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Simultaneously increasing the electrical conductivity and fracture toughness of carbon–fiber composites by using silver nanowires-loaded interleaves

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ABSTRACT

A simple method has been developed to simultaneously increase the electrical conductivity and the interlaminar fracture toughness of carbon fiber reinforced composite laminates. The key component of this function integration is a nylon veil surface-loaded with silver nanowires. By interleaving the electrical function-integrated veils into the laminate, the G_{IC} and G_{IIC} is improved 118% and 227%, and the conductivity perpendicular to the fiber direction and through-thickness direction is enhanced over 100 and 10 times, respectively.

1. Introduction

Continues and intensive research and development on structural carbon–fiber composites have led to the success that the latest aircraft like B787 is manufactured largely using these materials in the airframe structures. This is obviously due to the fact that carbon–fiber composites possess high specific strength and stiffness. However, one of the major concerns in design of aircraft composite structures is the impact damage resistance, especially due to low-velocity impact, causing barely visible damage [1–8].

Standard methods for providing toughness in carbon composites follow two approaches. The first one is to blend thermoplastics into a matrix resin by dispersion or dissolving, whereas the second one is to provide a discrete interlayer such as chopped fibers [1], veils [2–4], thermoplastic films [5] or particles [7] between the laminate plies to absorb impact energy and/or deflect damage growth. As an example for the second approach, T800H/3900-2 carbon/epoxy composite, whose interface contains a discrete thin layer of toughened thermoplastic particles, has shown very high impact damage resistance [7]. In a similar philosophy, lightweight, nonwoven veils have also been successfully used as interleaves to toughen the carbon–fiber composite laminates [2,3].

As the composite materials are toughened and their use increases in aircraft structures, there comes the need for the Electro Magnetic Interference (EMI) shielding and lightning strike protection [8–13], because the materials are electrically isolated compared to their metallic counterpart. The traditional lightning-strike protection method for aircraft composites is to directly cover the surface with a conductive layer, such as metal mesh [9,10,13]. However, the method increases the overall weight and many complex parts of aircraft cannot be adopted by the overlying metal appendages.

Currently, there is an increasing interest in developing electrically conductive polymers by incorporating vapor grown carbon fibers (VGCF), carbon nanotubes (CNTs) [14,16,17], graphens [15], or silver nanowires (AgNWs) [18] into the polymer matrix. It is reported that the absolute figure in the conductivity of these filled polymers is still low [14–16]; even there is a low percolation threshold. Additionally, directly filling of these nano-size particles into polymers is frequently accompanied by an increase in viscosity partially through the aggregation of the fillers and the interface problem between the filler and matrix, thus, affecting significantly the process conditions and the mechanical properties [16]. Therefore, structural carbon composites for aircraft application are commonly not filled.

Obviously, the ability for an aircraft to withstand and tolerate both the impact damage and the lightning strikes will be a significant advantage to the aircraft industry. In this paper we present a

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new approach to simultaneously improve the electric conductivity and the impact damage resistance of the standard carbon–fiber reinforced thermosetting resin composite for aircraft application. By applying the interlayer-toughening technology on these composite, an electrically function-added interleaf material is developed, which on one hand provides significant toughening efficiency, and on the other hand, it functions as a tough and flexible conductor through its surface loading of nano-size electrical conductive fillers [19].

2. Materials and methods

2.1. Materials

AgNWs was purchased from Beijing Nahui Kemao Co., Ltd. The average diameter of the AgNWs is about 70 nm and the length is between 20 and 80 μm.

A proprietary textile veil made of nylon was used as the interleaf material. The veil had a free-standing thickness of about 53 μm, and its areal density was about 16 g/m^2. The diameter of the nylon fiber was between 10 and 18 μm.

Carbon fiber prepreg under the trade name of T800/5228 is a product of Beijing Institute of Aeronautical Materials (BIAM). 5228 is an aerospace-grade epoxy commercialized by BIAM. The reinforcing carbon fiber was Toray T800. The ply thickness is about 0.125 mm.

2.2. Application of AgNWs onto the surface of nylon veils

The plain nylon veil was immersed in slurry of AgNWs (5 mg/mL in isopropanol) for 5 s at room temperature. The veil was then taken out and dried at room temperature. The process can be repeated to vary the AgNWs loading levels. Repeat the process 2 times to prepare the veils with the AgNWs areal density of about 1.5 g/m^2.

2.3. Preparation of the composite laminates

For the conductivity study, carbon fiber/epoxy matrix prepreg (T800/5228) of unidirectional (UD) orientation with $[0]_{24}$ stacking sequence was periodically interleaved with the veils surface-loaded. For the toughness study, i.e., to measure the G_{IC} and G_{IIC} properties, one PTFE film of 25 μm thickness was inserted into the symmetrical middle plane of the prepreg to form the pre-crack, followed by laying one veil layer surface-loaded and not loaded in the same mid plane. The laminates was prepared again containing 24 plies and with UD configuration. The preforms were then cured in an autoclave according to the manufacturer's cure cycle. Test samples were cut from the laminated composites according to the testing standards. All samples cured were non-destructively examined by ultrasonic scanning (C-scan) prior to the testing.

2.4. Characterization

Mode I fracture toughness tests were carried out according to the Chinese Aviation Industry Standard HB 7042-96, which is based on the American Society for Testing and Materials (ASTM) standard D5528-01. The samples were 25 mm wide and 180 mm long. The length of pre-crack made by inserting the PTFE film was 50 mm. The thickness of the PTFE film was 25 μm. Before testing, an initial loading was first applied to the specimen and let the delamination crack grow about 20 mm. Thus a fresh pre-crack was made. The specimen was then reloaded and the loading was stopped after an increment of a delamination crack growth of 10 mm. Repeat the process 5 times. Three specimens were tested for each sample. G_{IC} was finally calculated from the load–displacement data at the point where a set of stable crack growth occurring at a critical load.

Mode II fracture toughness tests were performed according to the Chinese Aviation Industry Standard HB 7043-96, which is based on the ASTM standard D790-00. The samples were 25 mm wide and 140 mm long. The length of pre-crack was 40 mm. Before testing, an initial loading was first applied to the specimen and let the delamination crack grow 5 mm to make a fresh pre-crack. The specimen was then also reloaded to obtain a value of G_{IIC}. Five specimens were tested. G_{IIC} was calculated from the load–displacement data at the point where the crack growth occurring at a critical load. A difference to the G_{IC} test is that the crack growth was unstable; it was faster propagated at the beginning from this point.

All samples for G_{IC} and G_{IIC} tests were UD configured with 24 prepreg plies.

The surface resistivity of the AgNWs-loaded veils was tested on the samples 5 mm wide and 100 mm long. The two opposite edges were silver-painted and tightly pressed with copper plate as electrodes. The surface resistivity was calculated by Eq. (1):

$$R_s = R \times \text{width}/\text{length} \tag{1}$$

where R_s is the surface resistivity, R is the resistance tested. R_s can be transferred into volume resistivity (R_v) by Eq. (2):

$$R_v = R_s \times \text{thickness} \tag{2}$$

The volume resistivity of the carbon composite laminate perpendicular to the fiber direction was tested on the samples 10 mm wide and 100 mm long. The volume resistivity along the fiber direction was measured on the samples 2–3 mm wide and 50 mm long. The volume resistivity through-thickness direction was measured on the samples 5 mm square. 5 samples were tested for each orientation. The two opposite edges or surfaces were silver-painted and tightly pressed with copper plate as electrodes. The volume resistivity was characterized by a two-point and a four-point method described in [16], respectively.

3. Results and discussion

3.1. Preparation of the conductive nylon veils

Fig. 1a and b shows the preparation process and optical images of the plain veil as received and the AgNWs-loaded veil. The preparation process was very simple and yielded a uniform AgNWs-coating on the veil. The repeated experiments have revealed that the process was easy and stable. The as-coated veil maintains most of its original characteristics. Its good drapability is demonstrated in Fig. 1c, where the nylon veil coated is exactly draped on a sharp right angle of a carbon composite T-joint. In the context, the surface loading does not affect the draping process conditions. The surface-loaded veil is still flexible and easy to handle.

Fig. 2a shows the veil areal density versus the immersion time. It is observed that the areal density increases linearly with the increase of the immersion times. Fig. 2b shows the dependence of surface resistivity on the areal density. There is a percolation-like transition found. At an areal density of 0.65 g/m^2, the electrical resistivity is 33 Ω/sq and at a density of 1.5 g/m^2, the resistivity decreases significantly to 5 Ω/sq. The decreasing trend is then leveled off with the curve turning asymptotic to 2 Ω/sq. When the areal density is higher than 2 g/m^2, the surface resistivity becomes very small, typically less than 2 Ω/sq. The AgNWs-loaded veil is apparently electrically highly conductive.

The as-coated nylon veil is still tough, highly flexible and porous. Fig. 3 shows typical scanning electron microscopy (SEM) images of the veil before and after surface-loading with AgNWs,