LIGHTNING STRIKE PERFORMANCE OF CARBON NANOTUBE LOADED AEROSPACE COMPOSITES

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Abstract

The increased use of carbon fibre composites in aerospace components brings to the surface issues related to their poor lightning strike performance. Metallic meshes or foils, co-cured within the outer layer of laminates, are currently used for protection. This solution comes at a cost in terms of weight and manufacturing complexity, presents difficulties in repair and most importantly does not provide full protection. The influence of multi-wall carbon nanotubes (MWNTs) on the lightning strike performance of carbon fibre composites is investigated in this work. A high temperature aerospace grade epoxy resin was modified with MWNTs. Panels of carbon fibre/epoxy, carbon fibre/epoxy with a protective copper mesh layer, carbon fibre with MWNT modified epoxy, and carbon fibre with copper protection and MWNT modified epoxy were produced. The existence form of the reinforcement enhanced nanoparticle filtration and resulted in a nanotube rich zone in the outer layers of the cured laminates. The specimens were subjected to simulated zone 2A lightning strike. Visual observations and ultrasonic C-scans revealed significant influence of the presence of the MWNT rich layer on lightning strike performance. Damage in laminates without copper protection is manifested as fibre tufting. In the case of protected laminates damage occurs at the surface and is manifested as mesh sublimation and resin degradation. The presence of MWNTs does not influence the type of damage occurring but limits the extent of damage significantly. The outcome of this work demonstrates that under optimal manufacturing conditions MWNT modification improves the lightning strike performance of carbon fibre composites. This can lead to direct application of hybrid composites within primary aerospace structures.

1 Introduction

The increased use of epoxy based fibrous composites in aerospace components brings to the surface issues related to their poor lightning strike performance. Lighting strikes can induce severe damages due to the dielectric nature of the host matrix even in the case where the reinforcement is highly conductive e.g. carbon fibers. Metallic meshes or foils, co-cured within the outer layer of laminates, are currently used for protection. This solution comes at a cost in terms of weight and manufacturing complexity and presents difficulties in repair.

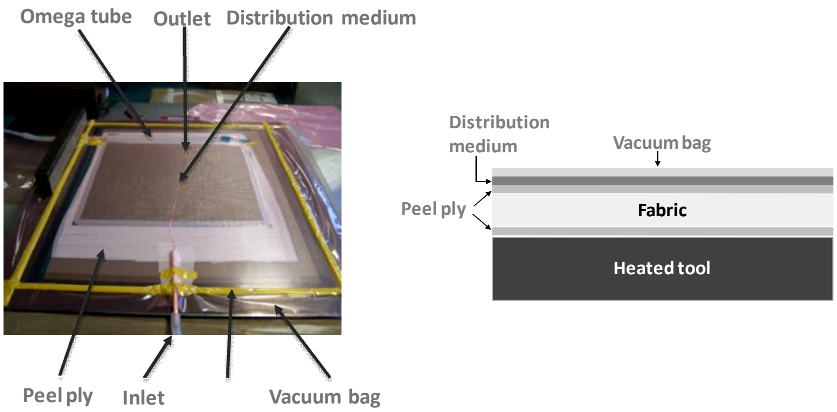
Various studies have shown that the incorporation of carbon nanotubes (CNTs) can significantly enhance the electrical conductivity of the host matrix in fibre reinforced polymer composites [1-4]. Following this, the possibility of enhancing the lightning strike response of fibrous composites by addition of carbon nanoparticles has been considered. Results on the use of buckypapers, which are the most highly loaded form of CNTs, did not indicate a significant improvement [5, 6]. As a consequence, use of low CNT loadings - corresponding to the case of matrix doping – has not been considered as a likely solution for lightning strike protection.

This work focuses on the lightning strike performance of CNT doped carbon fibre composites. The influence of the presence of nanotubes is evaluated both in the case of unprotected laminates and laminates protected using a copper mesh under conditions of simulated zone 2A strike. Evaluation of the damage produced is carried visually and using ultrasonic C-scanning.

2 Experimental details

A single component epoxy resin (HexFlow RTM6, Hexcel) was used as matrix. This resin is widely used in the aerospace industry and has become a standard for liquid composite moulding applications. Multi-wall carbon nanotubes (Nanocyl NC7000) with nominal average diameter of 9.5 nm and average length of 1.5 µm were supplied by Nanocyl S.A. The fibre reinforcement used was a carbon preform produced using two placement of a Porcher bindered tape. The preform comprised eleven layers arranged in a [0/-45/90/45/0/0/0/45/90/-45/0] layup.

The preparation procedure of the carbon fibre/epoxy/CNT composites can be summarised in three steps: (i) preparation of an epoxy/0.3wt.% CNT masterbatch, (ii) high shear mixing of the masterbatch followed by dilution to 0.1 wt.% CNT, and (iii) infusion of the diluted masterbatch in the carbon preform using the VARTM process followed by curing. The choice of the CNT loading of 0.1 wt.% was made as this concentration is well over the expected percolation in epoxy systems [7]. This loading induces only a modest increase in the viscosity of the system, thus not compromising the feasibility of the infusion process. The first step aims at the production of a masterbatch incorporating well dispersed CTNs. This is carried out by adding the appropriate amount of nanotubes in 250 ml of acetone. Subsequently, the CNT/acetone suspension is sonicated for 1 h using an ultrasonication bath (Elmasonic S 120 (H), 800W). Then the epoxy resin is added while the mixture is kept at 80ºC under continuous stirring, until complete evaporation of the acetone. The resulting epoxy/0.3 wt.% CNT masterbatch is shear mixed at 1500 rpm for 1 h using a DISPERMAT high shear mixer. Subsequently, the masterbatch is diluted to 0.1 wt.% loading by addition of the appropriate amount of epoxy and stirring. The quality of the dispersion was evaluated at certain stages during this procedure using transmission optical microscopy.



(a) (b)

Figure 1 Infusion set up: (a) assembly before infusion; (b) schematic of the full assembly.

The carbon preform fibre/epoxy/CNT composites were manufactured via the VARTM process using the setup illustrated in Fig. 1.a. It should be noted that the concentration of 0.1 wt% CNT refers to the epoxy content of the material and not to the whole composite. The VARTM setup comprises an ELKOM heated platen, upper and lower layers of peel ply, the dry reinforcement, the distribution medium placed on top of the reinforcement, and the vacuum bag as shown in Fig. 1.b. In the case of protected laminates the infusion assembly was modified to allow the incorporation of the bronze mesh field. This was carried out via the use of one layers of aerospace grade bronze mesh (Phosphor Bronze 166, square pattern, wire diameter: 63 μm, areal density: 370 g/m^2) placed in contact with the upper surface of the preform. The epoxy resin was degassed under vacuum at 80 ^{o}C and was transferred to the infusion assembly in a heated pipe. The metal tooling was kept at 120 ^{o}C until the infusion was complete and the pressure in the cavity equilibrated. Subsequently, the tool was heated up to 160°C and kept at that temperature for 2 h to cure. Before cutting and testing the material was post cured in an oven at 180°C for 2 h.

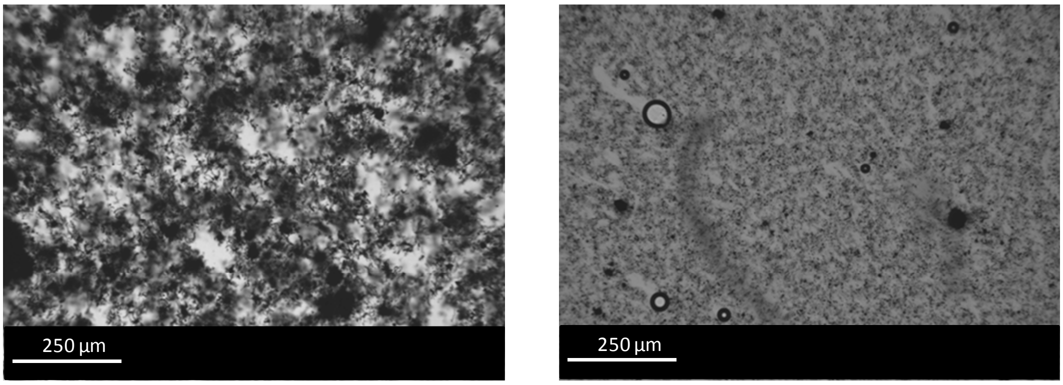
Transmission optical microscopy was used to evaluate the state of CNT dispersion in the liquid state using an Olympus BH-2 optical microscope equipped with a Q IMAGING (MicroPublisher 3.3 RTV) camera. The morphology of the produced composites was characterised by scanning electron microscopy (SEM) using a FEI SFEG-SEM microscope, operating at 5 kV. SEM was performed on surfaces produced by cryo-fracture on the plane formed by the thickness direction and the direction of the fibres in the outer layers of the laminate.

Four lightning strike test panels with in plane dimensions of 320 x 320 mm were produced. The specimens were subjected to simulated zone 2A lightning strike, comprising three current components: (i) D (100 kA, ≤ 500 μs); (ii) B (2 kA, ≤ 5 ms); and (iii) C(200 – 800 A, 0.25 – 1 s). The damage was evaluate visually and using unltrasonic C-scanning. The four cases considered to evaluate the influence of carbon nanotubes on the performance of unprotected and mesh protected laminates were as follows:

1. Unprotected carbon fibre/epoxy laminate (control).
2. Unprotected carbon fibre/epoxy/0.1 wt.% CNTs laminate (CNT).
3. Mesh protected carbon fibre/epoxy laminate (mesh).
4. Mesh protected carbon fibre/epoxy /0.1 wt.% CNTs laminate (mesh-CNT).

3 Results and discussion

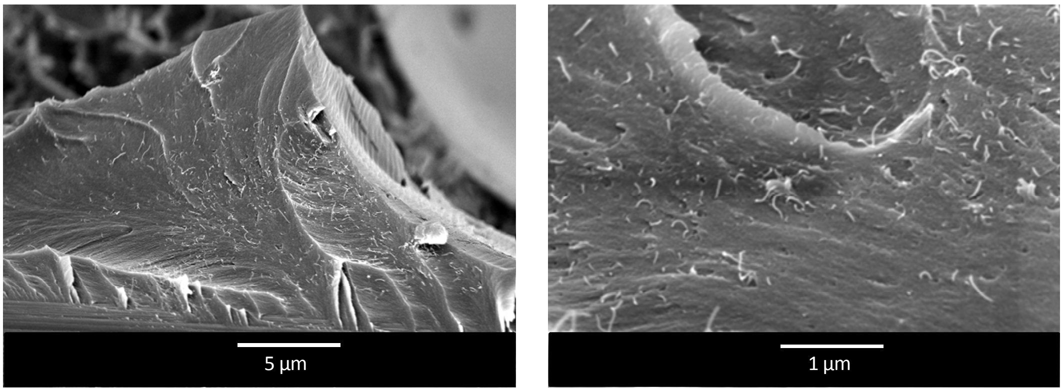
The evolution of the dispersion in the liquid state was evaluated at various stages during the preparation procedure using transmission optical microscopy. Fig. 2 illustrates micrographs at the end of acetone evaporation (Fig. 2.a) and after high shear mixing (Fig. 2.b). The as-received nanotubes are in the form of entangled rope-like aggregates [8]. Ultrasonication of the acetone suspension results in a loosely aggregated CNT network in the epoxy (aggregate size in the range of 50-100 μm), as shown in Fig. 2.a. Further treatment using high shear mixing breaks up these large aggregates which reach a size of a few microns (typical size 5-10 μm), as observed in Fig. 2.b. This good state of dispersion is preserved upon dilution with the only difference being the appearance of a less dense CNT network.



(a) (b)

Figure 2 Transmission optical micrographs showing the evolution of the CNT dispersion during preparation: (a) after acetone evaporation; (b) after high shear mixing.

The examination of fracture surfaces by SEM showed that the great majority of CNTs was filtered during the infusion and was distributed within the outer layer of the laminate (Fig.3), in a region extending 30-60 µm in the thickness direction. It can be observed that there is a high concentration of carbon nanotubes in the outer resin rich layer; whilst the distribution of CNTs in this region was uniform. It should be noted that this result is in contrast with observations in the same system when dry fabrics are used [4]. In the case of dry fabrics the existence of channels around non structural stitches for non-crimp fabrics or around tow undulations for woven fabrics facilitates the transfer of nanoparticles. In the case of bindered performs the reinforcement has an architecture similar to that of unidirectional pre-impregnated materials where flow has to occur exclusively through microchannels. Furthermore, the presence of binder promotes filtration further. Consequently, the use of bindered performs results in selective localisation of CNTs within the outer layer in contact with the distribution medium.

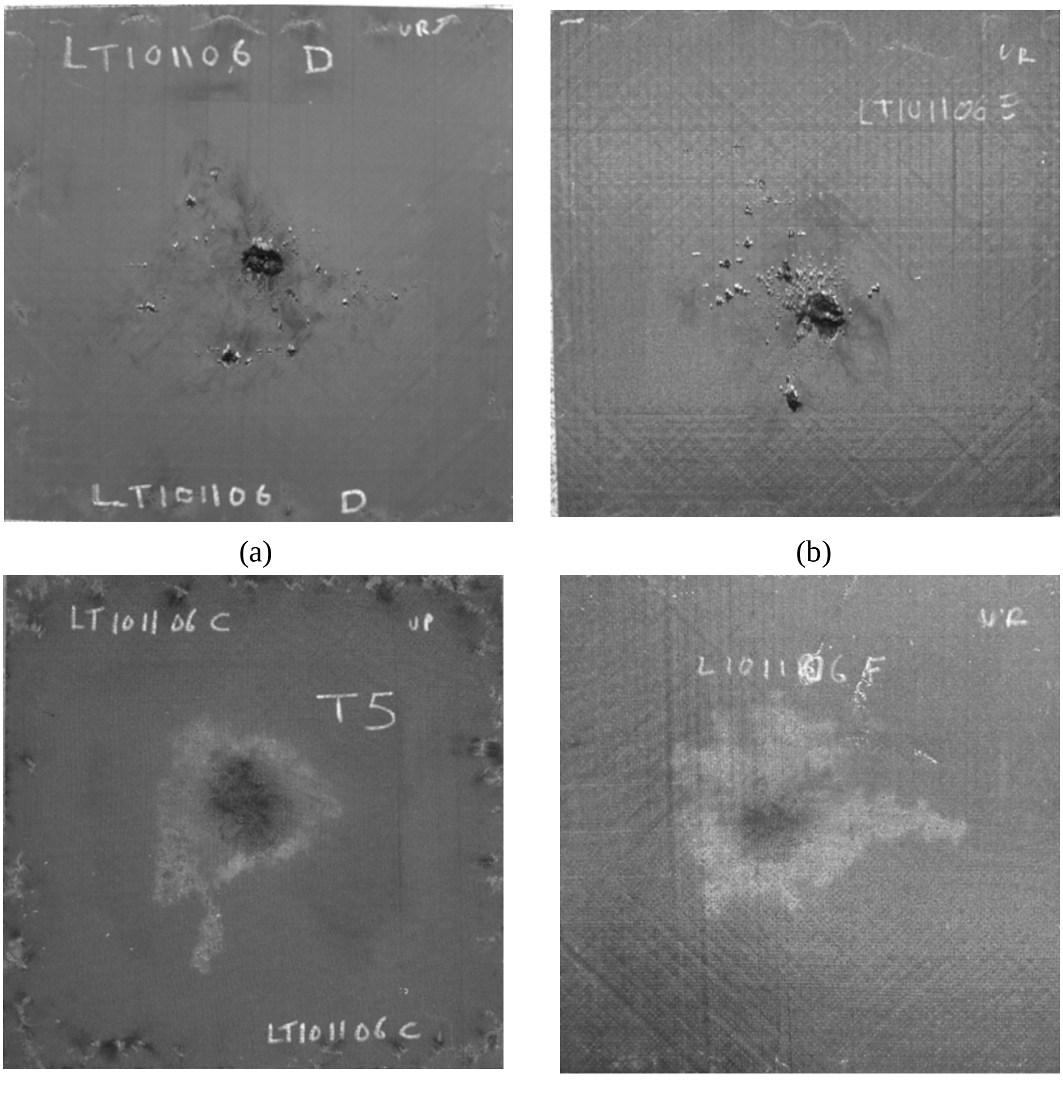


(a) (b)

Figure 3 Scanning electron micrographs of the outer layers of a laminate containing carbon nanotubes: (a) resin rich layer in contact with distribution medium; (b) detail of the surface resin rich zone.

Visual examination of the strike damage in the control laminate reveals fibre tufting, several layers deep, at the vicinity of the lightning attachment region as well as degradation of the upper resin rich layer (Fig. 4.a). Some damage of lower intensity occurs near the edges in the region in contact with the metallic frame of the testing assembly. The mode of damage in the CNT laminate (Fig. 4.b) is qualitatively the same in central regions; however, damage in the contact areas appears significantly less. The damage in protected laminates is limited to their surface and involves copper mesh sublimation and resin degradation, which as in the case of control are concentrated in the area around the lightning attachment point (Figs. 4.c-d). Some peripheral damage also occurs in the case of the mesh laminate (Fig. 4.c) which is not present in the mesh-CNT laminate (Fig. 4.d).

Ultrasonic C-scans allowed quantification of damage in the stroke specimens. Binary images of C-scans were analysed to determine the area of the damage around the lightning attachment point. It should be noted that this analysis is appropriate for comparing specimens with the same type of damage. The analysis showed significant improvement with the addition of CNTs; this correspond to about 40% in the case of laminates without mesh protection and about 60% for the mesh protected laminates.



(a) (b)

(c) (d)

Figure 4 Lightning strike damage laminates (image size corresponds to size of specimens): (a) control; (b) CNT; (c) mesh; (d) mesh-CNT.

These results can be explained by consideration of the critical role in lightning strike of the insulating resin rich layer. Inability of this layer to dissipate current intensifies the potential gradient and the field locally. Furthermore, the insulating behaviour forces transfer of higher fraction of the energy in the through the thickness direction, which subsequently is transferred in-plane in the inner and conductive layers of the material. Consequently, the addition of high loading of nanotubes results in a material that is conductive even at its surface which allows broader distribution of the strike energy in the in-plane direction as well as good electrical contact between composite and metallic components.

4 Conclusions

The outcome of this work demonstrates that under optimal manufacturing conditions MWNT modification improves the lightning strike performance of carbon fibre composites. This is due to the critical role of the insulating resin layer induced by the strongly non-linear character of lightning strike. This can lead to direct application of CNT doped fibrous composites within primary aerospace structures.

Acknowledgment

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