IMPROVED STRUCTURAL AND FUNCTIONAL PROPERTIES OF CARBON FIBRE COMPOSITES FOR LIGHTNING STRIKE PROTECTION

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Abstract
To overcome the lack of functional conductivity in carbon fibre reinforced polymer (CFRP) composites, carbon nanotubes (CNTs) were directly grown on carbon fibre fabric using chemical vapour deposition (CVD) technique forming fuzzy fibre, while graphene nanoplatelets (GNPs) were incorporated into epoxy matrix. Composite specimens were fabricated with the outermost ply modification by fuzzy fibre (with and without GNPs). Both structural and functional properties of all specimens were determined using electrical test, thermal test, and 3-point bending test. Fuzzy fibre composites resulted in approximately 400% electrical conductivity improvement in both in-plane and out-of-plane direction and 40% enhancement in out-of-plane thermal conductivity. The addition of GNPs on fuzzy fibre surface was further enhanced flexural properties and functional conductivities (electrical and thermal conductivity). A noticeable synergetic effect of both CNTs and GNPs create varied phonon transport and electron transfer conductive pathways between fibres and also strengthening of structural properties. These improvements offer another alternative potential hybrid CFRP composites with nanomaterials to encounter with lightning strike issue and to minimize or prevent the electromagnetic interference and structural damages providing an adequate capability in withstanding lightning strikes and increase flight safety standards.

1. Introduction

Lightning is one of the most unpredictable and harmful forces of nature that strikes commercial aircraft more than once a year. Most CFRP composite aircraft structures have been designed to withstand lightning strikes with less adverse effects by depending on conductive metallic mesh outermost skin creating the lightning current path to the ground. They present high conductivity and heat of vaporization that are necessary conditions to manage with massive current levels of lightning strike. However, they are comparatively heavy, less corrosion resistance, and weakening by the adjacent materials between metals and composites. Hence, the development of functional conductivities is a basic requirement for lightning strike protection (LSP) applications in aircraft structures to solve this parasitic electrical and thermal management issues such as discharging lightning current away from critical areas and shielding against electromagnetic interference (EMI).

Due to the current innovation and unique features of nano-materials, many researchers have developed directions of cognitive and applied works on nanocomposite materials. Type, size, and shape of nanofiller particles can affect the improvement of mechanical, thermal, electrical, and optical properties and also barrier. Introducing one of the most promising nanofiller CNTs [1-3] into CFRP composites may face some severe drawback of matrix viscosity, dispersion quality, and degradation of CNTs. Due to the higher percentage filler content, viscosity becomes a considerable problem related to the degree of dispersion. It increases the probability of agglomeration degrading stress transfer between matrix and fillers and also acts as imperfections in composites. As a result, to acquire well dispersion, high density, and good incorporation between CNTs and composite structures, growth CNTs on carbon fibre substrate forms fuzzy carbon fibre, which is suitable for enhancing conductivities. It is an incentive for many researchers to explore the influence of CNTs on carbon fibre with different parameter condition effects such as durations, temperatures, carbon sources, and catalyst [4-8]. These high quality and density CNTs nanofillers can directly adjoin carbon fibres, creating effective electrical and thermal percolation pathways throughout the composites. However, growing CNTs on carbon fibres by means of CVD decrease almost the initial mechanical properties of fibre composites and significantly degraded fibre properties due to high synthesis temperature [9, 10]. GNPs, which made of a few stacks of graphene layers, has extraordinary physico-chemical properties and great potential to improve polymer matrix properties with a very small loading. It was reported that both mechanical and functional properties were improved due to the addition of GNPs in fibre reinforced composites [11-13]

The principal objective of this study is to investigate the influence of fuzzy fibres with or without GNPs composites on the mechanical and functional properties. To provide a promising methodology to fabricate conductive carbon composites, fuzzy fibre fabrics were prepared to enhance electrical and thermal conductivities with minimum mechanical property degradation during CVD process. Hybrid laminates GNPs-coated on fuzzy fibres were further fabricated to investigate possible synergistic interaction that could further improve in structural and functional properties. It is anticipated that this research will further generate new hybrid composites with great mechanical, electrical, and thermal performances that can be applied for lightning strike protection application in aerospace industry.

2. Experimental Section

2.1. Preparation of hybrid nano-reinforced composites

Nickel-coated fibres were placed in a quartz tube to grow CNTs using CVD method at low temperature. GNPs suspension with three different percentage fractions of GNPs (0.05, 0.1, and 0.2 wt%) was then incorporated into epoxy resin. The epoxy and hardener were separately degassed to eliminate trapped solvent and air bubbles. Then, the amine-based curing agent was mixed into hybrid GNPs epoxy resin at an epoxy: amine ratio of 2.5:1. Fabricating 16 plies composites of resin-impregnated carbon fibres were prepared with only modified the uppermost ply by fuzzy carbon fibre fabrics (with and without GNPs nanofillers). Composites without any modified fillers had served as the reference panel.

2.2. Characterization Techniques

The morphology of growth CNTs on carbon fibres was imaged by Field Emission Scanning Electron Macrograph (FESEM) using HITACHI SU8010. CNTs were further characterized to investigate the diameter and length by a Transmission Electron Microscopes (TEM) using JEOL JEM-2011. Electrical conductivity was investigated using Micromanipulator Probe station 450PM-B with Keithley 4200-SCS Semiconductor Parameter Analyzer. The resistivity was conducted using a direct reading instrument and used to determine electrical conductivity. Thermal conductivity experiments were conducted using Anter Flashline™ 2000 laser flash according to ASTM E1461. The flexural properties were measured according to ASTM D7264-15 using an Instron 5982 mechanical testing system with 100 kN load cell.

3. Results and Discussions

3.1. Morphology of CNTs

The growth parameters were adjusted to acquire well-dispersed, dense, and long of CNTs growth over the entire fibre surfaces at low temperature. **Error! Reference source not found.**(a,b) display synthesized CNTs morphology on woven carbon fibre fabric by CVD technique with different quartz tube location, characterizing by FESEM. The surface of carbon fibre seemed to be covered by short growth CNTs as shown in **Error! Reference source not found.**(a) when the substrate was located in the middle of the tube. However, at a rearward position, the surface of carbon fibre was all covered with denser and longer CNTs as shown in **Error! Reference source not found.**(b). Therefore, a position of the sample affects the growth results due to the reactant mixture decomposes into a plurality of active species as heated in the furnace. The similar system and carbon source had been successfully grown CNTs on a silicon wafer with high synthesized temperature [14, 15]. CNTs were further measured by TEM verify the parallel wall structure that can be observed in **Error! Reference source not found.**(c). The distinct multiple walls construction is consistent with multi-walled carbon nanotubes.

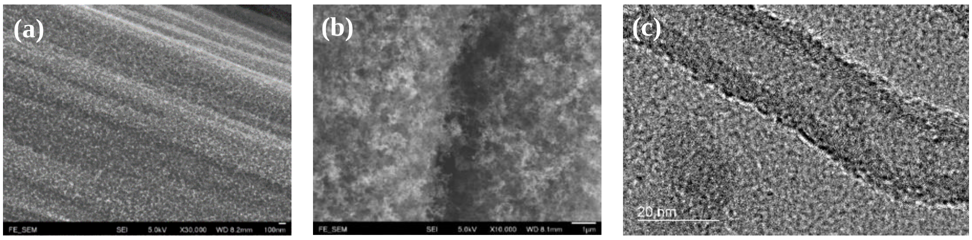


Figure 1. Images of CNTs growth (a) SEM images of CNTs growth at the middle of the tube, (b) SEM images of CNTs growth at rearward of the tube, and (c) TEM images of MWNTs.

3.2. Electrical Conductivity

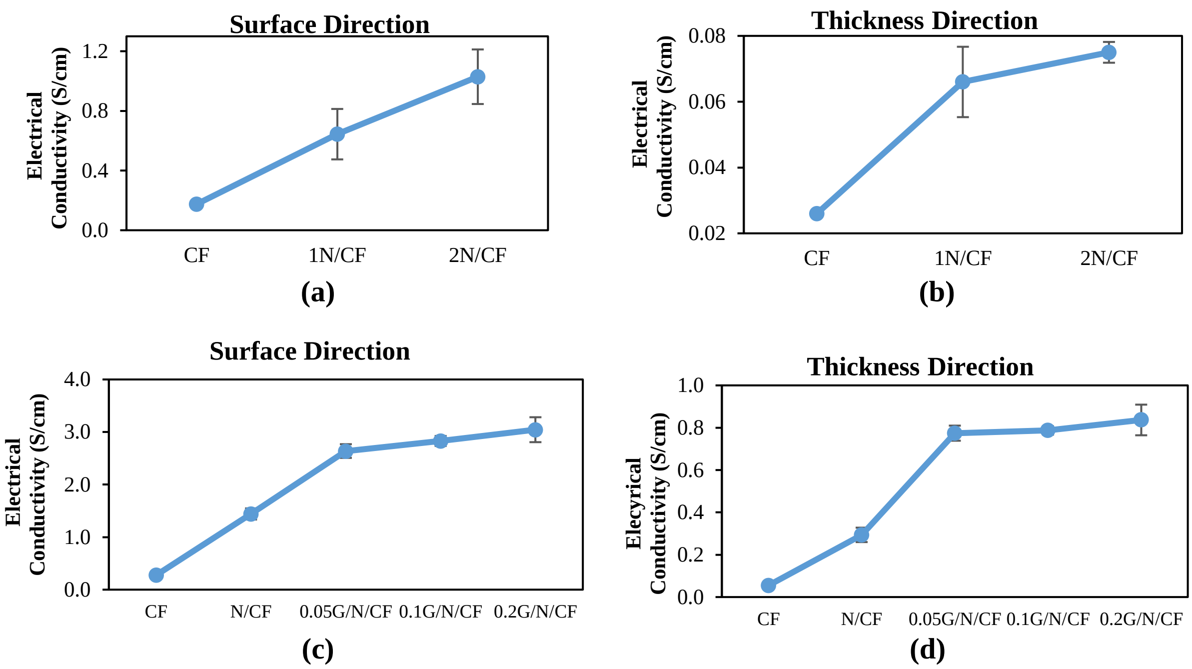


Figure 2: Electrical conductivity of carbon fibre and fuzzy carbon fibre composites (a,b) with 1 and 2 fuzzy carbon fibre layers (c,d) with and without GNPs.

Hybrid 8-ply composites were fabricated by replacing the outermost 1 or 2 plies by fuzzy carbon fibre. Figure 2(a,b) present a relatively improved in electrical conductivity for both surface and thickness direction. Due to the structure of CNTs, they increase the number of electrical percolation pathways from carbon fibre and form electrical contacts in the surface direction. Furthermore, they can also act as a bridge in the resin rich interlayers creating electrical percolation pathways within the interlaminar regions to enhance electron transport in through-thickness direction. Electrical conductivity values of 1 modified ply at the uppermost layer out of total 16 plies are shown in Figure 2(c,d). The incorporated GNPs on the surface of synthesis CNTs carbon fibre enhanced the electrical conductivity of composites in both in-plane and out-of-plane direction. Due to the synergistic effect of GNPs and CNTs, the conductive network was formed increasing conductivity even at very low percentage fraction of GNPs filler. This conductive percolation network structure may facilitate more efficient electron transport throughout the polymer matrix reducing electrical resistivity. The preserved long length of CNTs can bridge the gap between graphene and graphene and/or adjacent ply, forming and increasing the number of intra- and interlaminar percolation pathways.

3.3. Thermal Conductivity

A significant enhancement of the thermal conductivity is observed for replacing 1 fuzzy fibre (out of a total of 16 layers) at the uppermost ply in Figure 3. The presence of CNTs grown on carbon fibre surface can reduce phonon scattering from the interlaminar regions that are dominated by the thermally insulating polymer matrix. They may offer effective heat transfer pathways between CNTs and adjacent carbon fibre, allowing efficient phonon transport with the carbon fibre in the out-of-plane directions. Furthermore, the synergistic physical interactions between GNPs and CNTs is theoretically improving thermal conductivity. The combination of a different dimension of fillers may increase the number of physical interactions between GNPs and CNTs minimizing thermal contact resistance. However, there is a slight enhancement of thermal conductivity by adding GNPs into fuzzy fibre composites.

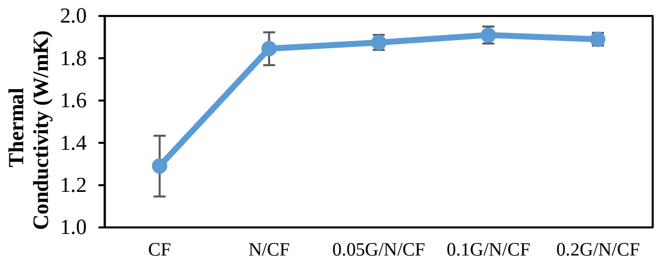
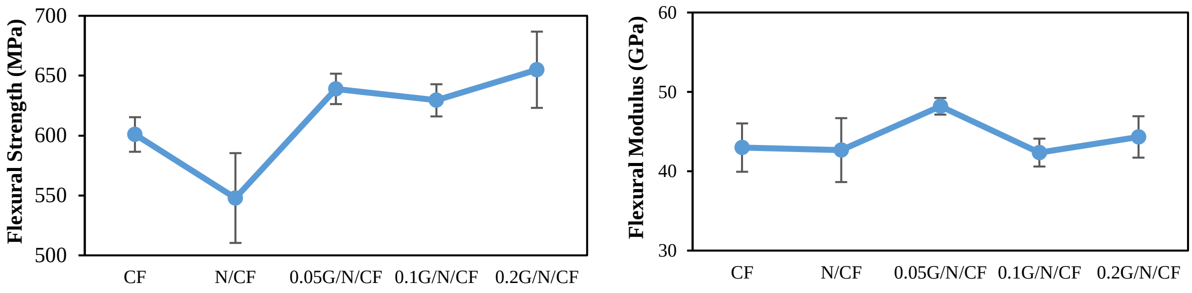


Figure 3: Thermal conductivity of carbon fibre and fuzzy carbon fibre composites with and without GNPs in the through-thickness direction

3.4 Flexural Properties

The flexural properties of carbon fibre with and without CNTs and/or GNPs are shown in Figure 4. The flexural strength of fuzzy fibre composites is moderately lower than that of reference composite due to the damage carbon fibre during high-temperature CNTs growth process, whilst GNPs-coated fuzzy fibre composites increased the flexural strength. Furthermore, the flexural modulus also increased with the adding loading of GNPs due to the reinforcing-ability and rigidity of GNPs filler. They had replenished porosity in the epoxy matrix and had also restricted the movement of the epoxy molecular chain. Hence, an incorporation of GNPs on fuzzy fibre could be promoted to better stress transfer across the matrix-fillers interface, which consequently led to a higher flexural stress and stiffness of the matrix system. The increment of flexural properties could also be attributed to the mechanical interlocking at the fibre-matrix interface. It related to the surface roughness of epoxy resin improving the interfacial adhesion bonding between fibre and matrix by the reinforcement of GNPs treatment [16]. On the other hand, the further increase of loading could, therefore, indicated an uneven distributed of fillers that resulted in weaker interfacial interaction due to the agglomeration of GNPs in the epoxy resin matrix. This is because the agglomeration of filler can act as stress concentration area that leads to an accumulation stress location forming cracks or other damages.



(a) (b)

Figure 4: Flexural properties of carbon fibre and fuzzy carbon fibre composites (with and without GNPs) (a) Flexural Strength (b) Flexural Modulus

4. Conclusions

Hybrid carbon fibre composites with necessary improvement in multifunctional properties can be fabricated to be used for LSP. This is achieved by modifying the uppermost ply of CFRP laminates and replacing the metal mesh/foil which is comparatively heavy and is known to be susceptible to a chemical reaction. A noticeable effect of GNPs-coated on fuzzy fibre has substantially enhanced functional properties of CFRP composites by creating varied phonon transport chains and electron transfer conductive percolation pathways between fibres because they act as bridges in the insulating interlaminar regions. Furthermore, the improvement in flexural mechanical properties is observed due to the mechanical interlocking providing efficient matrix-fillers stress transfer and better interfacial adhesion bonding between fibre and matrix. The development of conductive carbon fibre composites is explored to counter lightning strike-related issue during service conditions. This new commercial fibre composites with high electrical and thermal functionalities, therefore, offers an alternative to LSP applications and opens up new opportunities for innovation and industrial applications.

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