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Fabrication of an enriched graphene surface protection of carbon fiber/epoxy composites for lightning strike via a percolating-assisted resin film infusion method

Ben Wang [a], Yugang Duan [a, *], Zhibo Xin [a], Xueling Yao [b], Dilmurat Abliz [a, c], Gerhard Ziegmann [c]

[a] State Key Lab for Manufacturing Systems Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi Province, 710049, PR China
[b] State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University, Xi'an, 710049, PR China
[c] Institute of Polymer Materials and Plastics Engineering, Clausthal University of Technology, Clausthal-Zellerfeld, 38678, Germany

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ABSTRACT

A low-conductivity feature of carbon fiber-reinforced polymers (CFRP) needs to be engineered with lightning strike protection to decrease the vulnerability of the material to lightning strike damage. This paper reports a percolating-assisted resin film infusion method that achieves a conductive lightning strike protection via the accumulation of reduced graphene oxide (RGO) on the composite surface. In this method, the fibrous preform was sealed by the filter paper and the sealant tape to form a confined region that avoids the expansion of RGO from the fibrous preform while also limiting the RGO flow along the thickness direction, and thus RGO accumulates on the CFRP surface through filtration mechanisms. The enriched RGO on CFRP allowed high conductivity values (440 S/cm vs. 16 S/cm of CFRP) on the surface while also improving the thermal resistance of CFRP. As a result, RGO protection dramatically improved the lightning damage resistance as compared to CFRP. The residual strength, characterized via 3-point flexural testing after a simulated lightning test, only decreased by 23% as compared to its initial value, whereas a drastic reduction (66%) was observed for pristine CFRP.

1. Introduction

At present, because of their potential for reducing weight, composites are being proposed for widespread use in the principal structures of new-generation aircrafts [1,2]. Although these advanced composites have superior mechanical properties compared to conventional aluminum alloys, carbon fiber-reinforced polymers (CFRP) exhibit significantly lower electrical conductivity because of the insulating polymer matrix. This characteristic requires special considerations regarding the threat of a lightning striking the composite airframe [3,4]. When lightning strikes one unprotected structure, up to 200 kA of electricity seeks the path of least resistance [5]. This may cause catastrophic damage to CFRP via Joule heating effect, matrix resin decomposition, acoustic shock, and electromagnetic force phenomena [6,7].

To fulfill safety requirements, it is necessary to improve the electrical conductivity of the composite airframe such that it enables striking currents to flow through the overall aircraft surface without damaging the inner airframe structure. At present, aircrafts in service such as Boeing 787 and Airbus A380 have generally adopted a lightning strike protection (LSP) system comprising a metallic mesh or metallic foil on the surface of the composite structure to prevent excessive lightning damage. However, large amounts of this metallic material increase the total structural weight and the manufacturing costs. Moreover, the corrosiveness of the LSP increases maintenance costs and downtime thereby resulting in an inadequate protection [8].

These issues related to composite lightning protection have received increasing attention, specifically with the aim of developing a new solution to substitute the traditional LSP. One of the possible ways to provide sufficient lightning damage resistance involves replacing the insulating matrix material with a conductive one. For example, lightning damage resistance was improved by using a conductive resin matrix of polyaniline-based thermosetting resin [9,10], although the comparatively low processability and

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* Corresponding author.
E-mail address: ygduan@mail.xjtu.edu.cn (Y. Duan).

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mechanical performance of polyaniline limited its further application in composite manufacturing and applications. Several approaches have been adopted to mix superior conductive nanofillers (i.e., carbon nanofibers, carbon nanotubes, and graphene) with an insulating matrix resin to improve the electrical conductivity of the matrix [11–14]. However, filtering the nanofiller with textiles negatively affects the manufacturing process of the composite material and leads to a nonuniform distribution of the nanofiller [15]. Additionally, the resulting nano-hybrid composites cannot assimilate a sufficient amount of the conductive nanofiller to achieve electrical conductivity values high enough for lightning protection [3]. To supply a sufficient LSP system, a high surface conductivity is essential for providing a safe conductive path for lightning-strike dissipation on the surface of CFRP. Conductive nanofillers can be made into highly conductive films or buckypaper, which are bonded onto the surfaces of CFRP. For example, carbon nanofibers and nickel nanostrands as reinforced buckypaper were incorporated onto the surface of CFRP for lightning-strike protection and showed that the high surface conductivity contributed to a sensible reduction in the damage caused by a lightning strike [16]. Nevertheless, the application of buckypaper on composite structure such as a fuselage or aerofoil has been limited because of the onerous preparation process of buckypaper and because of its limited size.

The adequacy of LSP as a composite material used in aircraft demands sufficient electrical conductivity and also good processability and applicability in manufacturing the composite. This research focuses on improving the CFRP lightning damage resistance by depositing a uniform and sufficient protection layer on CFRP through a liquid composite moulding method to manufacture large-scale and complex aircraft structures in the future. In this study, graphene was selected as a nanofiller for reinforcement of polymers owing to its superior conductivity and large specific surface area characteristics [17]. Specifically, high loadings of reduced graphene oxide (RGO, up to 0.2 g) were dispersed in a resin film by a ball mill-assisted dispersion technology. A percolating-assisted resin film infusion (RFI) method was proposed to enrich sufficient amounts of nanofiller on the composite surface while maintaining a uniform distribution in-plane. The electrical conductivity and thermal resistance of the processing composite were analyzed and compared with the pristine CFRP, and the effectiveness of this method in suppressing the lightning-damage was also discussed.

2. Experimental

2.1. Materials

The epoxy matrix system used in this study was comprised of a bisphenol A epoxy resin (30 wt%, Epolam 5015, AXSON, France), a phenolic epoxy resin (40 wt%, Institute of Aeronautical Materials, China) and polyethersulfone (3 wt%, PES, Changchun Jilin University Special Plastic Engineering, China), while 4,4′-diamino-diphenylsulfone (27 wt%, DDS, Shanghai Experiment Reagent, China) was used as a hardener agent. RGO was obtained via oxidation of natural graphite flakes (according to the Hummers' method [18], Fig. S1), followed by exfoliation of graphite oxide via ultrasonic treatment [19]. PAN-based 12 K carbon fibers arranged in a 300 g/m^2 areal weight unidirectional fabric (T700S, Toray Industries, Japan) was used as fiber reinforcements. All vacuum bagging materials were supplied by Sino-composite Co. Ltd.

2.2. Composite preparation

The multi-scale reinforcement laminate was fabricated by a percolating-assisted RFI method, a schematic layout of which is shown in Fig. 1(a). The RFI method developed herein is advantageous in that it can reduce the relative flow distances to be overcome while also eliminating the need for a low viscous resin system [20]. A specific amount of RGO (0–0.2 g) was dispersed in a blending epoxy system of bisphenol A epoxy and phenolic epoxy using a high-energy ball milling method. (The preparation process is provided in the supplementary material). In this process, the bleeder cloth, the peel ply, and the filter paper (1–4 μm of the pore size) were first adhered on a heated mould in sequence. The as-prepared nano-hybrid resin film (150 mm * 150 mm) was placed on the filter paper, and then a fibrous preform of 8 layers was located (150 mm * 150 mm) in a stacking sequence of 0/90 and added on the top. The preform edges were tightly sealed with sealant tape as dams to ensure the resin flow in the thickness direction. After that, the bagging arrangement was sealed with a vacuum bag and sealing tape.

The entire process of infusion moulding can be divided in three steps, and the temperature and vacuum pressure profiles used in the process are shown in Fig. 1(b). First, as shown in Fig. 1(c), the residual gas was removed by pulling a vacuum on the sealed preform. Second, the fibrous preform was heated to 120 °C for 1.5 h without vacuum while completely melting the resin films and infusing amidst the fabric plies, and then the vacuum pressure was applied again. Third, the prepared laminate was placed in an autoclave and post-cured for 4 h at 180 °C and 2 h at 200 °C. The obtained composite was trimmed and labeled as n-RGO/CFRP, where n is the mass of RGO in the resin film. The sample was heated from 25 to 1000 °C at a rate of 20 °C min^{-1}.

2.3. Characterizations

2.3.1. Simulated lightning current test

An impulse lightning current of component A, as defined in SAE ARP-5412, was applied by using an impulse high-current generator (ICG, established by Xi'an Jiaotong University, Fig. 2(a)). This generator was capable of generating artificial lightning with a waveform of 8/20 μs (i.e., the time required for increasing the current to 10–90% of the maximum was 8 μs, while the time required to pass from 10 to 50% through 90% of the maximum current was 20 μs). Herein, artificial lightning with a peak current of 40 kA (corresponding to AI values of approximately 4×10^4) was utilized to inflict lightning damage to the samples (Fig. S3(b)). Prepared samples (150*150*2 mm) were fixed on a grounded copper plate (Fig. 2(b and c)), which was connected to the ground of the impulse current generator. In this setup, only the edge of the sample was retained by the base plate and the cover frame, which were screw-clamped together. The lightning current was applied in the center of the sample surface serving as an arc entry, and the gap between the tip of the discharge probe and the sample surface was 1 mm.

2.3.2. CFRP performance

The volume resistance of the pristine CFRP samples was evaluated using a multimeter (Keithley 2700) with a four-point probe testing model. The surface resistivity of the RGO layer was characterized using both the voltammetry method and the four-point probe method. The measurement details are provided in the supplementary material.

The morphology of the CFRP was studied using field emission scanning electron microscopy device (Hitachi Su-8010, SEM, Japan) and an optical microscope (Leica DM 4000 M, German). After the simulated lightning strike test, an overhead view of samples was obtained by a digital camera (Nikon, D7200) and an ultrasonic scanning (D9500, Sonoscan, USA). To further examine the internal damage, a microfocus X-ray system (Y.Cheetah, YXLON, German)