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Electrical conductivity, strength and microstructure of carbon nanotube multi-yarns ☆

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ABSTRACT

Since the inception of carbon nanotubes (CNTs), there has been a great deal of effort in developing CNT applications. One possible application is to utilize CNT yarn(s) in structural and electrical devices. This study investigated 13 different variations of CNT multi-yarns. The multi-yarns were evaluated and compared in terms of tensile load behavior and electrical conductivity as well as interrelationship and interdependence of these two properties with physical parameters and micro-structural features. The electrical conductivity of the CNT multi-yarn is not affected by the apparent diameter, number of yarns, tex or density, but instead by its interior compactness and acid treatment. The construction of single CNT yarn or multi-yarn can be tailored to achieve stress–strain behavior ranging from a stiff to ductile or highly non-linear behavior. CNT single-yarn is stronger and stiffer than a multi-yarn. The decrease in strength and stiffness of a multi-yarn does not depend directly upon the number of yarns. Thus, larger diameter CNT multi-yarn can be developed with less or no reduction in tensile properties in comparison to that of CNT array. Finally, this study's observations provide useful information for further improvement of the tensile and electrical conductivity performance of CNT yarn(s).

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1. Introduction

Carbon nanotubes (CNTs) are well known for their exceptional properties at the nano scale. Many researchers have been striving to maintain these high nano scale properties when CNTs are transformed into the bulk scale products. This is a challenging task due to the lack of lateral bonding among CNTs. However, one way to align the CNTs in a cohesive way is to use the ancient technology of fiber spinning [1]. Many researchers have been able to develop strong conductive fibers by this or similar method [2]. These methods can be classified broadly into four categories: (1) spinning from CNT solution, (2) spinning from a vertically aligned CNT array already grown on a substrate, (3) spinning from a CNT aerogel formed in a chemical vapor deposition reactor, and (4) twisting/rolling of a CNT film/sheet. This paper is focused on CNT-yarns fabricated by spinning from a CNT aerogel formed in a chemical vapor deposition reactor. This procedure has been found to be a very efficient in mass producing the high quality CNT-yarns [3].

CNT provides the basic strength and physical properties in the one dimensional field (1D) space i.e. only one dimension is larger than 100 nm. Bundled CNTs have weak lateral bonds, such as van-der-Waals and mechanical interlocking for producing 3D structures, such as ribbons. The ribbons are than twisted into yarns. Defects, voids and buckles can occur during the twisting process [4].

CNT-yarns produced from the spinning of aerogel show a wide range of or variation in properties. For example, the diameters range from 5 to 200 μm, strength from 0.4 to 1.25 GPa, and conductivity from 830 to 5000 S/cm [5–7]. The higher properties have been attributed to the liquid densification of CNT-yarn. Lu et al. attributed to several possible factors which could affect the mechanical properties of CNT-yarns [2]. First, the quality of CNTs can influence the strengths of the yarn. For example, it is desirable to have long CNTs with a large aspect ratio. The waviness of CNT can increase the strain of the yarn similar to a spring. Second, the strength tends to decrease as the CNT-yarn diameter increases. However this may be simply due to the difficulty of keeping CNT packing factor high at larger diameters. Third, the yarn twisting affects the load transfer from one CNT to another, and increases the densification leading to increased strength. However, the CNT-yarn can be over twisted resulting in the reduced strength. Fourth, liquid densification can increase the mechanical properties

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by increasing packing factor of CNTs resulting in better load transfer capabilities among CNTs. Fifth, polymer impregnation can increase intertube load transfer. Sixth, CNTs perform generally much better in compression than high modulus carbon fibers. Seven, interfacial strength in multifunctional nanocomposites can be as good as carbon/epoxy composite materials.

Lu et al. also summarized a breakdown of possible variables which affect conductivity. First, the individual CNT can have different conductivity qualities i.e. conductive or semiconductive. Second, the gap between each CNT will affect the contact resistance. Third, temperature significantly affects the electrical conductivity. Fourth, coating/doping of the CNTs may significantly increase the conductivity.

The low density of CNT-yarn makes them exceptionally good candidates in applications where weight is a major consideration, such as in aviation and space. Therefore CNT-yarns have been investigated under various thermomechanical loads under different environments (ambient, cryogenic and atomic oxygen) [8,9]. CNT-yarns, as potential conducting wires in low earth orbit (LEO) space structures, have been characterized [9]. CNT-yarns showed little change in stiffness or tensile properties when the strain rate was changed from 0.2 mm/min to 12 mm/min, which shows the mechanical properties are independent of strain rate within the tested range [10]. Fatigue behavior of CNT-yarns has been shown to depend on the number of yarns [11]. Also, their conductivity increased under the fatigue due to apparent densification of the CNTs [11]. Good fatigue properties and limited dependency on strain rate makes CNT-yarns ideal for space systems that need to withstand the forces required to lift it into flight/orbit as well as due to thermal excursions in the service.

There is limited investigation involving CNT multi-yarns in comparison to CNT single-yarn. However, it has been noted that transformation of CNT single yarns into CNT multi-yarns results in the reduced performance properties [12]. To alleviate this, there is a need for the better understanding of factors/parameters/mechanisms which are involved in or affect the CNT multi-yarns' performance. This study is focused in this direction where 13 versions of CNT yarns were evaluated and compared in terms of tensile properties and electrical conductivity. These two performance metrics, besides many others, about CNT-yarns are needed before they can be used in the real applications efficiently and reliably. The evaluations and comparisons of 13 CNT multi-yarn in this study provide the useful information how different parameters/factors affect tensile strength and conductivity of the CNT multi-yarns.

2. Materials and methods

2.1. CNT yarns

All CNT yarns of this study were procured from a single source; Nanocomp Technologies, Inc. Different versions were developed over the last five-six years as a part of the evolutionary process as well as dictated by certain requirements. 13 types of CNT-Yarns were studied which can be classified into three ways. One classification is based simply on number of yarns contained in the final product consisting of 1, 6, 11, 30, 60, 72, or 100 yarn(s). The other classification is based on treatment, i.e. without any acid treatment or with acid treated. The final classification is based on the tex (weight/length) of the yarn, i.e. either standard tex or Hi-tex. The exact process and treatments details are not available due to the proprietary concern and nature; however in general, Nanocomp Technologies, Inc produces CNT-yarns by direct spinning method. This process can be seen in Fig. 1. It is done by injecting grain alcohols and iron-based catalysts into a horizontal reactor furnace with hydrogen as the carrier gas. Individual CNTs are produced and exit the reactor under high temperature as an aerogel-like material. This material impinges on a rotating anchor and is pulled onto a bobbin in the form of a roving. Then the post-processing operation of the CNT-yarn is performed, such as drawing through an acetone bath or a nitric acid bath.

2.2. Area

Determination of the tensile strength and conductivity of the CNT wire requires the cross sectional area. The actual area of the CNT-yarn (single or multi-type) is difficult to determine accurately as it consists of multitude of CNTs in addition to nanoscale gaps. Further, even if area is determined from the conventional method (i.e. from the measurement of diameter), it still depends upon the packing details of CNT multi yarn, which further depends on several twisting parameters used during the spinning of yarn. Thus, presenting the properties in terms of tenacity (N/tex) allows a better approach. It is also preferred for the sake of the better comparison between different studies and fabrication methods. The mechanical properties are, therefore, presented in this study in terms of tenacity as well as based on area. The latter method was selected in spite of the mentioned shortcoming because it is a more conventional way to characterize the engineering materials. So, property based on the area will be referred to as "apparent property". The area was measured at several locations and orientation using image taken by a scanning electron microscope (SEM), and then taking the average.

2.3. Weight

An Ohaus Voyager Pro balance was used to find the weight of 100 mm long CNT wire specimen. The average linear density (g/km or tex) was calculated in each case.

2.4. Conductivity

A Keithley 2400 source meter was used to measure the electrical resistivity at a current of 0.01 A in 4 point probe mode. The probes were gold plated hook type clips. The distance between each probe was 10 mm.

2.5. Tensile test

The CNT-yarns were tested until they fractured under monotonic tensile loading condition using a MTS Tytron 250 bench-type test machine with a 50 N or 200 N load cell. CNT wire specimens with a gauge length of 50 mm were glued between two

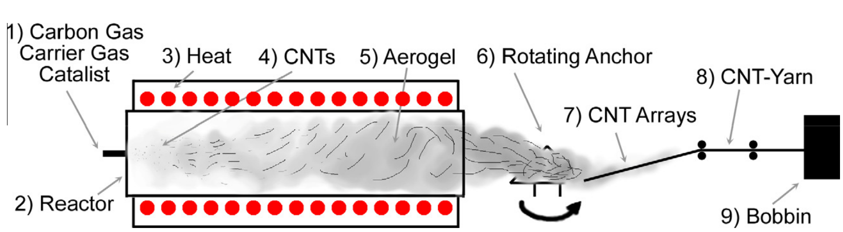

Fig. 1. Schematic of manufacturing process of CNT-yarn by direct spinning method.