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RESEARCH PAPER

Piezoresistive response of carbon nanotube yarns under tension: Parametric effects and phenomenology

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Abstract: Copper Carbon nanotubes (CNTs) are inherently sensitive to mechanical strain, making them ideal for sensing in composites. Because of this they were purposefully spun into macroscopic yarns to permit their utilization in structural components. This experimental study aims to determine the effect of quasi-static strain rate, mechanical properties and geometry of the CNT yarns on their piezoresistivity. Strain rates affect the failure mechanisms and electromechanical properties of CNT yarns, with high strain rates showing increased tensile strength and a positive piezoresistivity with low strain rates favoring a higher strain-to-failure and a negative piezoresistivity. The sensitivity or gauge factor (GF) of the free CNT yarn remains relatively unchanged with varying strain rates (GFs between 0.12-0.20 at 2.5% strain) but is strongly dependent on the strain level (GFs: 0.2, 0.5, 0.4 and 0.2 at 0.5, 1, 1.5 and 2.5% strains, respectively) and diameter (GFs: 0.16 and 0.29 at 3% strain for ~25 μm and 50μm diameter yarns, respectively). The linearity needed for a robust sensor is favored at higher strain rates with correlation coefficients more than 0.993 compared to values less than 0.832 at lower strain rates.

Key Words: Piezoresistive effect; Carbon nanotube; Sensor

1 Introduction

Carbon Nanotubes (CNTs) have been receiving increased consideration for structural health monitoring owing to their multifunctional properties and tailorable aspect ratio. They exhibit a unique change in their electrical resistivity under mechanical strain. This piezoresistive response can be tailored towards integrated sensing. However, when it comes to the observable factors that affect the electrical behavior of CNT fibers in a physical system [1-3], attention has been drawn mainly to temperature, mechanical properties and cyclic effects. Due to their complex morphology and delicate metrology, it is unsurprising that less attention has been paid to characterizing the properties of a macroscopic CNT assembly. There are several ways to produce CNT yarn but currently, dry-spun yarns have shown to possess the best mechanical properties [4-9]. Dry spun CNT yarn from spinnable arrays are produced by growing the nanotubes on a substrate in a chemical vapor deposition (CVD) reactor with the aid of a catalyst. A carbon source introduced into the reactor undergoes catalytic decomposition into carbon atoms generating tubules of CNTs at the catalyst locations. The nanotubes on the substrates are vertically-aligned into brush-looking short nanotubes that is referred to as forest or array [9]. To form a long continuous fiber, CNTs are drawn from these arrays in an end-to-end connection bound by weak van der Waals forces. The continuous web of CNTs are termed ribbons and they can be aggregated into bundles to form threads that could be spun into loosely bound fibers. The mechanical properties of CNT fibers are limited by imperfections in their structures like defects, discontinuities, twist, entanglements, misalignments, fiber packing density and orientation [10-16]. Defects are often present in the form of voids and residual metal catalyst particles. Discontinuities stem from the form of nanotubes as they do not span the gauge length of the fiber. The strength of a CNT fiber is derived from the strength of its constituent CNTs and the frictional forces between them. CNT fibers also have low packing density (volume fraction or specific weight) emanating from the CNTs separation or contact length. Low inter-tube friction causes a reduction in the tensile strength of CNT fibers. To minimize this effect, the spun fibers are twisted and densified to increase the actual contact length. Twists induce cohesion between CNTs and CNT bundles to prevent disintegration under lateral forces [9]. With improved cohesion, the elasticity of the fiber is enhanced by initiating uniform load bearing capability across the fiber's length. Twisted and often densified fiber bundles are called CNT yarns. Due to the rough nature of the yarn, even after twisting, uniform radial properties cannot be guaranteed. There is also a measured approach to twisting because over-twisting can introduce stress concentrations. The reported maximum value

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of the specific elastic modulus occurs at a twist angle of approximately 10°, while the maximum specific strength occurs at an angle of about 20° [11,17]. In the context of this work, CNT yarn refers to a fiber spun from a CNT arrays and condensed. Condensation can be achieved via twist, solvent densification or both.

From a displacement point of view, it has been shown that the loading rate affects the mechanical properties of fibers [18-21], and specifically CNT yarns [22-25]. The deformation mechanisms on the atomistic scale can be related to breaking of bonds, atomic rearrangements and dislocation movements. An increase in strain rate increases the yield strength of the CNT yarn. Zhang et al. [23] and Wang et al. [25] reported that high or dynamic strain rates improve the tensile properties while at the lower or quasi-static rates, they experience a higher fracture strain. For a material that exhibits piezoresistivity, these changes in mechanical properties are coupled with a change in its electrical properties. For sensing and actuation applications, it is pertinent to ascribe a rate of loading, within which the piezoresistive nature and behavior of the material can be predicted. Similar studies on the rate-dependent effects [22,23,25] have focused on the mechanical properties of CNT fibers while studies on the coupled electromechanical effects in CNT yarns under tensile deformation have either been conducted at a single loading rate [16] or focused on one strain rate regime in different tests [22].

The aim of this study is to determine the effects of the varying strain rates, slippage, mechanical failure and fiber geometry on CNT yarn's piezoresistivity. The comprehensive study on the effect of strain level and plasticity on the piezoresistive response of the CNT yarn are also done. This is to gain a deeper understanding of the piezoresistive behavior in CNT yarns and the underlying phenomena.

2 Experimental

2.1 Material

One-thread CNT yarns used in this study have diameters of approximately 25 μm and 47 μm with a twist angle of about 30°. The CNTs were grown into a vertically aligned CNT array on a substrate [4,5]. A 10 cm Si wafer having a 5 nm-thick alumina (Al_2O_3) buffer layer was used with an iron-based 1.2 nm thin film catalyst, both magnetron sputtered. The dicing process on the Si wafer substrates were performed by scribing and breaking into 5 cm-long and variable width (up to 3.75 cm) substrates, loaded into a CVD reactor. In the presence of Ar, the reactor was heated up to 400 °C for annealing. After 2 min, the temperature of the reactor was ramped to 750 °C, then a mixture gas (300 sccm of C_2H_4 and 1000 sccm of Ar) was introduced for about 20 min. The growth was achieved at a pressure of 98.7 kPa. Upon growth completion, 30 sccm of H_2O and 2000 sccm of Ar were delivered during cooling to promote CNT array detachment. The as-received CNT yarns were dry-spun from the sides of 400 m-high vertically aligned arrays composed of 15 nm-diameter multiwall carbon nanotubes (MWCNTs) [4,26]. Densification was achieved with acetone without altering the innate properties [27,28]. The CNT array consists of a distribution of nanotubes consisting of up to seven walls. A scanning electron microscopy (SEM) image of the one-thread yarn is presented in Fig. 1. Each spool (and each batch) of the CNT yarn used is 10 m-long. The calculated resistivity of the CNT yarn used in this study is about 1.7×10^{-3} Ω cm.

2.2 Experimental setup

The tensile test samples were made from a thick cardstock base with a diamond shape cut in the middle to provide a stage for the gauge length. The CNT yarn was centered along the centerline and taped on both ends. This configuration was to support the CNT yarn during fabrication of the sample and insertion into the test fixture, yet allowing the tested portion of the CNT yarn (the section that lies within the diamond cutout) to move freely in the vertical direction. A straight cut was made on the longitudinal arms of the diamond cardstock to ensure that the cardstock did not interfere with the loading and that elongation occurred only within the gauge portion. The contact between the wire and the CNT yarn was outside and within the cut-out gauge zone.

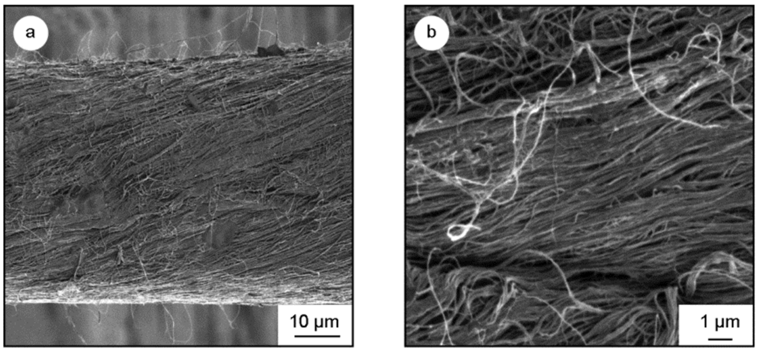

Fig. 1 SEM images of CNT yarn: (a) x1500. (b) x8000. Images taken with JEOL JSM-7100FA FE SEM.