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Uniaxial tension and compression characterization of hybrid CNS–glass fiber–epoxy composites

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ABSTRACT

In this work, unidirectional multi-scale, carbon nanostructure (CNS)–glass fiber–epoxy, composites were manufactured using a novel in-line continuous production scalable chemical vapor deposition based CNS manufacturing process. The processing parameters peculiar to the growth system, specifically growth chamber temperature, catalyst concentration and line speed, were varied to observe the effect on the CNS growth and parent filament degradation. Unidirectional tension and compression tests were conducted to measure the strength and modulus in the filament direction and failure mechanisms of the hybrid materials identified. Based on the results of tensile tests, gains in tensile strength and tensile modulus are achieved through a uniform coverage of short CNS. The greatest increases in CNS-enhanced composite compressive strength can be achieved through the combination of low weight percent CNS on the fiber and minimal parent filament environmental degradation. For stiffness governed applications, these CNS-enhanced composites may not provide the ideal solution. However, applications which demand significant deformation prior to failure or damage tolerance can benefit from the properties afforded by these CNS–fiber–epoxy composites.

1. Introduction

Glass and carbon fiber composite materials are used for many weight critical applications requiring high strength and stiffness including, but not limited to, recreational, industrial, and vehicle systems of all types. These structural composite systems often are utilized to exploit their specific strength and stiffness properties, in addition to thermal and electrical properties. In essence, fibrous composites consist of two or more phases: a high strength and stiffness fiber reinforcement phase and a matrix phase which holds the material together as a cohesive system, protects the fibers and transfers load between fibers.

Carbon nanotubes are allotropes of carbon with a cylindrical structure with diameters of a few nanometers and be grown with high aspect ratios up to 27×10^6:1 [1] and can exhibit tremendous mechanical properties. A single-walled carbon nanotube (SWCNT) is essentially a single atomic layer of graphite, called graphene, rolled into a seamless tube. A multi-walled carbon nanotube (MWCNT) can be envisioned as multiple concentric tubes. The reader is directed to a comprehensive review of the mathematical and experimental studies pertaining to the properties of carbon nanotubes in Srivastava et al. [2], Qian et al. [3] and Thostenson et al. [4]. Multi-walled carbon nanotubes can be grown with several manufacturing approaches. They can be grown using laser ablation, arc discharge, flame environments and most often using chemical vapor deposition (CVD). Thostenson et al. provide a comprehensive review of carbon nanotube processing and characterization [4].

Owing to the scale of the nanotubes, which to date have been successfully grown to lengths on the order of centimeters, the extreme mechanical properties of these nanotubes have not been directly utilized for macroscale structures. Considering this, these nanotubes can still offer improvements in mechanical properties when they are combined into current fibrous composite systems. The nano and microscale size of the CNTs and the van der Waals bonds between individual tubes impart the main challenge in incorporation into a composite. To ensure homogeneity and proper dispersion, the free CNTs are often mixed into the resin mechanically through calendaring, shear mixing or through sonification and the use of solvents. For a review of carbon epoxy nanocomposites, the reader is directed to Rana et al. [5]. Additional information is provided in Thostenson et al. where the current state of art of nanocomposites is reviewed [6].

Various researchers have shown increases in the stiffness and strength of the matrix material which has been reinforced with CNTs. However research is just beginning in three phase

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CNT-enhanced composites whose constitutive elements are as follows: a conventional fiber as the main reinforcement, a polymer matrix and CNTs. Thostenson et al. used a CVD based process to grown MWCNTs onto the surface of carbon fibers. In a single filament fragmentation test, increases in interfacial load transfer were observed [7].

Kim modeled and tested multiscale CNT composites consisting of woven carbon fiber cloth impregnated with epoxy resin which had CNTs dispersed within it. He concluded that the addition of CNTs affects the shear properties of the composite owing to matrix stiffness and toughness enhancement [8]. The growth of CNTs directly onto the surface of the main reinforcing fibers shows promise in increasing the interfacial properties of fibrous composites. The main benefit lies in the localization of CNTs onto the fiber surface, which eliminates the need for an extra manufacturing step of dispersing the CNTs into the matrix. Zhang et al. used a CVD-based growth process to grow MWCNT onto the surface of IM7 and T650 carbon fibers. Using a single fiber composite tensile test, they realized improvements for the unsized filaments but only for a certain growth temperature range, above which fiber degradation was observed [9]. Another example of a multiscale composite is reported by Bekyarova et al. In their study, electrophoresis is used to grow both SWCNTs and MWCNTs onto the surface of a woven fabric. They realized improvements in interlaminar shear strength of up to 30% [10]. The electrophoresis process causes less degradation to the filaments but the system is not easily scalable for production capabilities.

In this study: A novel ambient pressure continuous CVD growth process is used to grow directly onto a filament substrate [11,12]. The growth process used is production scalable allowing large quantities of nanostructure infused reinforcements to be manufactured. This results in enhanced fibers with a distribution of carbon nanostructures (CNSs) made up of carbon nanotubes on them that can be used to create composite parts using traditional methods. These components can be subsequently tested using accepted standard tension and compression macroscale tests designed to measure relevant bulk composite properties. These materials have been tested for interlaminar toughness and nanostructure pullout by Storck et. al with the deformation mechanisms and failure analysis presented in [new reference to add Steven Storck, Harry Malecki, Tushar Shah, Marc Zupan,'Improvements in interlaminar strength: A carbon nanotube approach' Composites Part B: Engineering. Volume 42, Issue 6, September 2011, Pages 1508–1516]. For this work, the strength of the individual nanotubes or nanostrucutures is not the focus, rather the overall effect of the nanoscale reinforcement on the mechanical properties of a macroscale composite.

2. Experimental

2.1. Material processing and specimen preparation

For this study, AGY 933 S2-glass fibers were used as the base material unto which nanostructures were grown. A unique open ended CVD growth process is used to grow multi-walled carbon nanostructures directly onto the S2-glass tow. For the CVD process, several key variables affect the growth rate and coverage including: growth chamber temperature, fiber line speed (which affects chamber residence time) and catalyst concentration. The parent filaments are passed through the growth chamber in a continuous fashion and re-spooled after processing for post growth component and test structure fabrication. Precise control over the growth chamber temperature, chamber residence time, catalyst concentration and fiber spread, among other factors, allows for process control over the nanostructures length and coverage. The nano-

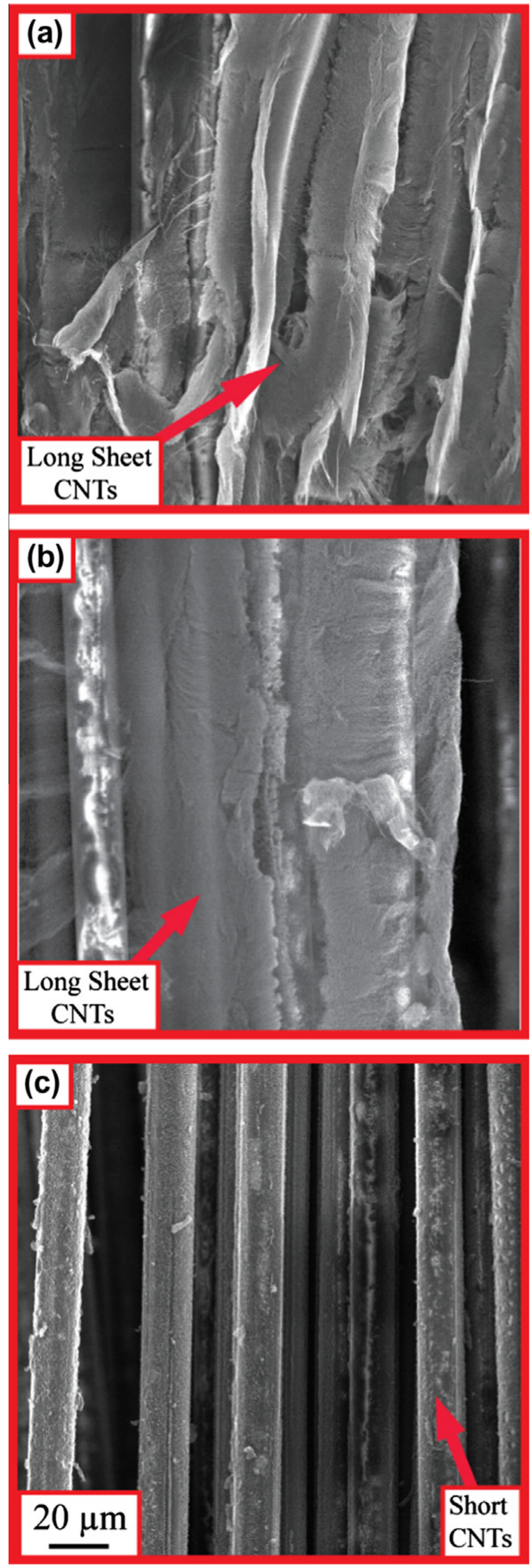

Fig. 1. Images of the CNS infused glass fibers processed for specimens in this study (a) sample G1 (b) sample G2 and (c) sample G3. A summary of the manufacturing process parameters is given in Table 1.