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Mechanical and electrical properties of laminated composites containing continuous carbon nanotube film interleaves

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A B S T R A C T

This study developed a new method of enhancing the mechanical and electrical properties of laminated composites by interleaving continuous carbon nanotube (CNT) film between laminae. CNT film was fabricated using the floating catalytic chemical vapor deposition method and directly deposited onto the fiber fabric surface. The content of CNT film in the laminate was well controlled by the number of CNT film layers deposited. The flexural strength and interlaminar shear strength (ILSS) of the composites initially increased with CNT film content, and then decreased. Meanwhile, the in-plane and out-of-plane conductivities of laminated composites were effectively enhanced after CNT film interleaving.

1. Introduction

The recent decades have witnessed the rapid development of fiber reinforced laminated composites and their increasing applications in aircraft, vehicles, sporting goods, and many other areas [1]. Usually, laminated composites have strong anisotropic properties [2]. The in-plane alignment of reinforcing fibers endows laminated composites with superb in-plane mechanical properties. However, it has been recognized that their out-of-plane properties are quite inferior to the in-plane ones, mainly because there always exists resin-rich areas between the laminae, and no fibers are aligned in the out-of-plane direction. Consequently, laminated composites are prone to suffer from delamination and cracking under axial compression, bending, and impact loading [3], which limits their engineering applications.

Several technologies have been developed to enhance the interlaminar properties, such as 3D-textile preforming [4,5], stitching [6], and z-pinning [7], just to name a few. However, stitching and z-pinning often result in an unavoidable reduction of in-plane mechanical properties due to in-plane fiber volume loss, fiber damage and misalignment arising from z-direction insertion. Recently, researches have shown that interleaving a sheet of electrospun polymeric nanofibers between laminae offered great potential in enhancing the delamination resistance, impact resistance, damping property, flexural strength, and fatigue resistance of laminated composites [8,9].

Carbon nanotubes (CNTs) have shown great promise in reinforcing polymers due to their extraordinary mechanical and physical properties [10,11]. The strength and modulus of CNTs are much higher than those of electrospun polymeric nanofibers, making them the prime candidate for improving the interlaminar mechanical properties of laminated composites [12]. Meanwhile, CNTs are also effective in improving multifunctional characteristics including electrical and thermal conductivities of laminated composites. For example, by electrophoretic deposition of CNTs onto both carbon fiber and glass fiber fabrics prior to the infusion of epoxy resin, Thostenson and coworkers [13–15] found that CNT coating could effectively increase the interlaminar shear strength (ILSS), fracture resistance, as well as the electrical conductivity of the laminated composite. Zhang et al. [16] developed a spray coating technique to deposit CNTs onto carbon fiber prepregs, and found that even low CNT loading (0.047 wt%) could increase the Mode-I fracture toughness of carbon fiber laminates by about 50%. Most recently, Liu et al. [17] inserted a CNT buckypaper into the middle interface of a laminated composite by using a pressure filtration method, and found that the buckypaper enhanced the G_{IC} and G_{IIC} of the laminated composite up to 74% and 82%, respectively. Obviously, the major challenge of these approaches is the

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preparation of large scale and high quality CNT dispersion. To circumvent this challenge, Wardle and coworkers [18,19] inserted vertical CNT arrays or horizontally aligned CNT films made by rolling down vertical CNT arrays between fiber fabrics. They concluded that these two CNT assemblies were effective in enhancing the mechanical and electrical properties of laminated composites. However, major efforts should be made to facilitate the fabrication of large area CNT arrays and their transfer onto fabric surfaces.

Without the prerequisite of CNT dispersion and CNT array fabrication, Li et al. [20] developed a dry-process of manufacturing continuous CNT film using floating catalyst chemical vapor deposition (FCCVD) method. In this process, a stocking-like CNT aerogel was formed in the high temperature reaction furnace, and then collected either as a film or a fiber at the outlet of the furnace. By interleaving such CNT film of 10–15 μm thick in laminated composites, Wang et al. [21] found that the composite electrical conductivity was effectively enhanced, while the tensile strength moderately decreased, mainly due to the insufficient resin infiltration in the thick CNT films.

In this study, we report a new approach of depositing continuous CNT film onto carbon fiber fabrics. CNT film, fabricated using the FCCVD method, was directly deposited onto the carbon fiber fabrics at the outlet of the reaction furnace. The content of CNT film was well controlled by the number of CNT film layers deposited. The microstructure of laminated composite, and the effects of CNT film interleaving on the flexural property as well as electrical conductivity of laminated composite have been studied.

2. Experimental

2.1. CNT film fabrication and deposition

The continuous CNT film was made using the FCCVD method. Fig. 1 shows the schematics of CNT film fabrication and its deposition onto the fabric surface. In this process, a feedstock consisting of about 96.5 wt% ethanol (carbon source), 1.9 wt% ferrocene (catalyst precursor) and 1.6 wt% thiophene (promoter) was injected into a hot furnace along with carrier gas (H_2 and Ar). The injection rates of the feedstock and carrier gas were about 0.15 ml/min and 600 ml/min, respectively. Upon entering the furnace at a temperature of around 1150 °C, these compounds broke down and reacted rapidly to form CNTs, which then interacted to form a continuous stocking-like aerogel. This CNT aerogel was continuously blown out at the exit of the furnace and directly deposited onto the surface of a unidirectional carbon fiber fabric (T700S fibers with 200 g/m^2 areal density) which was wrapped on a rotating spindle. The size of the CNT film coated carbon fiber fabric was scalable, depending on the size of the spindle. The content of CNT film deposited could be well controlled by the number of CNT film layers deposited. In this preliminary study, 1-, 3-, and 5-layer depositions were performed to study the effect of CNT film content on laminated composite properties.

2.2. Composite fabrication

Fig. 2 shows the schematics of laminate fabrication procedures. The CNT film coated unidirectional carbon fiber fabric was cut into 120 mm × 120 mm size (Fig. 2a). Then the dry fabric was infused with epoxy resin, which was dissolved in acetone with a solid content of 30 wt%, as shown in Fig. 2b. After acetone evaporation, twelve plies of the infused fabrics were stacked ply-by-ply in the same orientation, and then cured using a hot-press molding method to form a unidirectional laminate (Fig. 2c). The laminate curing cycle, as shown in Fig. 2d, involved heating at a rate of 3 °C/min from room temperature to 90 °C for 50 min, then curing at 130 °C and 2 MPa for another 2 h, followed by a post-cure process at 150 °C and 2 MPa for 1 h. The laminate was then demoulded and cut using a water-saw to make specimens for testing.

2.3. Characterization

The weight of dry carbon-fiber fabric, CNT film coated carbon fiber fabrics, and final composite was measured by a balance with a sensibility of 0.1 mg. CNT films were characterized by scanning electron microscopy (SEM) (Hitachi S4800, Japan) and transmission electron microscopy (TEM) (Tecnai G2 F20 S-TWIN, Japan). Flexural tests of laminated composites were performed using a three-point bending test according to ASTM D790 standard [22] to obtain flexural modulus and flexural strength. The ILSS was measured using the short-beam method according to ASTM D 2344 [23]. All tests were carried out using an Instron 3365 load frame in displacement control mode. The cross-section and the fractography of the laminates were also imaged by SEM. The long-beam bending specimens were about 36 mm long, 12.7 mm wide, and 2 mm thick. Short-beam bending specimens were about 12 mm long, 4 mm wide, and 2 mm thick. The electrical conductivity of the long-beam bending specimens was measured using a commercial resistance meter (Victor VC890D). Surfaces were polished by a sandpaper, and then silver paste was applied on the underside and topside of the specimens to improve the electrical contact between the probe and the specimens. Measurements were performed on at least five specimens for each mechanical and electrical test.

3. Results and discussions

3.1. Structure and morphology of CNT films

The content of CNT film in a laminate was determined by comparing the weight of the laminate with and without CNT film interleaving. The composite with no CNT film interleaving is referred as control composite. For the 1-, 3-, and 5-layer of CNT film

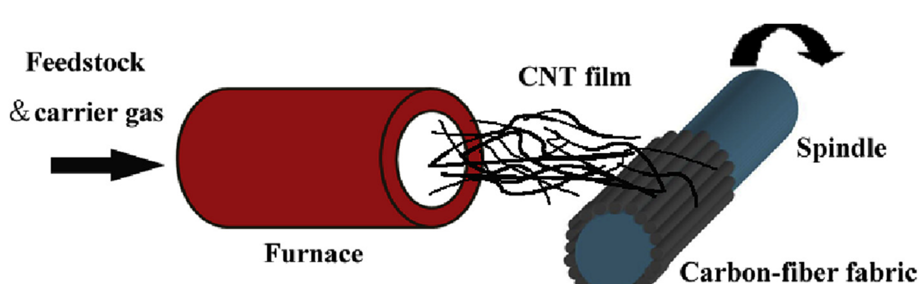

Fig. 1. Schematics of CNT film fabrication and its deposition onto carbon fiber fabrics.