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Low temperature growth of carbon nanotubes on carbon fibre to create a highly networked fuzzy fibre reinforced composite with superior electrical conductivity



T.R. Pozegic^a, I. Hamerton^b, J.V. Anguita^a, W. Tang^{a,b}, P. Ballocchi^c, P. Jenkins^c, S.R.P. Silva^{a,*}

^a Advanced Technology Institute, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford GU2 7XH, United Kingdom ^b Department of Chemistry, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, GU2 7XH, United Kingdom ^c Bombardier Aerospace, Airport Road, Belfast, Northern Ireland BT3 9DZ, United Kingdom

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ABSTRACT

We report a method for the growth of carbon nanotubes on carbon fibre using a low temperature growth technique which is infused using a standard industrial process, to create a fuzzy fibre composite with enhanced electrical characteristics. Conductivity tests reveal improvements of 510% in the out-of-plane and 330% in the in-plane direction for the nanocomposite compared to the reference composite. Further analysis of current-voltage (I–V) curves confirm a transformation in the electron transport mechanism from charge – hopping in the conventional material, to an Ohmic diffusive mechanism for the carbon nanotube modified composite. Single fibre tensile tests reveal a tensile performance decrease of only 9.7% after subjecting it to our low temperature carbon nanotube growth process, which is significantly smaller than previous reports. Our low-temperature growth process uses substrate water-cooling to maintain the bulk of the fibre material at lower temperatures, whilst the catalyst on the surface of the carbon fibre is at optimally higher temperatures required for carbon nanotube growth. The process is large-area production compatible with bulk-manufacturing of carbon fibre polymer composites.

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1. Introduction

Carbon fibre reinforced polymers (CFRP) have revolutionised industries that demand mechanically strong materials without the potential weight penalty [1–3]. However, in the aerospace industry, metals are still being incorporated into structures to impart electrical conductivity to avoid charge build up gained through air friction and lightning strikes. Charge accumulation could lead to discharge sparks and/or material failure. The addition of metals, however, adds weight, cost, leads to corrosion issues and has proven troublesome to consolidate with the carbon fibre composite. Hence, there is interest in enhancing the electrical conductivity without relying on metals. With the current advancements in nanotechnology there exists opportunity to not only improve mechanical properties, [4–11] but to substantially enhance the electrical [12–14] and thermal [15–17] properties; introducing the composite material into new applications. Fabricating

* Corresponding author.

E-mail address: s.silva@surrey.ac.uk (S.R.P. Silva). http://dx.doi.org/10.1016/j.carbon.2014.03.038 0008-6223/© 2014 Elsevier Ltd. All rights reserved.

CFRP with the most promising nanomaterial, carbon nanotubes (CNTs), has proven challenging with issues such as dispersion, degradation of the CNTs and matrix viscosity. The general trend has recently been focused on in situ-growth of CNTs [18-22] or attaching CNTs to the carbon fibre, [23-28] creating a 'fuzzy' carbon fibre reinforced polymer (FCFRP) composite. These methods are preferred over dispersing the CNTs in the polymer matrix [29]. Despite advances in the dispersion techniques of CNTs in the polymer matrix [19,30–32] using techniques such as: covalent and non-covalent modification, surfactant addition and by mechanical processing methods, the technology is still in its infancy with issues such as: poor nanotube alignment, limitation to small weight percentage additions, poor CNT graphitisation, CNT agglomeration, lack of morphology control, and poor matrix infusion capability when subjected to infusion techniques such as resin transfer moulding (RTM) and vacuum assisted resin transfer moulding (VARTM) [9,11,27,33,34].

Using carbon fibre as a substrate for CNT growth allows for well dispersed and high density of CNTs to be incorporated in the composite. The CNTs can bridge adjacent carbon fibres, creating electrical and thermal percolation pathways throughout the composite as well as enhancing the mechanical characteristics of CFRPs. These include the out-of-plane characteristics, as well as enhancing the interfacial adhesion between carbon fibres and resin-dominated processes such as the interlaminar shear strength or longitudinal fibre compression [27,35]. This is nontrivial considering that the most common failure mechanism of conventional composites is fibre bending and breaking due to the lack of support by the matrix. These parameters are factors that determine the limits of the mechanical performance of CFRP composites [36]. It should also be stated that the challenge of dispersing the CNTs is removed, as is the potential damaging methods currently used to disperse the CNTs. Thus, fewer defective CNTs are incorporated into the composite resulting in improvements in electrical and thermal properties.

From the onset of the early experiments [37] of carbon nanofibre growth on carbon fibre it has been emphasised the importance of preventing mechanical degradation of the carbon fibres by the intense heating required for CNT growth using standard chemical vapour deposition (CVD) techniques. Thostenson et al. [38] used this growth technique for surface addition of CNTs on pitch-based carbon fibres. This spurred many studies to investigate the influence of CNTs on the fibres by either CVD growth processing or attaching the CNTs on the carbon fibre. Parameters such as pre-treatment, [20] temperature, [9,35,39-41] catalyst [9,20,41-45] (metallic and non-metallic) and hydrocarbon source [41,43] were reported. The majority of the work in the area considered the mechanical improvements from interlaminar toughness to tensile strength, however, very few studied the implications on the electrical and thermal properties.

At present, growing CNTs on the surface of carbon fibre has the advantage over attaching CNTs in terms of the quantity, length, controllability of size of CNTs [45] and orientation [46] that can be incorporated into the composite. All of which are crucial if the nanophase is to compliment the CFRP composite. However, with growth temperatures usually above 700 °C and reactive atmospheres present within the standard CVD chamber, significant degradation of the fibre has been observed [35,39,47-49]. If FCFRP is to replace CFRP in industries, it is imperative that the mechanical properties which make CFRP useful are retained. We report a process that allows the growth of CNTs with minimum degradation to the underlying carbon fibre substrate by maintaining the substrate at lower temperatures than those normally used in conventional CVD techniques for CNT growth without compromising on quality, yield or production time of CNTs. Our Surrey Nanosystems 1000n photo-thermal chemical vapour deposition (PTCVD) growth system features a water-cooled substrate table (cooled to 5 °C) and uses optical radiation for thermal heating [50,51]. This arrangement enables part of the carbon fibre fabric to remain at low temperature, whilst the catalyst on the carbon fibre (that is directly exposed to the optical radiation) is allowed to reach a high temperature necessary for the growth of carbon nanotubes of high crystalline quality [35,39,41,44,49,52-59]. After CNT growth, the thermal radiation (sourced by an array of halogen lamps) can be turned-off quickly, enabling the PTCVD to cool down in a short time, ${\sim}5\,\text{min},$ which greatly improves the sample throughput yield (up to 8 times as many samples compared to conventional CVD systems) and reduces the amount of gas used for cooling. As it employs optical heating instead of resistive heating, where there is a much larger thermal resistance between it and the catalyst sites, the system reduces the amount of energy required for growth. Additionally, this method is large-area compatible and directly transferable to industrial manufacturing companies. A detailed description of the design of the commercially available PTCVD and its operation principles for CNT growth at low substrate temperature is available for the case of other types of substrates (temperature-sensitive semiconductor substrates) elsewhere [50,60,61]. These studies report successful growth of CNTs of high crystalline quality, at low substrate temperatures.

Plasma Enhanced Chemical Vapour Deposition (PECVD) has the potential to lower the growth temperature but with the drawback of growing poor quality nanotubes or the growth of only carbon nanofibres [50]. There is also the possibility of the plasma energy needlessly increasing the temperature of the substrate [62,63].

This paper shows improvements in the electrical properties of the composite whilst minimising degradation through using a PTCVD system. An industrially-relevant VARTM method is used to demonstrate a good infusion of the nanocomposite through the capillary action of wetting the fibres out instead of using a polymer sizing to improve the wet out [4].

2. Experimental section

Sized bi-directional 2/2 twill carbon fibre (Grafil Pyrofil TR30S) was used as the reinforcement in this study (unless otherwise stated) with a low viscosity, room temperature curing two-part DGEBA epoxy resin (IN-2 epoxy infusion, Easy CompositesTM). CFRP samples were prepared using the VARTM to infuse four, 100 mm × 100 mm plies of 2/2 twill carbon fibre with the lay-up [0,90]₄. A nylon peel ply was cut and placed over the lay-up with an infusion mesh on top, which was subsequently sealed to the metal mould using vacuum bagging



Fig. 1 – (a) DSC curve (10 K/min, nitrogen) of the untreated, sized carbon fibre. (b) TGA of the untreated, sized carbon fibre (20 K/min, flowing air). Overlap of the TGA results for the carbon fibre with the typical temperature range used in the CNT growth with the PTCVD. (A color version of this figure can be viewed online.)

tape with releasing agent having already been applied to the mould. Once a low pressure was achieved in the bag using a rotary pump, a resin line was attached which was connected to a resin reservoir containing a low viscosity, room temperature curing DGEBA infusion resin. Both the unmodified 2/2 twill carbon fibre (to fabricate the CFRP) and the fuzzy fibres (to fabricate the FCFRP) were infused in this manner. The resin:hardener ratio advised by the manufacturer is 100:30.

Carbon nanotubes were grown by initially depositing iron (6 nm) on both sides of the carbon fibre fabric surface using magnetron sputtering (JLS MPS500 DC sputtering). The sample was subsequently loaded into the PTCVD apparatus. After pumping down to its base pressure, hydrogen gas (100 sccm) was introduced into the chamber, which was maintained at a pressure of 2 Torr and optical heating (4 kW) was employed to reduce the iron oxide. After annealing for 5 min, acetylene (20 sccm) was injected into the chamber and the growth process was performed for 10 min on each side of the carbon fibre. The temperature was recorded by a thermocouple, which was in contact with the sample holder, which is exposed to same thermal treatment as the carbon fibre substrate. The

same set up for temperature measurement was also used by Anguita et al. [51].

Differential scanning calorimetry (DSC) was performed on chopped carbon fibres $(1.3 \pm 0.5 \text{ mg})$ in hermetically sealed aluminium pans under nitrogen $(50 \text{ cm}^3 \text{ min}^{-1})$ using a TA Instruments DSC Q1000 from 20 °C to at least 200 °C at a heating rate of 10 °C min⁻¹.

Thermogravimetric analysis (TGA) was carried out using a TA Instruments TGA Q5000 on fibre samples in a platinum pan in a flowing air atmosphere ($60 \text{ cm}^3 \text{ min}^{-1}$) from 20 to 950 °C at a heating rate of 20 °C min⁻¹.

Scanning electron microscopy (SEM) was performed using a FEI Quanta 200 operating at 20 kV with a spot size of 2 nm. For low magnification analysis a Leica DM 2500 P microscope was used.

Raman spectroscopy (Renishaw with Leica DM LM) was performed between 0 and 3000 cm⁻¹ with a scan duration of 30 s at a microscope magnification of 50×, providing a spatial resolution of ~1 μ m. A 514.5 nm laser was operated at a power of 17 mW.



To provide a comprehensive understanding on the impacts on the electrical conductivity for this previously anisotropic

Fig. 2 – SEM images of (a) a bundle of carbon fibres following CNT growth (low magnification), (b) a single carbon fibre following CNT growth (high magnification).



Fig. 3 – Raman spectrum of the fuzzy fibre (black line) and the carbon fibre (red line). (A color version of this figure can be viewed online.)

sample, the electrical conductivity was determined for the inplane (surface) and out-of-plane (thickness and volume) on both CFRP and FCFRP samples (40 mm \times 20 mm). The samples were cut in the 0/90 ° direction from each infused piece. The conductivity was determined from current–voltage (*I*–V) curves taken from a Keithley 4200 analyser by carrying out voltage sweeps from -5 V to +5 V with 0.1 V intervals. To improve the electrical contact, silver DAG was applied on each side, underside and top.

For the single fibre tests, a conventional single carbon fibre was deposited with iron catalyst (in accordance with the optimum growth conditions) and compared with a thermally treated single carbon fibre and a single unmodified carbon fibre. They were compared by testing each of their ultimate tensile strengths in accordance with British Standard, BS ISO 11566, 1996 [64] (on a minimum of 20 samples) using an Instron 1175 universal testing instrument (gauge length = 15 mm, cross-head speed = 1 mm min⁻¹).

3. Results and discussion

Prior to embarking on the procedure to grow carbon nanotubes, a thorough characterisation of the carbon fibre fabric was performed using thermal analysis techniques. A proprietary coating (a size based on a low glass transition (T_a) epoxy oligomer) is usually applied to commercial fibres to improve handling and processibility but it is considered that the presence of this size might inhibit CNT nucleation via the CVD process. Consequently, the carbon fibre was analysed to examine the polymer sizing. Dynamic scanning calorimetry (DSC) data (heat flow and derivative heat flow) are presented in Fig. 1a, from which a significant second order transition associated with a T_a at 150 °C is visible. This is consistent with the presence of a low T_a epoxy resin such as a diglycidylether of bisphenol A (DGEBA) as a sizing agent. There is also a small event (a weak exothermic peak at around 92 °C), which might be attributed to crystallisation taking place or oligomerisation of the sizing. Care was taken to minimise air gaps (poor thermal conductivity) between fibres that can prevent uniform thermal conduction, this led to repeatable results after the measurement was carried out four times. Thermogravimetric analysis (TGA) was performed on the unmodified, sized carbon fibre to complement the DSC data and to determine the weight percentage of epoxy size used on the fabric. The TGA data for the carbon fibre (Fig. 1b) shows a 1.5% weight reduction at 350 °C, which we attribute to the decomposition of the polymer sizing, as it compares with the expected polymer sizing loadings of around 2 wt%. A large drop in mass is observed at 650 °C, corresponding to the onset of thermal decomposition of the aromatic rings in the carbon fibres and by 900 °C less than 1% of mass remained. The residual 0.8 wt% remaining is likely to result from impurities. The temperature of the substrate during the growth of CNTs using the PTCVD technique was recorded by employing a thermocouple placed on the carbon fibre sample stage. This revealed that the substrate was at temperatures of 620 and 650 °C. This temperature range is shown superimposed on the TGA data for the carbon fibres (Fig. 1b). Considering Fig. 1b and the



Fig. 4 – TGA analysis (20 K/min, air) of (a) the fuzzy fibre sample and (b) overlay of the fuzzy fibre (red line) and the standard, untreated carbon fibre (black line). (A color version of this figure can be viewed online.)

range of typical growth temperatures of ~750 °C carried out in other studies, [35,41,52,54,59] it is expected to result in a substantial degradation and have deleterious effects on the fibres' mechanical performance if the carbon fibres in this study were used. Although it should be noted that the atmosphere in the TGA (air) is more aggressive than the atmosphere in the CVD chamber (wherein a small quantity of hydrogen and acetylene is used), it does indicate the importance of maintaining the growth temperature below 650 °C.

The PTCVD system was used to verify the effect of sizing on CNT growth and the quality and quantity of CNT growth was determined using scanning electron microscopy (SEM). The growth parameters were adjusted to obtain long, welldispersed CNTs over the entire surface of carbon fibres. The SEM images presented in Fig. 2 are of the most successful CNT growth and having established these conditions, all succeeding fuzzy fibre analysis and fabrication used the same growth conditions.

SEM images taken at different points around the carbon fibre sample revealed consistent and uniform growth of CNTs being observable even at a low magnification. It appears that the presence of epoxy sizing on the carbon fibre does not hinder the growth of CNTs which is surprising. This result is in contrast to other work in the literature, where the sizing needed to be removed for successful CNT growth [9,20,52]. The ability to grow CNTs without needing to remove the sizing reinforces the applicability of our growth processes and compatibility with current manufacturing methods as it avoids the deleterious effects of using polymer solvents on the carbon fibre or needlessly subjecting the carbon fibre to high temperatures just to remove the sizing. The CNTs grown display a distribution of diameters and lengths - with lengths up to 10 μ m which equates to a growth rate of approximately $1 \,\mu m \, min^{-1}$. This is comparable to another study by Shang et. al. [60] who used the same system but for a different substrate. The growth rate is about 6-20 times greater than that of studies carried out using traditional thermal CVD systems [65,66]. Although the CNTs display no alignment, they are observed to bridge the gaps between the carbon fibres (Fig. 2a), which is necessary to provide percolation pathways throughout the composite. The lengths and morphology of the CNTs are such that they will not introduce any additional thickness to the ply interlayer, which would degrade in-plane mechanical properties.

Raman analysis was carried out on both the carbon fibre and the fuzzy fibre fabric (Fig. 3) to confirm the presence of CNTs and analyse the quality. The Raman spectra acquired for both materials revealed the D peak (1315.7 cm^{-1}) and the G peak (1590.1 cm^{-1}), while the fuzzy fibre displayed an additional peak in the form of a second order G peak (2619.8 cm^{-1}) - a signature of a 2D graphene lattice which also provides information on the number of concentric tubes for MWCNTs [67]. Comparison of the Raman spectrum reveals the quality of graphitization, denoted by the ratio of the intensities of the G and D peaks, I(G)/I(D), changes following deposition of the catalyst and subsequent CNT growth. Replicate spectra were acquired for each sample and it was found that the fuzzy fibres had the most defective carbon structure - a result also observed by Boura et al. [68]. As the Raman signal from the fuzzy fibre sample consists of the signal from the CNTs



Fig. 5 – Electrical conductivity for CFRP and FCFRP in (a) inplane, (b) the out-of-plane direction (thickness) and (c) the out-of-plane (volume) direction. (A color version of this figure can be viewed online.)

and the carbon fibre (spot size of the Raman system $\sim 6 \mu m$) the induced defects could be associated with the damage to the carbon fibre, the introduction of CNTs or both. The radial breathing mode (RBM) signature signal from single-wall CNTs is not observed, which indicates a multi-walled nature of the CNTs as the RBM signal is too weak for multi-wall CNTs as the ensemble average of the inner tube diameters broadens the signal [69]. Furthermore, the absence of the G⁺-G⁻ mode in

the spectrum was attributed to the large distribution of the diameters of the multi-wall carbon nanotubes (MWCNTs) smearing out the splitting [70].

TGA was carried out on the fuzzy fibre sample (Fig. 4a). A pronounced weight loss, that was only seen on the fuzzy fibre sample, was observed at 700 °C, that is attributed to the complete oxidation of CNTs to gaseous products. This phenomenon was observed by Zhang et al. whom also attributed it to the CNTs [35]. The CNTs in the present study show a much higher thermal stability, decomposing some 120 °C higher than the samples reported in the study by Zhang et al., which is indicative of the growth of more graphitic (less defective) CNTs in this study. As is the case with a previous report, [35] no weight gain was observed below 300 °C, which is believed to result from the oxidation of the iron catalyst. Once again, this result suggests that there are no bare particles of catalyst.

The overlaid TGA data for the fuzzy fibre (red line) and the unmodified carbon fibre (black line) are presented in Fig. 4b showing that the fuzzy fibre displays superior thermal stability (0–600 °C) before the complete decomposition of the sample. There was negligible weight loss of the fuzzy fibre material compared to the fabric at \sim 300 °C which is consistent with the removal of the epoxy sizing during the thermal treatment to produce the CNT on the carbon fibre fabric. It was also observed that the fuzzy fibre experiences decomposition (600–850 °C) at a much lower temperature than the carbon fibre (denoted by the black line in the Fig. 4b). This is attributed to the partial degradation of the carbon fibre after CNT growth since it has already experienced a thermal cycle in this process prior to another thermal cycle of the TGA.

The unmodified carbon fibre and the fuzzy fibre plies were infused using the VARTM technique and allowed to cure. The subsequent CFRP and FCFRP laminates were cut to obtain $8 \times (40 \times 20)$ mm samples. The dimensions having been chosen to obtain the maximum number of samples from each infused piece whilst being large enough to be representative of the composite. Both CFRP and FCFRP samples were analysed under an optical microscope to test the quality of the infusion. No voids were observed for either composite adding evidence that even after the removal of the polymer sizing the CNTs help wet out the fibres through the capillary effect [33]. To determine whether or not changes in fibre volume influenced the electrical conductivity, the following formulas to calculate the fibre volume (V_f) were used along with known densities of epoxy resin (ρ_{matrix}) and carbon fibre (ρ_{fibre}) and measured composite mass (mass of fibre (M_{fibre}) + mass of matrix (M_{matrix})):

$$\frac{V_{\rm fibre}}{V_{\rm matrix}} = \left(\frac{M_{\rm fibre}}{M_{\rm matrix}}\right) \left(\frac{\rho_{\rm matrix}}{\rho_{\rm fibre}}\right) \tag{1}$$

$$V_{matrix} = \frac{1}{1 + \begin{pmatrix} v_{fibre} \\ \overline{v_{matrix}} \end{pmatrix}}$$
(2)

$$V_{\text{fibre}} = 1 - V_{\text{matrix}} \tag{3}$$

Calculations revealed that the fibre volume of the composites was \sim 50%, consistent for before and after CNT growth. Silver DAG was applied to each side, underside and top, to improve the electrical contact, as indicated in Fig. 5. It was ensured that no silver DAG bridged the gap between adjacent contacts so abrasive sand paper was applied to the edges of each sample to remove any possible silver deposits. The electrical conductivity was determined for both CFRP and FCFRP in the in-plane (surface) and out-of-plane (through-thickness and volume) directions - Fig. 5a-c, respectively. The inclusion of both in-plane and out-of-plane electrical conductivity measurements is a consequence of the anisotropic nature of CFRP with the conventional benchmark material having lower electrical conductivity in the out-of-plane direction than the inplane direction (first bar; Fig. 5a-c). Fig. 5a-c shows the electrical conductivity increased significantly for the in-plane (330%), out-of-plane thickness (510%) and out-of-plane volume (500%), with the use of fuzzy fibres as opposed to unmodified, reference carbon fibres. As expected, the improvements are greater in the out-of-plane directions as CNTs are bridging the resin rich interlayers, using the carbon fibres as electrical percolation pathways. Whereas the conductivity enhancement in the in-plane direction is limited by the already present electrical percolation pathways from the carbon fibres. Nonetheless, the improvement in the inplane direction clarifies that the observed entanglement seen in the SEM pictures of CNTs connected to different carbon fibres has increased the number of percolation pathways. The improvement of the electrical conductivity in the out-ofplane direction suggests that the material has made a shift



Fig. 6 – I–V curves for the out-of-plane measurement for (a) the charge-trapping CFRP and (b) the Ohmic-behaving FCFRP.

from being anisotropic to isotropic, allowing for a more efficient dispersal of electrons. To clarify the impact of CNTs on the electrical conductivity of the composite, a study of the CNT density against conductivity should be considered for future work.

Additionally, non-linear to linear current–voltage (I–V) measurements for the out-of-plane measurement (Fig. 6) suggest changes in electron transport behaviour from the charge – trapping CFRP (Fig. 6a), to the Ohmic-behaving FCFRP (Fig. 6b). The charge trapping for the CFRP is a result of the resin rich interlayers that are bridged by the CNTs for the FCFRP.

The improvement in conductivity of the FCFRP over our benchmark CFRP is greater than the improvement observed by Lee et al. [71] and Bekyarova et al. [72] for their own modified sample against their benchmark sample and is sufficiently suitable to be used as an electromagnetic shield [30,73].

As only the carbon fibre has been modified it is imperative to test for any potential degradation that is a result of the CNT growth. The temperature of the growth process is the main influence in degrading the mechanical performance of the carbon fibre as examined by the TGA data (Fig. 1b). Therefore, tensile testing of a single unmodified carbon fibre ('Uncoated' - Figs. 7 and 8) was compared against a single carbon fibre with the iron catalyst deposited ('Catalyst Coated' - Figs. 7 and 8), as well as compared against another fibre that had undergone the same thermal treatment as that of the fuzzy fibre ('Thermally Treated' - Figs. 7 and 8). This technique, that has been used by Zhang et al. [35] avoided handling and being exposed to CNTs. A paper mounting was employed to aid handling and once the fibre and holder were placed in the grips of the testing rig, the frame was cut on both sides along the dashed line running horizontally through the mounting. This procedure is in accordance with the British Standard, BS ISO 11566 [64]. Optical microscopy performed for the preliminary tests determined that the fibre was fracturing within the gauge length and not 'sliding' through the glue.

The standard stipulates that a minimum of 20 samples be tested, but the total number of tests carried out were: clean carbon fibre (n = 51), carbon fibre with the deposited catalyst (n = 43) and the thermally treated carbon fibre (n = 44). From the histograms it can be seen that the peak for carbon fibre (Fig. 7a) is positioned at a higher ultimate tensile force, greater than the value recorded for the catalyst coated carbon fibre (second highest position) (Fig. 7b) and the thermally treated carbon fibre (carbon fibre (Fig. 7c). It should also be noted that the distribution for the tensile force is relatively narrow for the catalyst coated carbon fibre compared with the conventional carbon fibre. These differences in distribution are probably more influenced by sample numbers rather than inadvertently conducting a test using two fibres instead of one.

The mean tensile strength of the uncoated carbon fibre was (0.165 ± 0.004) N, catalyst coated of (0.159 ± 0.003) N and thermally treated: (0.149 ± 0.004) N. The measured tensile strength of the unmodified carbon fibre of 4570 MPa compares with the manufacturer's quoted value of 4410 MPa.

Considering Fig. 8, the tensile properties of the carbon fibre when coated with and without a catalyst are equivalent, with the tensile performance decreasing by only 9.7% when the single carbon fibre is subjected to the CNT growth process temperatures, shown as 'Thermally Treated'.

Zhang et al. carried out a similar test but only in an inert gas and vacuum and reported a 40% degradation in tensile strength [35]. The gas atmosphere tested in this experiment is more aggressive than that of an inert atmosphere as it was critical for this study that the same gases were used for two reasons: to achieve the same temperature as the CNT growth as the temperature is dictated by the heat capacities



Fig. 7 – Histogram displaying the ultimate tensile force of (a) uncoated, (b) coated and (c) thermally treated single carbon fibre.



Fig. 8 – Average ultimate tensile values with errors of uncoated, catalyst coated and thermally treated carbon fibres.

of the gases used (and their quantities) and to mimic the conditions as close as possible to have a more comprehensive understanding of the effects. Qian et al. reported a 15% reduction in tensile strength [49] and in a separate paper, Qian et al. grew CNTs on silica fibres and reported a 30% reduction in tensile strength [74]. Sager et al. reported [53] a 30% reduction from the unsized fibres alone with a reduction in tensile properties from the sized fibres expected to be even greater. Therefore, the method of growing CNTs using the PTCVD method has been demonstrated to be the least damaging to the carbon fibre than the methods in other studies. Once infused into a FCFRP composite, the enhancements in the adhesion between the fuzzy fibre and the epoxy resin is expected to offset the degradation to the carbon fibres resulting in a net improvement in the mechanical properties of the FCFRP composite.

4. Conclusions

The growth of carbon nanotubes on carbon fibre using a low temperature photo-thermal chemical vapour deposition technique has successfully yielded fuzzy fibres. The growth is the least harmful to the mechanical properties of the carbon fibre than other studies and will improve the prospect of employing fuzzy fibres in industry. Vacuum assisted resin transfer moulding has been used to successfully infuse the fuzzy fibres even after the removal of the polymer sizing, to produce composites with enhanced electrical conductivities over the conventional carbon fibre composite. The in-plane and outof-plane electrical conductivity are enhanced by 330% and 510%, respectively over the unmodified carbon fibre composite.

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