CARBON NANOTUBE WEB: A PROMISING HEATING ELEMENT FOR ANTI-ICING/DE-ICING APPLICATIONS

Xudan Yao[1], Brian G. Falzon[1*] and Stephen C. Hawkins[1,2]

[1]School of Mechanical and Aerospace Engineering, Queen's University Belfast, UK, BT9 5AH
Email: xyao01@qub.ac.uk, b.falzon@qub.ac.uk, Stephen.Hawkins@qub.ac.uk,
Web Page: http://www.qub.ac.uk

[2]Department of Material Science and Engineering, Monash University, Clayton, Victoria, Australia, 3800
Email: Stephen.Hawkins@monash.edu, Web Page: http://eng.monash.edu.au

*Corresponding Author: Brian G. Falzon b.falzon@qub.ac.uk

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ABSTRACT

A carbon nanotube (CNT) web is a continuous sheet or film of horizontally oriented CNTs obtained by drawing from specially grown CNT forests produced by chemical vapour deposition (CVD). As the CNTs are highly conductive and predominantly aligned along the draw direction, by controlling the aspect ratio of these CNTs and the number and orientation of stacked web layers, a tailored resistance may be achieved. Consequently, the CNT web is a promising choice for an electro-thermal heater for anti-icing/de-icing applications.

Layers of CNT web were compared to plies of carbon fibre (CF), as the heating elements within a glass fibre laminate assembly. Copper foil was used for distribution buses. The CNT web structure had a higher heating and cooling rate than the CF, which indicates that it needs less time and energy to reach the desired temperature whilst meeting the requirement of rapid de-icing. Moreover, the temperature variation across the CNT web specimen, as shown by IR imaging, was negligible compared with that for CF. In addition, compared with eight CF plies (0.314 g/cm^2), a 20-CNT-web heater (37.8 μg/cm^2) is more than 8000 times lighter. Consequently, owing to its rapid and uniform heating, as well as its negligible weight, CNT web is a promising heating element for anti-icing/de-icing applications. Both de-icing and anti-icing performance have been verified and composites with 30 or 40 layers of CNT web as the heating element showed rapid ice protection.

1 INTRODUCTION

In the latest generation of wide-body passenger aircraft, carbon fibre reinforced polymer (CFRP) composites have been widely used, owing to their superior specific strength and stiffness, high corrosion and fatigue resistance. However, the relatively low thermal conductivity and greater-than-ever emphasis on energy efficiency demands a new approach to prevent ice accretion and retention on susceptible aerodynamic surfaces. An electro-thermal system, which is based on an electrical heating element, can be used for both anti-icing and de-icing. Different novel materials have been investigated as the heating element, including an electro-conductive textile [1], carbon nanotubes (CNTs) [2,3], sprayable metal layer [4], carbon fibres (CF) [5,6] and constantan wires [7].

Different forms of carbon fibres, such as woven fabric, unidirectional fabric and short fibre mats, have been used as the heating element, which can be used for ice elimination as well as for curing the composite [8]. Carbon fibre is a promising choice for anti-icing/de-icing, as it is the same material as the structural material. As indicated in previous work by the authors [9], composites with carbon fibres aligned parallel to the electrodes have adjustable resistance and such assemblies were used as part of this study.

A directly drawn CNT web is produced by drawing a continuous sheet or film of horizontally oriented CNTs from specially grown CNT forests produced by chemical vapour deposition (CVD)

[10], which is available within the Advanced Composites Laboratory at the Queen's University Belfast. The web is typically only 50 nm thick when densified, has an areal density of approximately 1.5 to 2 μg/cm^2 and the CNTs are highly aligned and conductive along the draw direction. As illustrated by Musameh et al [11], the sheet resistance of a laminated CNT web decreases in inverse proportion to the number of layers. Also, within a single web, the length of CNTs can be controlled during the CVD procedure. Accordingly, by controlling these two parameters (number of layers and length of CNTs) the desired electro-thermal properties of the CNT web can be achieved.

In this work, woven glass fibre (GF) prepreg was used to support and insulate the CNT web. For comparison, GF prepregs were also applied to the CF plies. Composites with different layers of CNT web as well as different plies of CF were prepared and assessed for their heating performance, de-icing and anti-icing capability.

2 EXPERIMENTAL

2.1 Materials

Gurit SE84LV/HMC CF/epoxy unidirectional prepreg and SE84LV/RE295 GF/epoxy woven prepreg were used in this work. Strips of 10 mm wide copper foil were used as the electrical buses to connect the samples to a power supply. The CNT forests were fabricated by CVD of acetylene at a temperature of 700 °C, grown on a silicon wafer with iron as the catalyst [12], yielding an average CNT length of 300 μm and an average diameter of 10 nm. The obtained CNTs were drawable (Fig. 1(a)) and can be drawn directly into a fine continuous web (Fig. 1(b)).

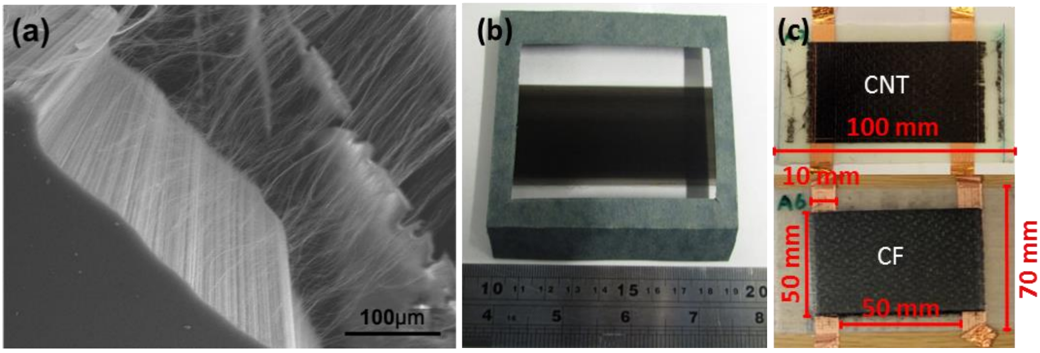

Figure 1. (a) SEM image of drawable CNT forests (b) CNT web layers (c) GF/CNT/epoxy and GF/CF/epoxy composite

2.2 Sample preparation

Different layers of CNT web and CF prepreg of size 70 mm × 50 mm, as shown in Fig. 1 (c), were embedded between two plies of woven GF prepreg (100 mm × 70 mm). Copper foil buses were placed between the heating element and GF, leaving a test area of 50 mm^2 (Fig. 1 (c)). After the layup, the composites were cured at 120 °C for 1 hour using vacuum bagging, and the parameters of the samples are listed in Table 1.

Table 1. Parameters of the samples with different layers of CNT web or CF plies

No. of CNT layers / CF plies	Laminates with CNT web layers				Laminates with CF plies			
	10	20	30	40	1	2	4	8
Weight (g)	6.12	6.16	6.09	6.13	7.75	9.27	12.62	19.14
Thickness (mm)	0.45	0.45	0.46	0.46	0.73	1.01	1.59	2.79

2.3. Characterization

A JSM-6500F Field emission Scanning Electron Microscope was used to observe the morphology of CNTs (Fig. 1 (a)). An Agilent 34450A 5½ Digit Multimeter was employed to measure the resistance of the samples, using the four-probe method. The resistive heating performances of the composites were investigated. The current was supplied by a DC power supply, the temperatures of the samples were recorded by RS-1384 4 Input Data Logging Thermometers using K-type thermocouples, and the temperature distribution was monitored by an FLIR SC640 thermal imaging camera.

For the de-icing and anti-icing test, a reservoir was built over the sample, using vacuum bagging tape, to hold water over the sample (approximately 7.5 mL with a depth of 3 mm). An environmental chamber was used to create icing conditions, and a digital camera was mounted inside the chamber to monitor the specimens. Thermocouples were applied to measure the temperature variation during these tests.

3 RESULTS AND DISCUSSION

3.1. Heating performance

GF laminates with different layers of CNT web as well as different plies of CF were prepared with copper foil as the distribution buses. The resistance and heating performance at room temperature were compared and investigated. Fig. 2 (a) shows that for both CNT web and CF, increasing the number of the layer, decreased resistance. The resistances of samples with ten and twenty layers of CNT web were noted to be similar to samples with four and eight layers of CF respectively. To assess heating performance, a constant voltage of 16 V was applied to the samples. Temperatures were measured and recorded by thermocouples, in the middle of each specimen, and the results are shown in fig. 2 (b). The samples with CNTs as the heating element have higher heating and cooling rates. As constant voltage was applied, samples with lower resistances reached higher temperatures, and GF laminate with 40 layers of CNT web obtained the highest temperature.

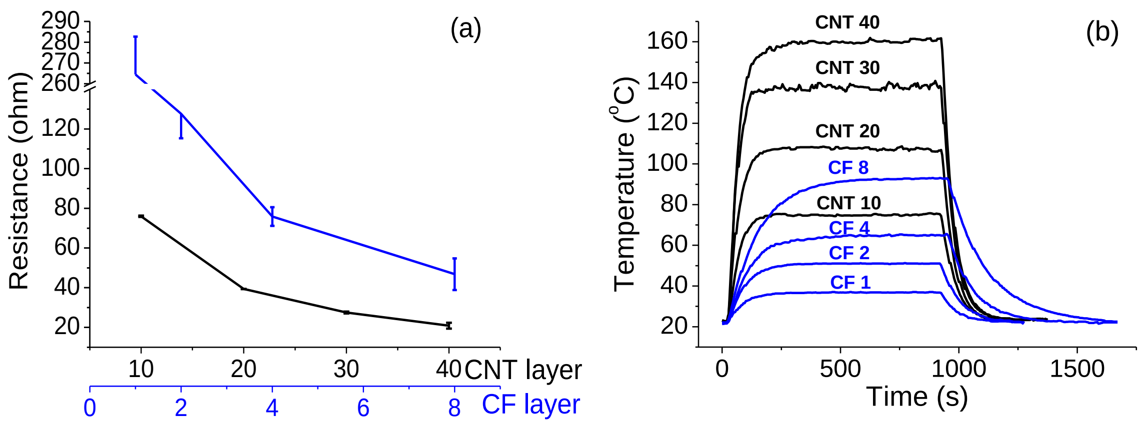

Figure 2. (a) The resistance variation with the change of CNT web or CF layer (b) Room temperature heating performance of samples with different layers of CNT web or CF plies as the heating element, under a constant voltage of 16V.

In order to investigate the uniformity of heat distribution, four thermocouples were applied to each sample and an IR camera was used to monitor the heat distribution. Samples with eight layers of CF (Fig. 3 a, d); twenty layers of CNT web (Fig. 3 b, e); and constantan wires [5] (Fig. 3 c, f) as the heating element, were compared. Although having similar resistance, the CNT web structure had a higher heating and cooling rate (Fig. 3b) than the CF (Fig. 3a), which indicates that it needs less time and energy to reach the desired temperature and meets the requirement of rapid de-icing. Moreover, the temperature variation across the CNT web specimen, as shown by IR imaging (Fig. 3e), is negligible compared with that for CF (Fig. 3d), while for the constantan wire-heated specimen the temperature is highly variable (Fig. 3 c, f). In addition, compared with eight CF plies (0.314 g/cm^2), the 20-CNT-web heater (37.8 μg/cm^2) is more than 8000 times lighter. Consequently, owing to its rapid and uniform heating, as well as its negligible weight, CNT web is a promising heating element for anti-icing/de-icing applications.

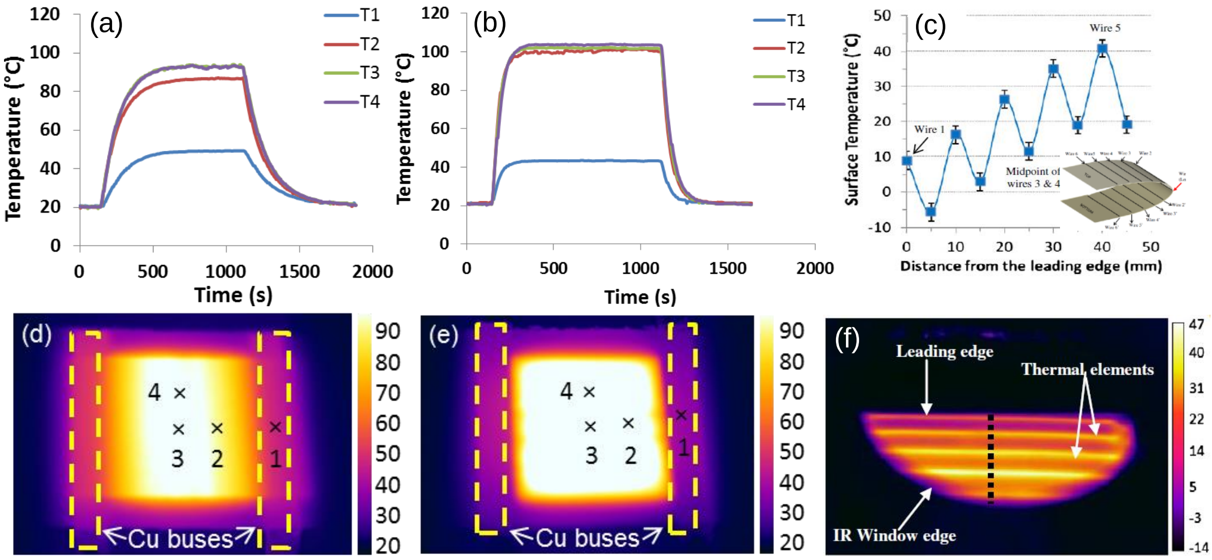

Figure 3. Temperature history under constant voltage 16 V for (a) GF laminate with 8 layers of CF (b) GF laminate with 20 layers of CNT web; steady-state temperature distribution and thermocouple locations for (d) GF/CF and (e) GF/CNT samples; (c) surface temperature distribution of device with constantan wires as the heating element and (f) temperature distribution on top surface [7]

3.2. De-icing

The de-icing performance of the GF laminate with different heating elements was studied within an environmental chamber. A camera was placed inside the chamber to monitor the de-icing procedure, recording an image every 10 seconds. The ice was formed on one side of the samples in advance, and the samples were fixed upright, with a thermocouple attached to the centre of the surface on the other side. A constant voltage (16 V), was applied to the samples. The results are shown in Fig. 4. It indicates that the GF laminate with 30 or 40 layers of CNT web as the heating element could remove the ice within 25 to 50 seconds. Samples with 20 layers of CNT web or eight layers of CF needed 150s and 190s respectively, while with 10 layers of CNT web or four layers of CF needed around 300s. Composites with one or two layers of CF, were unable to shed the ice.

Considering the significance of time during in-flight de-icing, rapid de-icing is necessary. Owing to the rapid heating of the CNT webs, they could heat up the surface and remove the ice rapidly. The negligible weight of the heating elements, which may be tailored to provide specific resistance, coupled with a desired power input, demonstrated the viability of this CNT-based device for energy efficient de-icing applications.

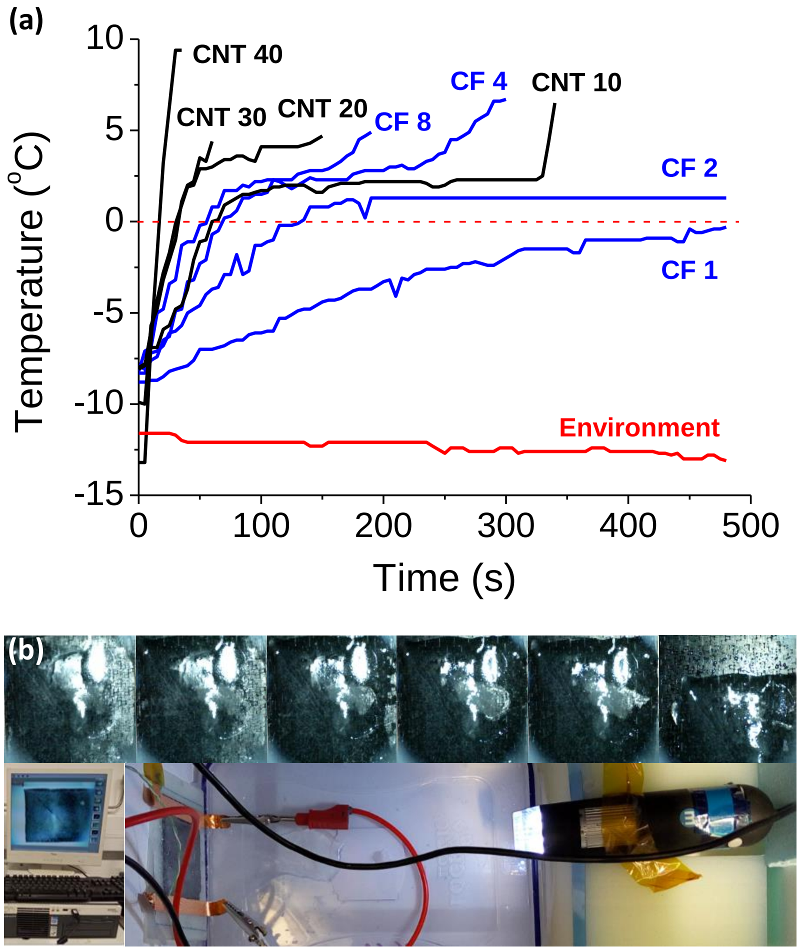

Figure 4. (a) Temperature history during the de-icing procedure under a constant voltage of 16 V and (b) Experimental setup showing the evolution of de-icing for the CNT 30 sample.

3.3. Anti-icing

As de-icing requires additional energy to overcome the latent heat of melting, anti-icing, for preventing ice build-up on an aerodynamic surface, requires less energy. In this instance, 10 V was supplied as the constant voltage. The samples were pre-cooled in an environmental chamber, and ice water was applied to their surfaces using a similar arrangement to that for the de-icing studies. The temperature history during the anti-icing procedure, and the performance of the various specimens, are summarized in Fig. 5.

Composites with 20, 30 and 40 layers of CNT webs displayed a similar trend, characterized by three stages. In the first stage, the samples and water reached a steady state temperature (second stage). Subsequent heating caused the water to evaporate and with no cooling liquid over the composite surface, the temperature increased to a higher steady-state value (third stage). Composites with one, two and four layers of CF or 10 layers of CNT web exhibited a similar trend, which also have three stages. The first stage was also the heating up stage; while in the second stage, the input power was not sufficient to prevent the water from freezing. After all the water was frozen, the absorbed heat and the released heat reached a new thermal equilibrium.

From the images of the final states of the various samples, composite surfaces with 30 and 40 layers of CNT web are shown to be dry; with 20 layers of CNT web or eight layers of CF the specimens are mostly dry with some icing around the edges. This is consistent with the temperature distribution shown in the IR images of Fig. 3 (d) (e). However, GF laminate with one, two, or four layers of CF or 10 layers of CNT web could not achieve effective anti-icing, where ice is still observed on the specimen surfaces.

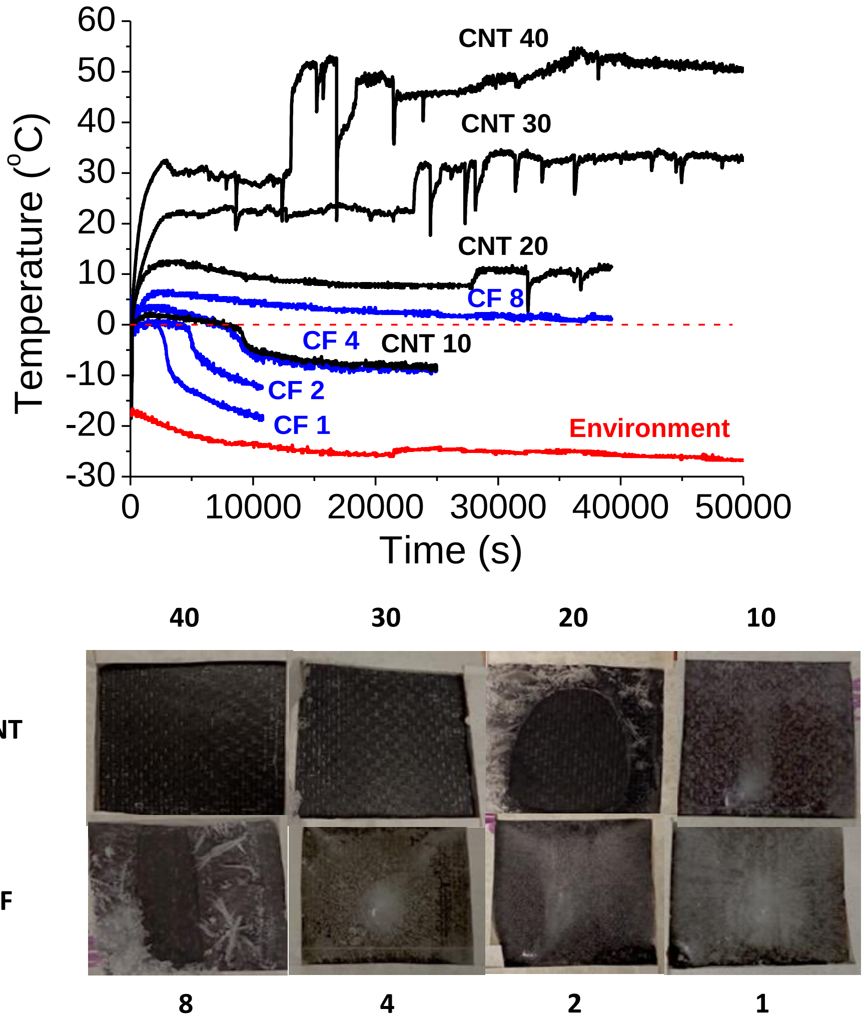

Figure 5. Temperature history during anti-icing and final states under a constant voltage of 10 V

4 CONCLUSIONS

Compared to the use of CF plies as heating elements in a GF assembly, a CNT web structure demonstrated a higher heating and cooling rate. The temperature variation across the CNT web specimen, as shown by IR imaging, was negligible compared to that for CF specimens. In addition, for equivalent resistance, compared with eight CF plies (0.314 g/cm^2), the 20-CNT-web heater (37.8 μg/cm^2) was more than 8000 times lighter. Consequently, owing to its rapid and uniform heating, as well as its negligible weight, CNT webs are a promising heating element for anti-icing/de-icing applications.

In order to verify the CNT web's function as an effective heating element for ice protection, both de-icing and anti-icing studies were conducted. As de-icing requires additional energy to overcome the latent heat of melting, anti-icing requires less energy. The results show that compared with de-icing, anti-icing needs less power sustained over a longer period. In addition, the GF laminate with 30 and 40 layers of CNT web reached both rapid de-icing and anti-icing successfully. In particular, for de-icing, with a constant 16 V voltage supply, the GF laminate with 40 layers of CNT web could remove accreted ice within 25 seconds.

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