



Hierarchical composites of carbon nanotubes on carbon fiber: Influence of growth condition on fiber tensile properties

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ARTICLE INFO

Article history:

Received 27 May 2008

Received in revised form 19 October 2008

Accepted 4 December 2008

Available online 16 December 2008

Keywords:

A. Carbon fibers

A. Carbon nanotubes

B. Mechanical properties

B. Interface

E. Chemical vapor deposition (CVD)

ABSTRACT

Growing carbon nanotubes (CNT) on the surface of high performance carbon fibers (CF) provides a means to tailor the thermal, electrical and mechanical properties of the fiber–resin interface of a composite. However, many CNT growth processes require pretreatment of the fiber, deposition of an intermediate layer, or harsh growth conditions which can degrade tensile properties and limit the conduction between the fiber and the nanotubes. In this study, high density multi-wall carbon nanotubes were grown directly on two different polyacrylonitrile (PAN)-based carbon fibers (T650 and IM-7) using thermal Chemical Vapor Deposition (CVD). The influence of CVD growth conditions on the single-fiber tensile properties and CNT morphology was investigated. The mechanical properties of the resultant hybrid fibers were shown to depend on the carbon fiber used, the presence of a sizing (coating), the CNT growth temperature, growth time, and atmospheric conditions within the CVD chamber. The CNT density and alignment morphology was varied with growth temperature and precursor flow rate. Overall, it was concluded that a hybrid fiber with a well-adhered array of dense MWCNTs could be grown on the unsized T650 fiber with no significant degradation in tensile properties.

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1. Introduction

Fiber-reinforced composites have been widely used in aerospace applications because of their high performance and their ability to vary fiber architecture to meet final performance requirements. Performance of composite materials depends not only on properties of fiber and matrices, but also on the interface between them. Good interfacial adhesion provides composites with structural integrity and efficient load transfer from fiber to matrix. Carbon fiber-reinforced composites, in particular, have enabled remarkable improvements in structural performance due to their desirable and tailorable mechanical properties. However, ultimate performance of carbon fiber composites can be limited by resin dominated properties such as interlaminar shear strength or by longitudinal fiber compression. By incorporating highly conductive and high strength elements between fibers, tows, and lamellae; it could also be possible to create robust networks which controllably bridge resin rich areas to significantly improve mechanical, thermal and electrical properties. Both chemical and physical methods have been explored for increasing the adhesion between the fiber and matrix, including surface treatments [1], fiber whiskerization and roughening [1,2]. However, these methods can also

introduce mechanical defects onto the fiber and create bulky or impenetrable additional phases around the fiber. By directly growing nanomaterials with a high aspect ratio and desirable thermal, electrical and mechanical properties onto the reinforcing fiber, it is anticipated that hybrid fibers with highly tailored surface area and properties can be created with either improve ultimate properties or new functionality within a structural composites [3].

Many studies have sought to improve the properties of high performance composites through addition of nanomaterials into the resin [4,5]. Carbon nanotubes (CNTs) are thought to be promising candidates for selective reinforcement of matrix-rich interlaminar regions due to their nanoscale diameter, high aspect ratios and desirable mechanical, electrical, and thermal properties [5]. These same attributes are also useful for the modification of interfacial properties. When properly designed, carbon nanotubes have the potential to work with carbon fiber to make multifunctional, lightweight structural composites with superior strength. Growth of CNTs at the surface of carbon fibers to create hierarchical carbon structures is a promising approach for improving mechanical, electrical, and thermal properties of a structural composite [3,6,7].

CNTs have been grown by many methods including electric arc-discharge [8], laser ablation [9], and chemical vapor deposition (CVD) [10,11]. Of the techniques available, CVD appears the most promising based on easy scale-up, the limited equipment required and previous success in producing uniform CNT growth on com-

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plex surfaces [12–14]. The direct growth of CNTs on carbon fiber using thermal chemical vapor deposition has been previously reported [1,6,7,12]. Initial reports demonstrated that the combination of traditional carbon fibers with carbon nanotubes enhances the fiber/polymer interfacial strength by 15–475% [3,7,16]. Recently, it was reported that multi-walled carbon nanotubes grown on 2-D woven fabric SiC fibers led to such dramatically enhancements in mechanical and electrical properties within an epoxy matrix as a 348% improvement on Mode I fracture toughness, a 54% improvement in interlaminar shear strength, and an increase in-plane electrical conductivities from 7.5×10^{-7} S/cm to 3.44 S/cm [17].

For carbon fiber substrates, the high temperature and reactive conditions used during carbon nanotube growth can introduce defects that can significantly degrade mechanical properties [1,12,15]. For example, carbon fibers are easily attacked by oxygen at temperatures as low as 400 °C [18]. They could also be degraded by the iron catalyst particles used for CNT nucleation when the temperature is above iron–carbon eutectic temperature of 723 °C [15]. An important challenge for the growth of CNTs on carbon fibers is obtaining the desired CNT density, coverage, length, and orientation while simultaneously mitigating the processes that can compromise the mechanical properties of the carbon fiber substrate.

Direct chemical vapor deposition by co-feeding hydrocarbon and catalyst vapors has been used successfully to synthesize CNTs on quartz substrates and has resulted in uniform coverage of long CNT with population densities as high as 10^{10} tubes/cm² [19,20]. CNT morphologies can be varied widely depending on the growth conditions. However, the formation of CNTs on carbon substrates differs from that on quartz substrates due to the temperature limitation of the substrate and to the potential reactions of catalyst or carbon source with the carbon fiber substrate. Zhao et al. [13] produced CNTs on carbon fibers using CVD from xylene and ferrocene vapors over carbon paper heated to temperatures from 700 to 900 °C. However, the CNTs formed only locally on the carbon fibers and overall population densities were several orders of magnitude lower than those reported on quartz substrates. Sonoyama et al. [15] reported that the addition of H₂S to the vapor phase at a concentration of 0.014–0.034 vol% yields CNT population densities as high as $2\text{--}6 \times 10^9$ tubes/cm² on carbon fiber. CNT arrays with the same quality as those currently achieved on quartz have yet to be produced on carbon fiber.

Here we report the synthesis of multiwalled carbon nanotube on carbon fiber substrates with high density and uniform coverage via injection of a xylene–ferrocene solution into a CVD furnace. The aims of the present research work are: (1) to investigate the influence of CNT growth conditions on the tensile properties of individual single carbon fibers (CF); (2) to examine the influence of CNT growth conditions on CNT morphology (3) to identify CVD growth conditions that do not significantly reduce mechanical properties of the carbon fiber or the qualitative sacrifice interfacial properties of the CNT/CF assemblies.

2. Experimental

2.1. Carbon fiber materials

T650 (Fabric Development Inc.) and IM-7 (Textile Products Incorporated) are PAN-based carbon fibers that have been widely used in aerospace fiber-reinforced composites. They are commercially available as “sized” and, in the case of T650, “unsized” fibers. Sized fibers are typically produced via a proprietary process and involve coating the fiber with thin epoxy-based materials that is specifically formulated to enhance tensile and interfacial properties

Table 1
Measured properties of “as received” T650 and IM7

Carbon fiber	IM7-GP-12 K (sized)	T650-35 (unsized)	T650-UC-309 (sized)
Tensile strength [MPa (std dev.)]	3800 (± 676)	2855 (± 645)	3599 (± 950)
Tensile modulus [GPa (std dev.)]	200 (± 23)	200 (± 22)	217 (± 35)
Ultimate elongation [% (std dev.)]	1.8 (± 0.3)	1.5 (± 0.3)	1.9 (± 0.4)
Diameter (μm)	5.8–6.0	7.0–7.3	7.0–7.3

during handling and final use. Unsized fibers do not have this surface treatment. This study focuses largely on sized and unsized T650 fiber (referred to as T650-UC-309 and T650-35, respectively). Comparison to sized IM7 fiber will also be made. Single fiber tensile properties from the “as-received” woven fabric are given in Table 1 for a sample size of at least 20 single fiber samples per fiber type.

2.2. Carbon nanotubes grown on carbon fiber

The experimental set up for growing multi-wall carbon nanotubes (MWCNTs) on carbon fibers (CFs) is shown schematically in Fig. 1. Three different thermal chemical vapor deposition (CVD) methods were employed to investigate the effect of growth condition. These procedures vary in both growth temperature (800 °C, 750 °C and 700 °C) and the flow rate of the carbon source/catalyst (xylene/ferrocene) mixture (10 sccm, 5 sccm and 5 sccm, respectively). These procedures have been previously shown to yield high density, long, and uniformly covered CNT arrays with different orientation on quartz substrates [20,21]. In each case, a small bundle of less than 100 carbon fibers are spread across a ceramic tray and placed into a quartz tube. The tube is purged with argon, raised to the specified temperature and injected with the reactive gas mixture for 5, 10, 15 and 30 min. Before the sample was removed, the tube and sample was cooled under flowing argon to room temperature.

2.3. Analyses of solid products from CVD

The morphology of CNTs on the carbon fiber (CF) surface was characterized using a high resolution field emission scanning electron microscope (SEM Hitachi S-4800). A typical MWCNT diameter of 150 nm was noted. The thermal stability of CF and CNT/CF samples were performed using thermogravimetric analysis (TGA-TQ-500) in air and in nitrogen. Estimates of CNTs density at CF surface were made by using the respective weight loss fraction of CNT's and CF in air as measured via integration of the area under the curve of the derivative of the weight loss as a function of temperature. A regular array of MWCNT of average diameter and uniform length with individual density values consistent with the literature was assumed. The average diameter of CNT (~ 150 nm) and CNT/CF diameters were measured by SEM. The density values of CNT and CF are assumed to be 1.4 g/cm^3 and 1.8 g/cm^3 , respectively.

Examination of the relative adhesion of CNT on the carbon fiber surface was performed via SEM examination before and after exposure to ultrasound and low shear mixing in different solvents (~ 2 mg CNT/CF⁺/10 ml solvent). The treatment time for both ultrasonic bath (70 W, 55 kHz) and magnetic stirring (500 rpm) was 15 min.

2.4. Single fiber tensile testing

Single fiber tensile testing was performed with a 1 in. gauge length in accordance with ASTM D 3379-75 with approximately 20 duplicate samples per set. The single fiber was mounted to the 1 in. paper tab. The diameter was measured using an optical

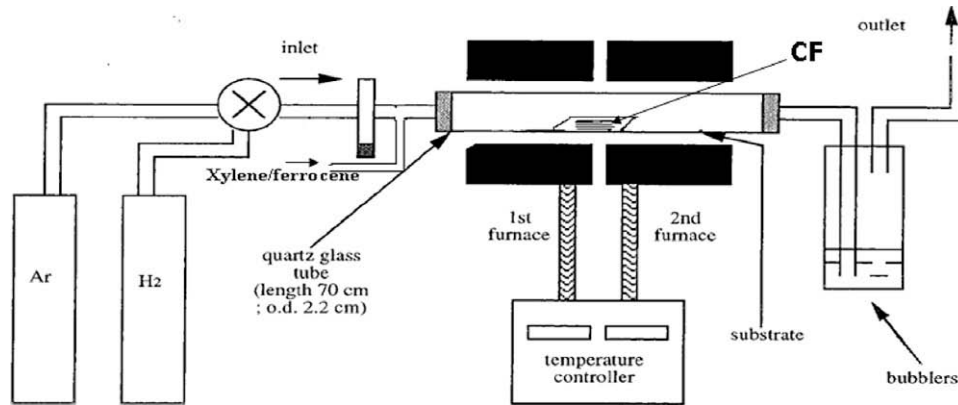


Fig. 1. Schematic illustration of the procedure for the growth of carbon nanotubes on the carbon fibers. A vapor mixture made from a 0.01 g/ml mixture of ferrocene in xylene is carried with flowing argon and hydrogen to the heated quartz chamber with outside tube temperature of 700–800 °C. CNT's grow upon a carbon fiber substrate within the quartz tube for a given length of time.

microscope equipped with a Vickers- A.E.I. Image Splitting Eye-piece (VIPE). Mechanical loading was performed using a stepper motor driven Sintech test frame at a rate of 0.05 in./min. Data was collected using Data Acquisition & Control (DAC) software at a rate of 5 pts/s. Force and displacement measurements were taken and used to determine the ultimate tensile strength and axial modulus of the specimen. Except for the occasional curve shifting due to variation in fiber slack, the tensile curves were simple linear elastic until failure (not shown). Though the diameter of the CNT/CF composite fiber was measured, no significant dependence on CNT length or morphology was noted. It was assumed that the CNT arrays carried insignificant axial load in comparison to the CF. Thus, all tensile properties are reported based on the diameter of the CF.

3. Results and discussion

In order to determine the relative effect of CVD growth conditions on the mechanical properties of the CNT/CF assembly, growth time and temperature was varied. The carbon source/catalyst flow rate was also adjusted. The effect of these variations on the CNT morphology, relative tube density and mechanical properties was quantified using SEM, TGA and single fiber tensile testing.

3.1. Thermal stability of carbon fiber

Because high temperature conditions are involved with the CVD method, carbon fiber thermal stability plays an important role in the CNT growth processing. The thermal stability of the T650-35,

T650-UC-309 and sized IM 7 carbon fibers were investigated by TGA testing at a 20 °C/min heating rate in nitrogen (Fig. 2a) and in air (Fig. 2b), respectively. The results under nitrogen indicate that by 500 °C, the sized IM7 and sized T650 (T650-UC-309) underwent a larger weight loss than the unsized T650 (T650-35) (~1.4% and 1.2%, respectively versus 0.6% as shown in Fig. 2a). This is attributed to thermal degradation of the organic sizing layer which comprises roughly 1% of the weight loss of the fiber. In air, the temperature of thermal degradation of sized T650 and sized IM7 were 80 °C and 110 °C lower than the unsized T650 (Fig. 2b). Note that the sized IM7 showed significant degradation in air from 680 to 750 °C which encompasses the temperature range used for CNT growth. In this study, both sized and unsized T650 showed significantly better stability in air for the CNT growth temperature used. The actual atmospheric conditions present during CNT growth is expected to be less aggressive than air, but less inert than nitrogen due to the presence of both chemical reacting species and flowing argon gas.

3.2. The effect of atmosphere on the mechanical properties of carbon fiber

The effect of different atmosphere conditions on the fiber mechanical properties was investigated in the CNT growth chamber for the most and least thermally stable fibers (unsized T650 & sized IM-7) as determined by TGA. A series of 30 min thermal exposures were performed under flowing argon and under continuous evacuation (pressure = 10^{-3} Torr) for sized IM7 and unsized T650 (T650-35) carbon fibers.

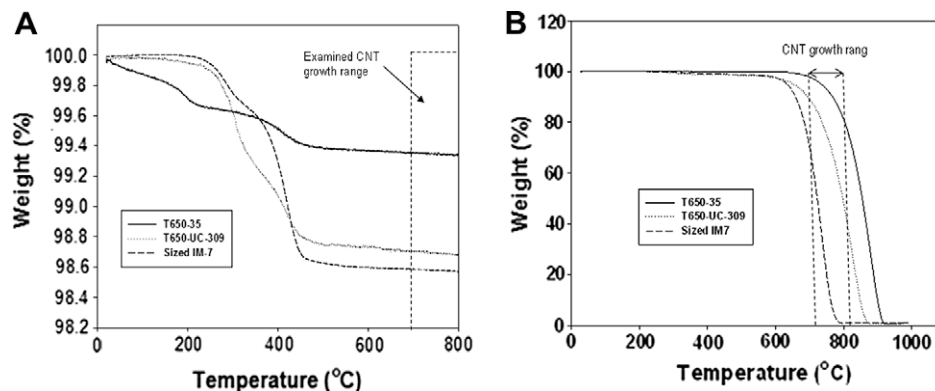


Fig. 2. Thermogravimetric analysis (TGA) for thermal stability of (A) CF in nitrogen with heating rate at 20 °C/min and (B) CF in air with heating rate at 20 °C/min.

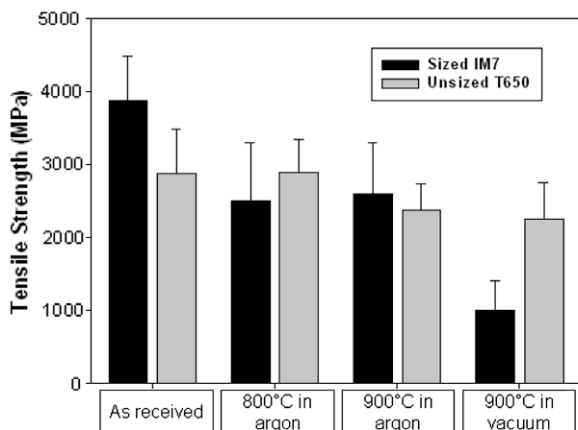


Fig. 3. The effect of different atmosphere conditions within the CVD chamber on the tensile strength of single carbon fiber (error bars denote the standard deviation of the measurement).

The results of Fig. 3, which was based on over 25 tested samples, indicated that tensile strength of the single carbon fibers of sized IM7 is greatly degraded under vacuum conditions at elevated temperature in comparison to flowing argon gas. It is likely a small amount of oxygen was present in the continuously evacuated atmosphere which can lead to fiber oxidation similar to that observed via TGA in air and to a corresponding decrease in the strength of the carbon fiber [20]. In the case of the unsized T650 carbon fiber, the tensile strength of those at 800 °C in flowing argon are nearly identical to those of the untreated fiber. In contrast, the IM7 strength is reduced by approximately 40% in the inert environment and decreased to approximately 75% of the original strength in the vacuum environment, which likely contains a small amount of oxygen. Thus, in comparison to IM-7, the unsized T650 shows both enhanced thermal stability and enhanced retention of tensile strength for the high temperature exposures similar to those that might occur during CNT growth. Since the chemical nature of the sizing and the fiber processing parameters are proprietary, it is difficult to further deduce the origin of these differences. The tensile moduli of the carbon fibers were less affected by thermal exposure and equivalent within the error of the measurement.

3.3. Synthesis of CNTs on the carbon fiber surface by CVD

The growth of CNTs on the carbon fiber surface by CVD processing was varied by changing three parameters: (1) growth temperature, (2) flow rate of the carbon source/catalyst mixture, and (3) growth time. These parameters not only affect CNTs morphology,

density and coverage, but also can significantly impact mechanical properties of CNT/CF assemblies. The investigation of these factors was performed using CVD procedures which vary in temperature (700 °C, 750 °C and 800 °C) and feed rate of the hydrocarbon/catalyst vapors (5 sccm and 10 sccm) as a function of CNT growth time on unsized (T650-35) and sized (T650-UC-309) carbon fiber surfaces. The morphology of CNTs/CF and the CNT density were characterized by SEM and TGA. Due to the previously discussed thermal degradation in oxidizing environments at high temperature, CNT growth above 800 °C was not investigated.

3.3.1. The effect of CNT growth temperature and gas flow rate

According to the CNT growth mechanism, the CNT density and morphology on the carbon fiber surface could be influenced by either the feed rate or temperature. Fig. 4 shows SEM images of CNTs/CF “as-grown” samples that were grown for 30 min at different temperature and flow rates. From these images, we can see that morphology and density (coverage) of CNTs are different with various temperature and xylene/ferrocene mixture flow rate.

At a temperature of 700 °C, the density of CNTs on the carbon fiber surface is very low. Some researchers have attributed this to the low solubility of carbon in iron catalyst at temperature lower than the carbon–iron eutectic temperature of 723 °C [16]. The insufficient thermal activation of ferrocene decomposition by the iron catalyst needed for the nucleation and/or of growths processes on the carbon fiber surface may also play a role. As the growth temperature increased from 700 to 750 °C, the density of CNTs on carbon fiber surface increased substantially. With the further increase in growth temperature from 750 to 800 °C and the feed rate from 5 to 10 sccm, the morphology of CNTs changed from being predominantly aligned and uniform in length to predominantly non-aligned and variable in length. The increase in array disorder with increased temperature and flow rate is likely due to the activation of competing nucleation and growth mechanism. At a moderate temperature of 750 °C and a lower feed rate of 5 sccm, the kinetics appear to favor stable growth of CNT to produce aligned CNTs with uniform lengths. This trend is similar to that observed on quartz [19–22], but was not consistently observed.

3.3.2. The effect of CNT growth time

In addition to dictating CNT morphology with processing condition, growth time is another important variable that can be used to both understand the growth process and tailor the interfacial properties of the resulting assembly. In this study, the CNT morphologies on sized and unsized T650 fibers were examined as a function of growth time at two growth temperatures (800 °C and 750 °C) by high resolution SEM. Fig. 5 displays typical CNT morphology as a function of growth time for 5, 10, 15 and 30 min at 800 °C and 750 °C, respectively. From these results, several trends can be inferred. Early nucleation and growth of CNT appears to

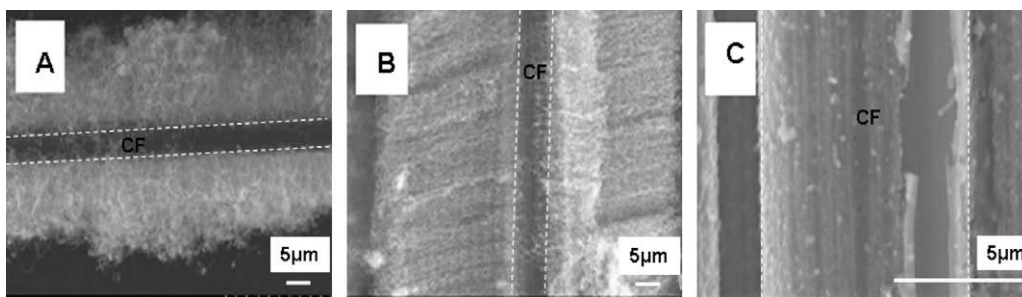


Fig. 4. The effect of CVD temperature, xylene: ferrocene flow rate, and time (temp/rate/time) on CNT morphology procedure A: 800 °C/10 sccm/30 min, procedure B: 750 °C/5 sccm/30 min; and procedure C: 700 °C/5 sccm/30 min.

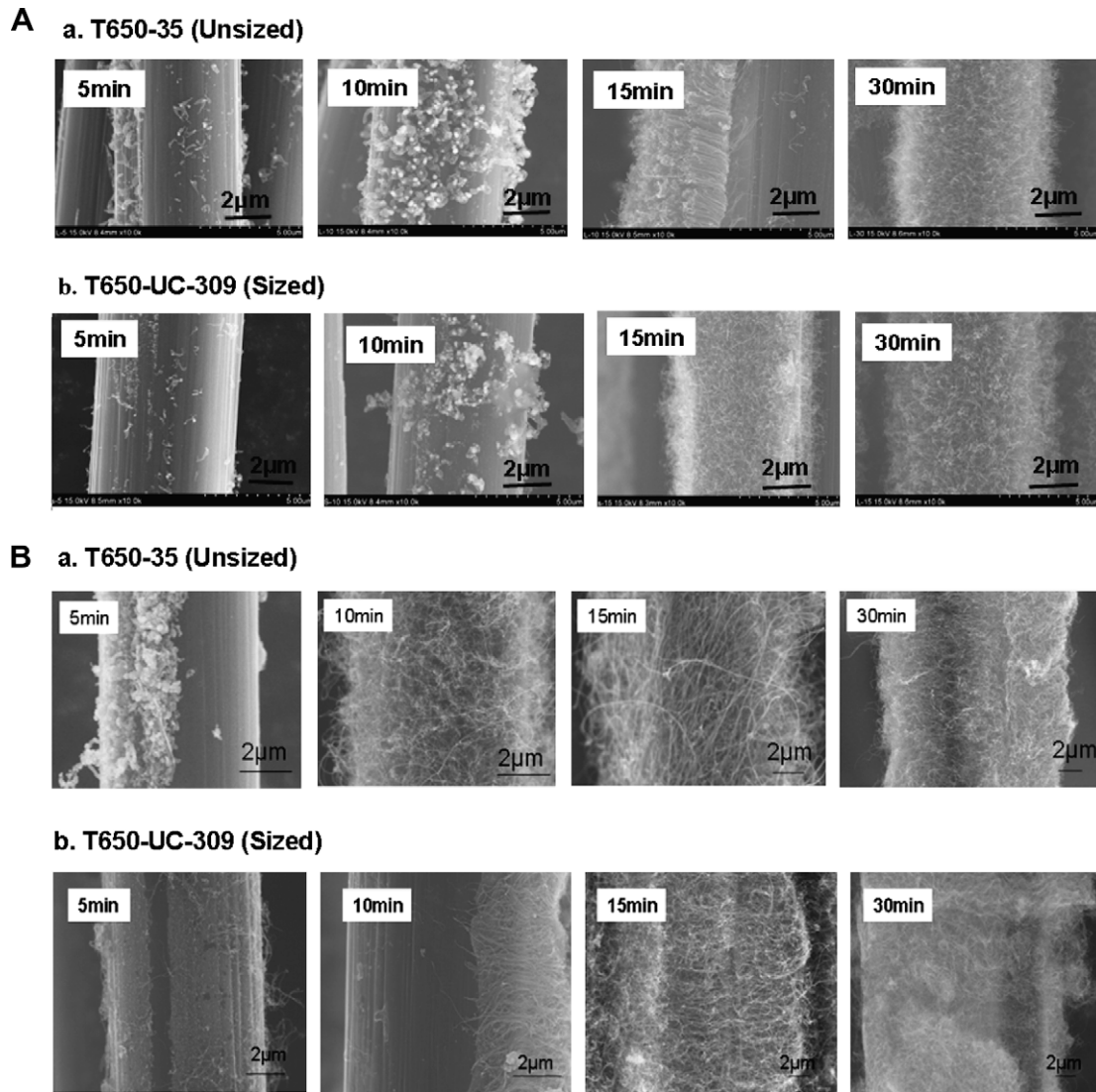


Fig. 5. CNT morphology as a function of growth time at (A) 750 °C and 5 sccm for (a) T650-35 and (b) T650-UC-309, and at (B) 800 °C and 10 sccm for (a) T650-35 and (b) T650-UC-309.

be favored for the unsized T650 fiber in comparison to the sized T650 as more growth occurs earlier in both cases. At 750 °C (Fig. 5A (a & b)), it appears that very little CNT grows before 5 min. However, at 800 °C (Fig. 5B (a & b)), the growth has progressed to the point that the unsized fiber 5 min morphology appears similar to that of the same fiber at 10 min at 750 °C.

In the case of the growth at 800 °C, the enhanced early growth for the unsized fiber is consistent with the time required to achieve uniform coverage (10 min for unsized vs. 15 min for sized fiber). At 750 °C, the time to achieve uniform coverage is earlier for the sized fiber than unsized fiber (15 min vs. 30 min). However, this may be due to the fact that unsized fiber grown for 15 min at 750 °C tended to grow relatively long CNT's at selective sites rather than uniformly across the entire surface. Though the fibers for this study grown at 750 °C were not as aligned as previously observed in Fig. 4, they did maintain a more consistent length at 30 min than the disordered tubes grown at 800 °C which appeared denser and thicker. These trends are largely consistent with the enhanced flow rate and kinetics of the decomposing ferrocene for the CNT's grown at 800 °C. It also illustrates that with sufficient time, uniform coverage similar to that obtain for system which deposit catalyst directly onto the CF surface can be obtained [21].

3.3.3. The density of CNT on carbon fiber surface

Fig. 6 displays the weight loss (left axis) and weight loss derivative (right axis) results for "as received" sized IM-7 in comparison to a carbon fiber with CNT grown at 800 °C for 30 min upon the surface. It was assumed that the pronounced weight loss near 580 °C involved the complete oxidation of CNT to gaseous products. Using the procedure previous discussed in the experimental section, CNT morphologies, such as the length and average diameter, can be determined by SEM imaging. The mass fraction of different materials can be measured on area under derivative weight loss curve by TGA testing. Assuming a regular array of CNTs having the measured average diameter, the measured average length, and an individual nanotube density of 1.4 g/cm³; the CNT population density at the carbon fiber surface can be calculated to be as high as 8.0×10^9 tubes/cm². This value is roughly twice as dense as previously reported by Sonoyama and coworkers [15] and provides nearly 750-fold increased in surface area. The results of SEM and TGA demonstrated that CVD can be successfully used to synthesize CNTs on carbon fibers with high density, high coverage, and selectable CNT morphology by controlling growth conditions such as temperature, time and/or flow rate.

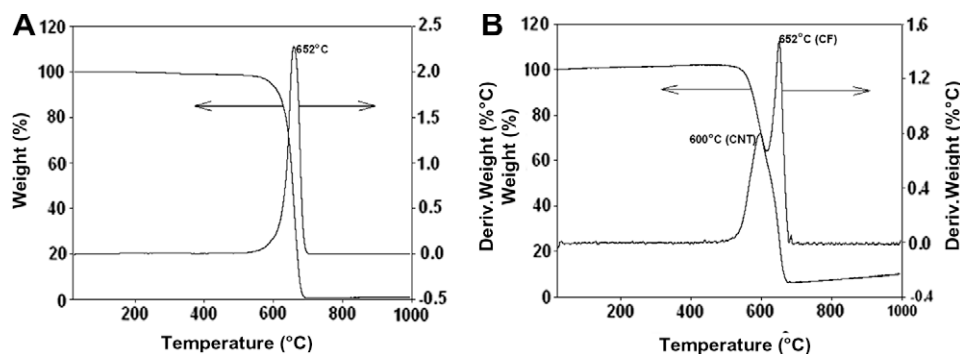


Fig. 6. TGA results for “as received” IM7 fiber (A) and CNT cover fiber (B) in air with a heating rate of 10 °C/min.

3.3.4. The adhesion of CNT on carbon fiber

Hierarchical structure of CNT on the carbon fiber surface could enhance the interfacial bonding between matrix and carbon fiber due to the significantly increase in surface area, morphology modulation, and chemical interaction. The presence of CNT at the fiber–matrix interface is expected to enhance the reinforcement matrix bonding when the CNT are well attached to the fiber surface and resin has sufficiently penetrated into the CNT array. The research result has shown that randomly oriented CNT and aligned CNT coated carbon fiber demonstrated a 71% and 11% increase in interfacial shear strength over unsized carbon fiber based on epoxy matrix [23]. More detailed investigations on the interfacial shear strength of similar CF/CNT assemblies using a single fiber segmentation test in epoxy indicate shear strength values approaching those of highly optimized sized T650/35 fiber with good resin penetration and are discussed elsewhere [23].

Another method for assessing the relative attachment strength of the CNT to the CF surface involves exposing the assemblies to a range of solvents while either in a low shear mixer or an ultrasonic baths. For example, it has been previously reported that CNTs which were grown on thin Ni films deposited by Plasma Vapor Deposition (PVD) were entirely removed with ultrasonic treatment in acetone due to the weak attachment strength [24]. For this study, a small amount CNT/CF (about 2.0–2.5 mg) of unsized T650 fibers with CNTs grown at 800 °C with a flow rate of 10 sccm for 30 min were placed into four different liquids (10 ml of distilled water, acetone, methanol and isopropanol) and then placed in either an ultrasonic bath or a low shear (magnetic) mixer for 15 min. Before treatment, the fibers were uniformly coated with a dense and disordered CNT network as shown in Fig. 4a. Aside from sample exposed to ultrasound in water which expanded

slightly, the network of CNTs surrounding the carbon fiber were generally unperturbed (Fig. 7) and demonstrated good bonding between the CNT and the CF surface.

3.4. CNTs/CF mechanical properties – the effect of CNT growth temperature and time

As discussed above, the processing temperature is an important factor for controlling density and morphology of CNT grown via the CVD method. High processing temperatures and oxidative environments can also affect the mechanical properties of carbon fiber [18]. In order to investigate how quickly mechanical degradation is occurring during the CNT growth process for both sized and unsized T650 fiber, a series of single-fiber tension tests were made as a function of growth time. For each data point, over 50 samples have been tested. The results for tensile strength and tensile modulus are shown in Figs. 8 and 9, respectively. IM-7 fibers were omitted due to their poor handling characteristics.

The results in Fig. 8 indicate that the average tensile strength for sized carbon fibers (T650-UC-309) is decreased within 15 min processing under CNT growth condition. This is attributed to the removal of the sizing layer, which otherwise can improve the tensile strength of the sized carbon fiber, and introduction of flaws. Note that the unsized T650 fibers experience a similar, but smaller, relative decrease at 800 °C. Perhaps the most encourage result from the perspective of maintaining tensile properties while growing a CNT array with uniform coverage and tailored morphology occurs for the unsized T650 with CNT grown at 750 °C. The results indicate that within the statistical variation of the measurements, the tensile strength, modulus, and ultimate strain is uncompromised and equivalent as a function of time.

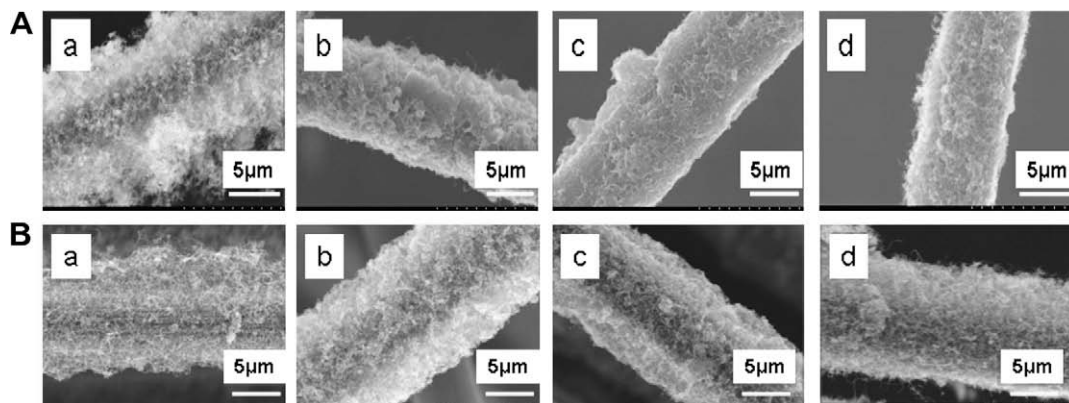


Fig. 7. SEM images of CNT/CF after 15 min treatment A: 15 min in bath ultrasound in: (a) water, (b) acetone, (c) methanol, (d) isopropanol and B: 15 min in magnetic stirrer in: (a) water, (b) acetone, (c) methanol, (d) isopropanol.

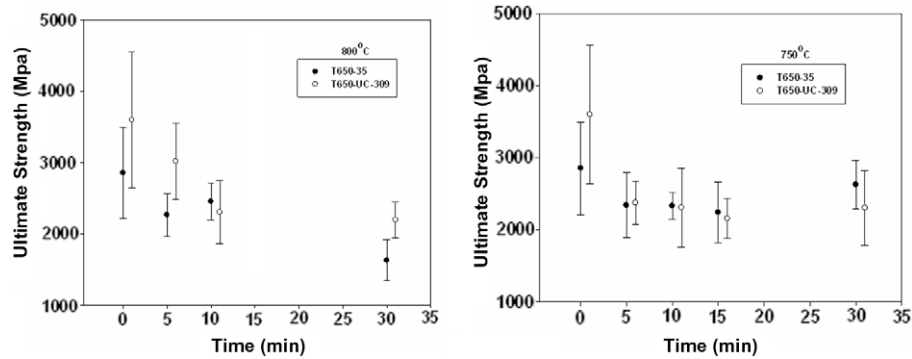


Fig. 8. Effect of CNT growth time in CVD chamber on single fiber tensile strength under procedure A at 800 °C (left) and procedure B at 750 °C (right) (symbols offset for clarity).

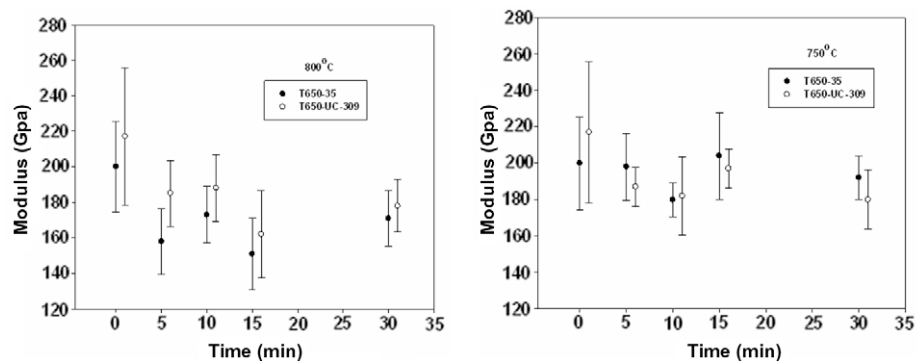


Fig. 9. Effect of CNT growth time in CVD chamber on single fiber tensile modulus under procedure A at 800 °C (left) and procedure B at 750 °C (right) (symbols offset for clarity).

Similar results were obtained for ultimate strain (not shown) while the modulus remained less sensitive to conditions as Fig. 9 shown. Results for sized fibers grown at 700 °C for 30 min growth (limited growth) displayed no significant difference in tensile properties from those grown at 750 °C. In general, the sized T650 fiber simply had higher initial tensile strength (prior to CNT growth) and was reduced by nearly 40% due to exposure to the high temperature growth conditions. The final mechanical properties of the CNT/CF assemblies after growth at 750 °C were similar for the sized and unsized T650 fiber.

4. Conclusions

High density multi-wall carbon nanotubes have been successfully synthesized directly on carbon fiber without significantly compromising tensile properties when a thermally stable unsized fiber and appropriate CNT growth condition are used. The morphology of CNTs can be changed by varying the temperature and feed rate of xylene/ferrocene into the reacting furnace. The tensile properties of the sized T650 fibers are degraded when CNT growth temperatures of 700–800 °C are used. However, the unsized T650 fibers maintains tensile strength at CNT growth temperature of 750 °C, but begins to degrade by ~46% at the higher temperature of 800 °C. Investigation of the tensile strength properties as a function of time under different temperatures and atmospheric conditions revealed that tensile strength for sized carbon fiber were greatly decreased at the beginning of CNT growth processing. This degradation is attributed to the loss of the organic material at the CVD growth temperature and to the introduction of mechanical defects. In comparison, unsized fibers grown at 750 °C displayed insignificant changes in their

mechanical properties. The applications of CNT arrays at the surface of carbon fibers is a promising approach for tailoring interfacial properties without compromising tensile properties. It has particular promise for use as a functional coating with high surface area, high thermal stability and low compliance interpenetrating coatings.

Acknowledgements

The authors would like to acknowledge the Wright Brothers Institute for funding and John Camping, Tara Storage, Ran Kim, Josh Briggs and Thao Gibson for the technical assistance.

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