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Fabrication and assessment of a thin flexible surface coating made of pristine graphene for lightning strike protection

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ABSTRACT

A thin flexible coating made of pristine graphene was fabricated and applied on the surface of a commercial carbon fiber epoxy prepreg laminate to protect it against the lightning strike. To assess the coating's effectiveness, the coated laminate was subjected to the simulated lightning strike as well as the electromagnetic interference shielding effectiveness (EMI SE) testing. It was observed that the damaged area and volume in the coated laminate were reduced by 94% and 96%, respectively, as compared to the laminate without the coating. Moreover, the coated laminate had an average EMI SE of 51 dB over 100–2000 MHz range, 55 dB over 8–12 GHz range, and 60 dB over 12–18 GHz range marking 22%, 44%, and 49% improvement in EMI SE for each frequency range, respectively. The results indicate a great potential for the developed coating to protect the commercially available prepreg composites against the lightning strike.

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1. Introduction

It is estimated that every commercial aircraft experiences a direct lightning strike once every year. However, since the aircraft skin is conventionally made of aluminum which is an electrically conductive material, the physical damage of lightning strike has often been limited to the burn marks on the skin and the trailing edges. Also, the aircraft metallic skin acts as a Faraday cage during lightning strike, protecting the avionics from electromagnetic interference (EMI) [1].

With the advent of composite materials in aerospace structures, protecting aircraft against lightning strike has become an important task since the fiber reinforced polymer composites (FRPCs) are considerably less conductive as compared to their metallic counterparts [2,3]. Several methods have been employed in aerospace industry for lightning strike protection (LSP) of composite structures. The main functionality of LSP is to provide a continuous conductive path throughout the aircraft exterior especially in the zones more susceptible to lightning strike such as nose, wingtips, nacelles, radomes and extremities of the empennage. Commonly, LSP consists of a lightweight metallic mesh or foil made mainly of aluminum or copper and to a lesser extent phosphor bronze, titanium embedded in the outmost laminate ply which connects the outer surface to a metallic ground plane such as an engine [4–6]. Nevertheless, the metallic meshes embedded in carbon fiber structures increase the weight of the structure. Moreover, they are susceptible to pitting, oxidation and galvanic corrosion, and hence lose their electrical conductivity over the time [7]. To embed the mesh more effectively in the composite structure, many aerospace material suppliers impregnate the metallic mesh with adhesive films, surfacing films, or prepregs. More recently, highly conductive nonwoven veils fabricated with randomly oriented nickel or copper coated carbon fibers and prepregs made with continuous fibers coated using nickel vapor deposition have been developed and tested for LSP applications. Sprayable conductive paints or surfacing films made with nickel nanostrand enhanced polymeric materials is another LSP method currently being considered for aerospace applications [5].

As an alternative solution to the current state-of-the-art in the aerospace industry, nanomaterials such as carbon nanofibers, nickel nanostrands, graphene, and carbon black have been shown to enhance electrical and mechanical properties of FRPCs [8–14]. Gou et al. [8] developed a special paper made of carbon nanofibers and nickel nanostrands and used it as a coating for carbon fiber reinforced polyester composites fabricated with resin transfer molding. Zhang et al. [9] reported that inclusion of 3 wt% of carbon black and copper chloride in the resin, effectively improved electrical conductivity hence lightning strike protection of carbon fiber reinforced epoxy composites. Yamamoto et al. [12] observed that electrical conductivity of alumina fiber reinforced laminates exceeded 100 S/m, marking a 6–8 orders of magnitude

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improvement as compared to the baseline after 1.5 wt% aligned carbon nanotubes were directly grown onto the fiber mat. Morales et al. [11] reduced electrical resistivity of polyester glass fiber composites from the fully insulator down to 10^3-10^5 Ω by adding 0.5 wt% to 1 wt% carbon nanofibers to the resin. The panels in their study were fabricated by hand lay-up and vacuum bagging. Domingues et al. [13] improved the through-the-thickness conductivity of glass finer epoxy composites fabricated using resin infusion by an order of magnitude to 1.4×10^{-3} S/m by inclusion of 0.1 wt% nanotubes into the resin.

Besides physical damage, the lightning strike results in electromagnetic interference (EMI) which could cause severe safety concerns for the advanced avionics equipment in an aircraft [15–17]. The magnetic fields can be calculated by:

$$H = \frac{I}{2\pi r} \quad (1)$$

where H is the field strength (A/m), I is the lightning current (A), and r is the distance between the fuselage and the lightning channel, and π is a constant (equal to 3.14) [18]. Finding an efficient way to eliminate or shield the electromagnetic interference is a critical factor in designing aircraft. As shown in Fig. 1, EMI shielding mechanisms include reflection, absorption, and multiple reflections of electromagnetic radiation to prevent it from penetrating through the material. The shielding material needs to have electrons and holes present, in order to act as mobile carriers to interact with the electromagnetic field. Consequently, shielding materials become electrically conductive. Furthermore, electric and magnetic dipoles are the essential absorption properties of shielding materials because they can interact with the electromagnetic fields when EMI occurs. Shielding materials have high values for the dielectric constant and provide more electric and magnetic dipoles [19–25]. The shielding effectiveness (SE) of a material can be estimated using the following equation:

$$SE_{Total} = SE_A + SE_R + SE_{MR} \quad (2)$$

where SE_{Total} is the total shielding effectiveness, SE_A is the shielding effectiveness due to absorption, SE_R is the shielding effectiveness due to reflection, and SE_{MR} is the shielding effectiveness due to multiple reflections [26]. The shielding effectiveness depends on the material characteristics as well as the frequency of the electromagnetic field. On one hand, SE_R increases with increasing electrical conductivity and SE_A increases with increasing magnetic permeability. On the other hand, SE_R mainly decreases, and SE_A increases with increasing the frequency of the electromagnetic field. Combined reflection and absorption, or multiple reflections, is another mechanism of EMI shielding. This requires both a large surface area and shielding interface area. Fiber-reinforced polymeric nanocomposites are a typical example of shielding with a large interface area, and they form porous materials having a shielding property with a large surface area [27]. Therefore, EMI shielding effectiveness includes the total loss, in decibels (dB), from absorption, reflection, and multiple reflections. The SE is affected by the thickness of the shielding skin. EMI only interacts with the upper-surface region, if it is of a high frequency; therefore, the skin depth (δ) where the electric field drops to 1/e of the incident value is given as

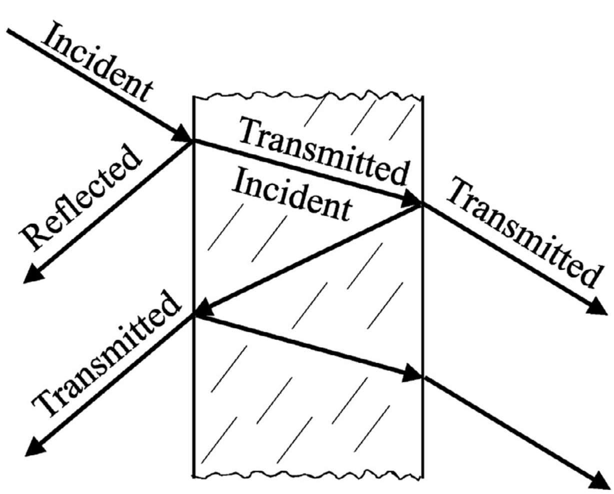

Fig. 1. Schematic of electromagnetic shielding mechanisms consisting of reflection, absorption, and multiple reflections [47].

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \quad (3)$$

where f is the frequency, μ is the magnetic permeability, and σ is the electrical conductivity (S/m).

FRPCs, unlike metals, are vulnerable to EMI due to the inherent electrical insulating properties of polymers. The EMI shielding effectiveness of FRPCs can be improved by enhancing their electrical properties using nanomaterials [12,28–32]. Table 1 shows the EMI shielding effectiveness of different nanocomposite materials. It has been shown that at low frequencies, absorption is the primary EMI shielding mechanism in polymer Nanocomposites enhanced by carbon nanofillers [33,34]. Moreover, several studies have concluded that conductive fillers with a higher aspect ratio, L/D (where L is the length and D is the diameter or thickness of the nanofiller particles) offer better EMI shielding effectiveness than conductive fillers with a lower aspect ratio [35,36]. Amongst all carbon based nanomaterials, graphene sheets provide the best protection against EMI [37]. This was attributed to the high aspect ratio of graphene sheets as well as formation of a 3D network which helps establish a close contact between the particles dispersed in the polymer. More recently, Song et al. reported shielding effectiveness of up to 27 dB for paraffin-based sandwich structures enhanced with multilayer graphene/polymer composite films [38].

Since many composite structures are currently made of prepreg composites cured in an oven or autoclave, it is important to investigate novel methods to protect prepreg laminates against lightning strikes. In this study, the effectiveness of a novel coating made of pristine graphene to protect carbon fiber epoxy prepreg laminates against lightning strike is investigated. For the panels protected with the coatings, the reduction in physical damage as well as the effectiveness of EMI shielding are reported and compared with the base panel fabricated with no coating.

2. Experimental

2.1. Materials

The composite laminates were made using MTM® 45-1 epoxy prepreg reinforced by Toray T-800S 24 k unidirectional carbon fiber with 196 gsm fiber areal weight and 32% resin content supplied by Advanced Composites Group (Tulsa, Oklahoma). The pristine graphene powder (product number: N006-010-P) was purchased from Angstron Materials, Inc. (Dayton, Ohio). The physical dimensions of this fine grayish-black carbon in powder form are less than 5.00 μm in the x and y, and 50–100 nm in the z dimension. Pristine graphene contains 0.6% hydrogen, 0.5% nitrogen, and 0.8% oxygen.

2.2. Methods

2.2.1. Fabrication of graphene thin film

To fabricate the graphene thin film, 4 grams of pristine graphene was mixed and stirred with 500 mL deionized water in a flask for one day. The solution was then lab-scale sonicated at