accumulated over many years and material properties that have already been approved within the scope of airworthiness [28]. However, quality-patent processes are quite complex due to the characteristics of composites, the versatility of weaving, multiple production processes, production environment, and testing methods. Moreover, it is very difficult to obtain patents until additional tests are performed after the manufacture of complex composite parts [29]. Due to the complex nature of composite material properties, it is necessary to spend a lot of time and budget on qualification procedures.

Due to difficulty and risk, the patent procedures for the aviation and space industry are quite expensive and require long periods of time, as well as being uncertain and constantly renewing dynamic processes. For example, the FAA's regulations have over 1,000 pages and are constantly being developed to include new technologies. Additionally, the certification process is quite expensive: According to a study by the AIA, the average cost of certifying in the United States is approximately $1 billion, with the average time being approximately seven years. Finally, certification in the aerospace industry requires a high level of technique and expertise. Startups are therefore forced to rely on consultants or partners for certification [30].

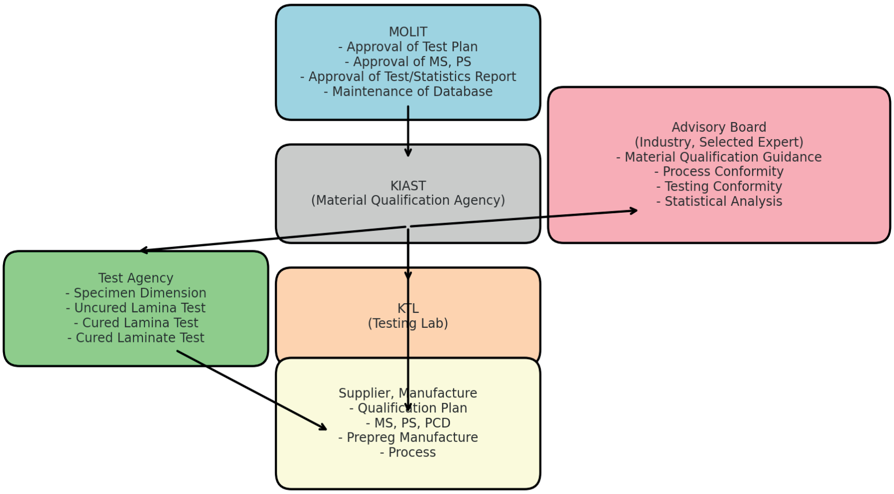

Figure 3. Composite Material Qualification System

f) Fast Prototyping

New approaches in the aerospace industry may provide solutions to existing problems, but they also come with significant risks and costs that require investment in technology. Long time periods are therefore needed to reduce risk. Adaptive wings or wingtips, reducing turbulent friction resistance, etc. are processes that require a long time [31]. For example, the problem of increasing cruising speed (Mach number) and the intense drag increase that occurs due to the presence of intense and strong shocks are both theoretical and very complex processes to produce materials resistant to these strong shocks.

Although composite materials have significant advantages, they also have some disadvantages, for example relatively low interlayer strength, poor durability, and brittleness due to exposure to ultraviolet radiation [32]. Therefore, new types of material studies are vital. In addition, topics such as cost trends and long-term maintenance and repairability are decisive for composite selection and determine the usability limit of the material. The aerospace industry must keep the design process long due to aerodynamic heating and thermal management, structural integrity and material limitations, propulsion and engine design challenges, thermal stress analysis, structural design optimization, hypersonic experiment constraints, etc.

2.2. Nanomaterials

CNTs are cylindrical structures with diameters typically ranging from 3 nanometers, formed by the arrangement of carbon atoms in a hexagonal lattice [33]. CNTs have a Young's modulus of approximately 1 terapascal (TPa) and a strength 10-100 times higher than that of steel due to their sp^2 hybrid covalent bonds [34]. Furthermore, they have electrical conductivity ranging from 10^5 to 10^7 S m^{-1} [35]. CNTs have a high aspect ratio, enabling them to convert an insulating polymer into a conductive composite even at very low loadings [36]. Following the pioneering work by Iijima and colleagues on carbon nanotubes, there has been great interest in nanomaterials [37]. For instance, boron nitride nanotubes (BNNTs) are structural analogs of carbon nanotubes, but instead of a carbon-carbon pair, they are arranged by substituting a boron-nitrogen pair [38]. Moreover, there are differences in electron density distributions between BNNTs and CNTs [39]. BNNTs have an elastic modulus of 1 TPa and a tensile strength of 60 GPa and their excellent flexibility makes them very suitable for composite applications. They exhibit excellent thermal conductivity (~350 $Wm^{-1}K^{-1}$) and maintain stability even at high temperatures such as 900 °C and above 1000 °C in an oxygen-rich environment [40]. BNNTs exhibit superior thermo-oxidative stability compared to CNTs, making them suitable materials for harsh environments. BNNTs, especially in conjunction with the 10B isotope, have a significant neutron absorption and scattering cross-section, making them highly potential candidates for radiation shielding. It is conceivable that they could be used to protect satellites in low Earth orbit from radiation. Furthermore, BNNTs not only exhibit chemically inert behavior but also serve as electrical insulation, unlike CNTs. This characteristic is due to the wide energy bandgap (5-6 eV) of boron nitride, making BNNTs an ideal candidate for electrical insulation applications in aerospace and electronic components.

In the aerospace industry, it is highly critical for a material to simultaneously possess various desired properties. Multifunctional nanocomposites are well-suited for this task. Such composites contribute to simplified production processes, reduced system complexity, cost savings, enhanced product performance, and increased reliability. The ability of BNNTs to bond with CNTs due to their structural similarity has paved the way for the development of advanced composite materials. Zhang et al. (2009) [41] developed hetero-nanotubes that combine carbon and boron nitride elements. These hetero-nanotubes demonstrated that the stability of C-BN hetero-nanotubes (C-BNNTs) is similar to carbon nanotubes and that they are semiconductors.

2.3 CNTs in Aerospace

a) Electrical Applications

CNTs possess exceptional conductivity and high surface area, making them highly efficient materials for electrical applications [42]. Due to their high aspect ratios, CNTs need to be loaded into the matrix at 1.5-4.5% by weight to form conductive pathways, thereby achieving uniform electrical properties. The integration of CNTs into fiber-reinforced polymer composites significantly enhances electrical conductivity, with increases of 10^6 for in-plane and 10^8 for through-thickness directions. This feature makes them suitable for structural health monitoring (SHM) and non-destructive evaluation (NDE), which are of critical importance for space applications. Bellucci et al. (2007) [43] demonstrated that even small changes in CNT content can significantly affect electrical resistivity and mechanical properties. The addition of 0.5% CNTs by weight to composite materials indicates a significant improvement in electrical conductivity. These properties are crucial for electromagnetic interference shielding.

Experimental studies have shown that an increase in current density through the bond reduces resistance and allows for a controlled electric current. However, increasing the density damages the bond. Additionally, it is known that the specific contact resistivity decreases with the amount of nanotubes, and the mechanical integrity of the bond, when measured in terms of shear strength and fatigue resistance, is unaffected by the current. However, high concentrations of MWCNTs reduce bond resistance, which negatively impacts fatigue resistance [44]. Additionally, the experiments showed that the volume resistivity of epoxies decreased with increasing MWCNT aspect ratio, which in turn increased electrical conductivity [45]. CNT-based sensors can facilitate rapid electron transfer, enhancing electrochemical reactivity, and allowing for their use in strain sensors where conductance changes reproducibly with strain or bending, and enabling in-situ monitoring of health (e.g., pilot health). The incorporation of multi-walled carbon nanotubes (MWNTs) into aerospace-grade epoxy resin composites can enhance lightning strike performance. Panels containing 0.1 wt.% MWNTs have been reported to show improved lightning strike performance [46].

b) Mechanical applications

CNTs integrated into glass fibers can function as strain sensors, helping to detect mechanical stresses such as strain, cracks, and delamination in real-time. This feature is highly important for aircraft architecture [42]. The fracture toughness of alumina composites was increased by 24% with a 10 vol-% loading of multi-walled nanotubes (MWNTs), while the addition of 1 wt-% carbon nanotubes improved the elastic stiffness of polystyrene by 36-42% and resulted in a 25% increase in tensile strength. They have considerable potential for extensive use in the aerospace sector. Tensile and Charpy impact tests confirmed the improved mechanical properties of CNT-reinforced composites. For example, the ultimate tensile strength of epoxy-impregnated CNT buckypaper was measured at 56.6 MPa. Charpy impact tests showed a 42% improvement in Young's modulus and a 10% increase in the ultimate tensile strength for CNT-reinforced composites [39]. The reinforcement of carbon fiber composites by inserting vertically aligned carbon nanotubes (VACNTs) between the layers has increased in-plane strength, which is of critical importance for aerospace applications. These improvements include a 30% increase in bolt-bearing strength, a 10% increase in open-hole compression strength, and a 40% increase in L-shaped laminate bending tests. VACNTs act like nano-stitches, strengthening the interfaces without compromising the structural integrity of the composite, unlike traditional reinforcement techniques [47]. The incorporation of MWCNTs into woven carbon fiber (CF) laminae has been shown to increase the fracture toughness of the cured composite by approximately 50%. Additionally, the flexural modulus of the composite increased by about 5%, indicating an improvement in structural stiffness [48]. Polymer matrix composites reinforced with carbon nanofibers and carbon nanotubes (CNTs) have demonstrated significant improvements in vibration damping. Dynamic mechanical analysis (DMA) revealed that nanocomposite beams with carbon nanopaper sheets exhibited a 200-700% increase in damping ratios at higher frequencies compared to those without sheets. Therefore, such materials hold strong potential for use as structural components in aerospace applications.

c) Thermal applications

Changes in the mechanical resonant frequency of CNTs can be utilized to develop thermal sensors, and the high aspect ratio and large surface area of CNTs can enhance the sensitivity of thermal applications.

d) Coating applications

The application of CNTs as coatings for lightning strike protection is due to their thermal and conductive properties. Additionally, it leads to improvements in strength and durability. CNTs were dispersed into a thermoplastic polyurethane (PU) matrix to be used as de-icing coatings. The integration of 1 wt.-% MWNTs into the PU matrix also enhanced the tensile strength of the coating. Thermal stability is crucial for aerospace coatings. Thermogravimetric analysis (TGA) has shown that the addition of MWNTs improves the thermal stability of nanocomposites [49]. The volume resistivity decreased from 10^{13} Ω·cm for pure PU to 10^{8} Ω·cm for composites with 0.5 wt.-% MWNTs and to 10^{7} Ω·cm for composites with 3.0 wt.-% MWNTs. This substantial reduction in resistivity protects the structure from electrostatic discharge damage [49] Thermal diffusivity determines the coating's ability to conduct heat. The thermal diffusivity of the nanocomposites showed a 24% improvement compared to pure PU with the addition of 1.0 wt.-% MWNTs. Improved thermal diffusivity at optimal MWNT concentrations enables the coating to manage thermal energy efficiently and helps prevent ice accumulation in aerospace architecture [49].

2.4. BNNTs in Aerospace

BNNTs possess exceptional mechanical strength, thermal conductivity, and electrical insulation properties [50]. Therefore, BNNTs are highly suitable for aerospace applications, particularly for structural reinforcement, thermal management, and electromagnetic shielding.

a) Electrical and Thermal Applications

Semiconducting BNNTs are ideal electrical insulation materials, regardless of chirality or diameter [51]. Due to these functions, they are of great importance for thermal management in aerospace electronics. Materials with low dielectric constant values are used to reduce power consumption in high-frequency circuits [52]. BNNTs possess a low relative dielectric constant range, from 1.0 to 1.1 (50 Hz - 2 MHz) [52]. These properties offer advantages for applications that require high insulation and low energy loss. Huang et al [53] achieved significant improvements in the dielectric properties of BNNT composites compared to pure epoxy resin. Such properties of BNNTs suggest that they may offer a promising solution to the reliability issues commonly encountered in aerospace applications.

b) Mechanical Applications

BNNTs hold a significant place in mechanical applications due to their high thermal stability, mechanical strength, and piezoelectric properties. For example, BNNTs have significantly reinforced aluminum composites. On the other hand, molecular dynamics simulations have shown that BNNT-Al composites exhibit enhanced elastic properties [54]. Another study revealed that ceramic composites containing 1.5% BNNTs showed significant improvements in flexural strength, fracture toughness, and thermal shock resistance [55]. Additionally, similar results were obtained for BNNT-added

Si3N4 ceramic composites [56]. BNNTs have an average Young's modulus of approximately 906.2 GPa. However, it was found that the outer diameter of BNNTs decreases due to impact effects, forming a defective shell and reducing the Young's modulus to approximately 662.9 GPa. Despite this reduction, the modulus remains three times higher than that of steel. These results indicate that BNNTs possess material properties suitable for extreme environments such as space.

c) Shielding Applications

Harrison et al. (2008) conducted research on the synergistic potential of Boron Nitride (BN) composites for enhancing protection against space radiation, such as galactic cosmic rays (GCRs) and solar energetic particles (SPEs) [57]. Thibeault et al. (2016) demonstrated that hydrogen-containing BNNTs provide effective protection against cosmic radiation and neutrons over a broad energy range [13]. Yamamato et al. observed that by applying aligned carbon nanotubes (CNTs) to alumina fiber-reinforced laminates, the thermal and electrical conductivities of the composite increased. Increasing electrical conductivity has been noted to be useful for electrostatic discharge and sensing applications and can be used for both electromagnetic interference (EMI) shielding and deicing. It is envisaged that with this method, fire-resistant structures and the change in electrical or thermal resistance resulting from damage will be minimized [58]. BNNTs have been integrated into CNT-BNNT-CNT nanostructures for the purpose of developing gas sensing applications. Such structures exhibit high sensitivity and selectivity for gases such as NO_2 and O_2 due to the quantum mechanical tunneling process [59].

3. CONCLUSION

The high strength, thermal resistance, and thermal stability, electrical conductivity, chemical stability, and corrosion resistance of CNT (Carbon Nanotubes) and BNNT (Boron Nitride Nanotubes) structures provide versatile benefits across different areas, from aircraft bodies to the internal components of spacecraft. Additionally, they can be used to offer protection against radiation in space environments, contributing to the safety of spacecraft and astronauts. BNNTs are chemically inert and exhibit excellent resistance to many chemical substances, making them highly durable against chemical corrosion and harsh space conditions. CNTs also demonstrate chemical resistance under certain conditions. They are a durable option for aerospace and aviation components that may be exposed to corrosive substances or oxidative environmental conditions. CNTs and BNNTs can enhance the mechanical, thermal, and electrical properties of composite materials. For example, making aircraft bodies lighter and more durable can lead to energy savings and increased flight safety. Additionally, composites made with these materials offer high impact resistance and durability. Furthermore, CNTs have the ability to absorb radar waves, making them applicable for use in military aircraft and other aerospace applications. This property allows them to reduce radar visibility and align with stealth technology.

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