TUNABLE ELECTRO-THERMAL SYSTEM BASED ON ORIENTATION AND LAYUP OF HIGHLY-ALIGNED CARBON NANOTUBE WEBS

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Abstract

Directly drawn carbon nanotube (CNT) webs were previously studied, by the authors, as a promising heating element for an electro-thermal anti-icing/de-icing system. Further tailoring of these electro-thermal properties may be achieved by the novel approach of exploiting the effect of the orientation and layup of these highly-aligned CNT webs, which exhibit anisotropic conductivity.

Test coupons with different aspect ratios (L/W in 0.25, 0.73, 1.0, 4.0, 8.9) and web orientations (θ = 0°, 10°, 22.5°, 45°, 67.5°, 90°) were prepared and their conductivity compared to analytical predictions based on the conductivity theory of anisotropic solids with infinite and finite dimensions. Depending on the aspect ratio of the specimens, the conductivity as a function of web orientation is bound by two theoretical curves: $L/W \to 0$ and $L/W \to \infty$. Furthermore, heating elements with different CNT web layup were prepared, where it is shown that their electrical properties may be predicted by the analytical model.

This study demonstrates that CNT web orientation and layup can be used to tune and pattern the electrical conductivity, as well as the heat distribution of an electro-thermal system.

1. Introduction

Owing to their superior specific strength and stiffness, carbon fibre reinforced polymer (CFRP) composites have been increasingly used in the primary structure of aircraft. The latest generation of passenger aircraft, the Airbus A350 XWB and Boeing 787, are more than 50 wt.% [1]. The traditional anti-icing/de-icing (AI/DI) system, the hot air bleed system, which ducts hot air from the engine, is not preferable due to the lower thermal conductivity of composites compared to metals. As a consequence, novel AI/DI systems are urgently needed to reach the demands of high energy efficiency and low structural and maintenance complexity. An electro-thermal system is proposed in this work to meet this requirement.

In an electro-thermal system, the heating element is the key component. Currently, a sprayed metal film, between glass-fibre plies, is used on the Boeing 787 [2], but faces the problems of interfacial compatibility, bonding and weight. Carbon nanotubes (CNTs) [3,4] are attractive alternatives, as a result of their high compatibility with CFRP composites, rapid heating and negligible weight. Additionally, they may also contribute to the composite structural properties [5,6].

In particular, the directly drawn highly-aligned CNT web has been studied and verified as a promising heating element, for the electro-thermal anti-icing/de-icing system proposed in our previous work, owing to its high tuneability, flexibility and anisotropy [7]. The resistance of a laminated CNT web decreases inversely with the number of its layers. Also, within a single web, the length of CNTs can be controlled during the CVD procedure. For further tailoring the electro-thermal performance, as the CNTs are highly aligned and conductive along the draw direction and exhibit orthotropic conductivity, the effect of orientation and layup of CNT webs are discussed in this work.

2. Materials and methods

2.1. Materials

The CNT forests (Fig. 1a,b) were synthesised by chemical vapour deposition (CVD) of acetylene, at 700 °C, grown on a silicon wafer with an iron catalyst [8]. The obtained CNTs, with an average length of 300 μm and an average diameter of 10 nm, were drawn directly to form the aligned continuous CNT web and wound onto mounted frames to the required thickness. Then transferred and embedded between two plies of SE84LV/RE295 GF/epoxy woven prepreg, with copper foil (Alfa Aeser, 25 µm thick) used as the electrical buses to connect samples and power supply.

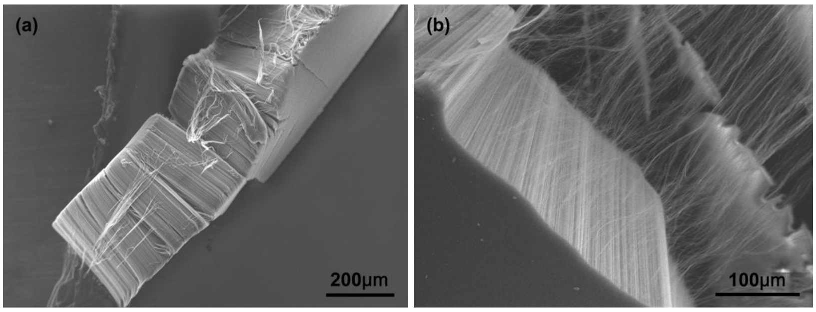

Figure 1. (a, b) SEM images of highly aligned CNT forest.

2.2. Sample preparation and characterization

Test coupons with different aspect ratios (L/W of 0.25, 0.73, 1.0, 4.0 and 8.9, where 'L' refers to the web length between copper buses and 'W' refers to the width of web in contact with each bus) and CNT web orientations (θ = 0°, 10°, 22.5°, 45°, 67.5°, 90°, where θ is the angle between the CNT web alignment and the electric potential) were prepared. In addition, composites with different CNT web layups ($[0_4]$, $[45_4]$, $[90_4]$, $[0_2/22.5_2]$, $[0_2/45_2]$, $[0_2/90_2]$, $[+22.5_2/-22.5_2]$, $[+45_2/-45_2]$, $[+67.5_2/-67.5_2]$ and $[22.5_2/-67.5_2]$, corresponding to samples 1-10 respectively in Fig. 3) were prepared with L/W=1 or 4. In this work, 20 layers of CNT web were applied for all the samples, based on the previous study [7]. Vacuum bagging was used to cure the composites, at 120 °C for 1 hour. The obtained samples were cut to the desired geometry by a Struers Accutom-50 cutting machine. A JSM-6500F Field Emission Scanning Electron Microscope was used to observe the morphology of CNTs (Fig. 1a,b). An Agilent 34450A 5½ Digit Multimeter was employed to measure the resistance of the samples, using the four-probe method. An FLIR SC640 thermal imaging (IR) camera was used to monitor the heat distribution of the samples.

3. Results and discussion

3.1. Effect of CNT web orientation and sample aspect ratio

An analytical model was developed to predict the electrical conductivity of the samples, based on the thermal conductivity theory of anisotropic solids [9-11]. The values of longitudinal (σ_l) or transverse (σ_t) conductivity, which are not related to the sample aspect ratio, were used as the base points. When L/W→0, the conductivity is given by Eq. 1:

$$\sigma_x = \sigma_l \cos^2\theta + \sigma_t \sin^2\theta \tag{1}$$

while when L/W→∞, Eq. 2:

$$\sigma_x = (\sigma_l \cos^2\theta + \sigma_t \sin^2\theta) - \frac{(\sigma_l - \sigma_t)^2 \sin^2\theta \cos^2\theta}{\sigma_l \sin^2\theta + \sigma_t \cos^2\theta} \tag{2}$$

The calculated conductivites and experiment results of samples with various orientations and aspect ratios are shown in Fig. 2a. For all samples, the conductivity decreased with increasing angle, θ, where θ=0º (90º) implies that the CNT web is aligned perpendicular (parallel) to the copper buses. For samples with increasing aspect ratio, the conductivity shifted towards the L/W→∞ curve as expected, and all experimental results are bounded by the two theoretical curves of L/W→∞ and L/W→0.

In order to study the effect of the CNT web orientation on the heating performance, samples with L/W = 0.73 were monitored by an IR camera at a constant voltage of 12 V (Fig. 2b). Most heat was generated along the aligned CNT web direction. With increasing angle, the conductivity, maximum temperature and heating area was shown to decrease.

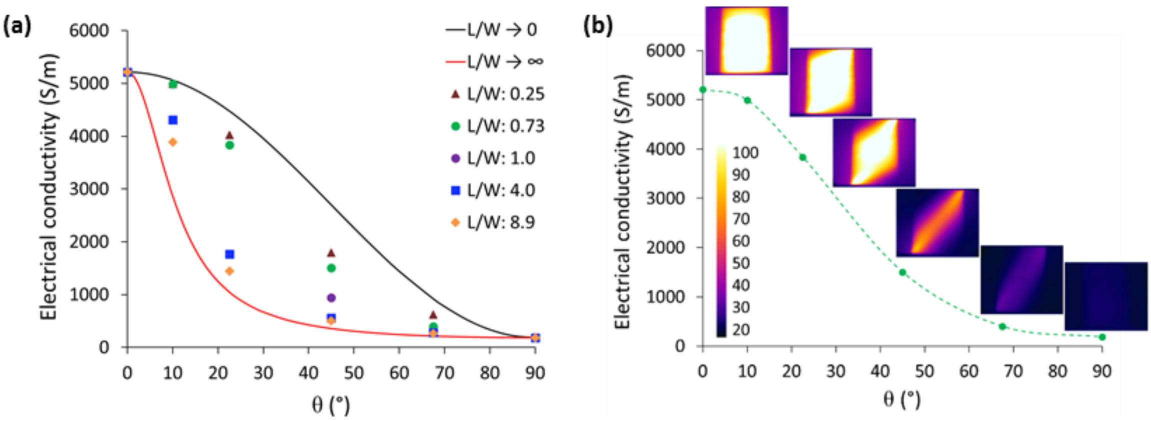

Figure 2. (a) Electrical conductivity of CNT web composites with different orientations and aspect ratios. (b) Steady-state heat distribution of the composites with L/W = 0.73, a constant voltage of 12 V.

3.2. Effect of CNT web layup

For further tailoring the conductivity and heating performance, heating elements with different layups were fabricated, with 20 layers of CNT web in total. Based on the above analytical model, for samples with bidirectional laminate layups (n_1 layers of CNT web orientated at an angle θ and n_2 layers at φ) and L/W→0, the following equation was used, Eq. 3:

$$\sigma_{\theta,\varphi}^{c0} = p_\theta(\sigma_l \cos^2\theta + \sigma_t \sin^2\theta) + p_\varphi(\sigma_l \cos^2\varphi + \sigma_t \sin^2\varphi) \tag{3}$$

When L/W→∞, Eq. 4:

$$\sigma_{\theta,\varphi}^{c\infty} = p_\theta \left[(\sigma_l \cos^2\theta + \sigma_t \sin^2\theta) - \frac{(\sigma_l - \sigma_t)^2 \sin^2\theta \cos^2\theta}{\sigma_l \sin^2\theta + \sigma_t \cos^2\theta} \right] + p_\varphi \left[(\sigma_l \cos^2\varphi + \sigma_t \sin^2\varphi) - \frac{(\sigma_l - \sigma_t)^2 \sin^2\varphi \cos^2\varphi}{\sigma_l \sin^2\varphi + \sigma_t \cos^2\varphi} \right] \quad (4)$$

Where $p_\theta = n_1/(n_1+n_2)$, $p_\varphi = n_2/(n_1+n_2)$, are the proportion of each orientation.[12]

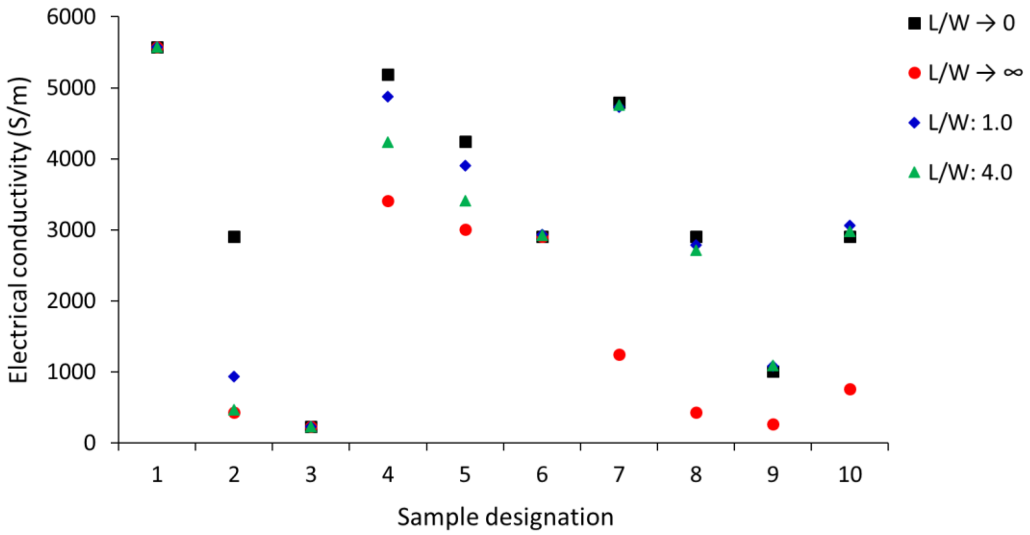

Figure 3. Calculated (L/W→0, ∞) and experimental (L/W = 1.0, 4.0) electrical conductivity of CNT web composites with different layups

For samples with a strongly biased layup direction, i.e. sample 2 ([45_4]), 4 ([$0_2/22.5_2$]) and 5 ([$0_2/45_2$]), similar to the above unidirectional samples (θ: 10° to 67.5°), the aspect ratio has a significant effect on their conductivity. While for all the other layups, sample geometry has little effect owing to their unbiased structures. As a result, all the experimental results show similar values as the L/W→0 calculations (Fig. 3). In particular, when $|\theta - \varphi| = \pi/2$ and $n_1 = n_2$, samples 6 ([$0_2/90_2$]), 8 ([$+45_2/-45_2$]) and 10 ([$22.5_2/-67.5_2$]) are equivalent, with the conductivity at the average value of σ_l and σ_t (sample 1and 3), as well as the average value of samples 7 ([$+22.5_2/-22.5_2$]) and 9 ([$+67.5_2/-67.5_2$]) (Fig. 3).

4. Conclusions

Composite laminates with different CNT web orientations, aspect ratios and layups were prepared, and an analytical model proposed. All the experimental results were bounded by predicted theoretical values of L/W→0 and L/W→∞. This verified the high alignment of the CNTs within the web. Combining the CNT web orientation and layup with CNT length and the number of CNT web layers, a highly tuneable electro-thermal system may be achieved.

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