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POLYMER-EMBEDDED CARBON NANOTUBE YARNS: UNVEILING THEIR PIEZORESISTIVE RESPONSE AND SENSITIVITY THROUGH PARAMETRIC STUDIES

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Introduction

The ability to measure strain using embedded micron-size sensors could revolutionize structural health monitoring and allow real-time monitoring of critical areas where direct access is not possible. Carbon nanotube (CNT) yarns[1] are microscale continuous assemblies of CNTs exhibiting a piezoresistive response that could be tapped for strain measurement[2]. The piezoresistive response of free or unconstrained CNT yarns and their sensitivity or gauge factor have been extensively studied including the effects played by the angle of twist and porosity, strain level, strain rate and other parameters like their geometry[3,4]. The piezoresistivity of CNT yarns originates from the intrinsic resistance of the carbon nanotubes, and from the inter-tube resistance including that of nanotubes in physical contact or the tunneling resistance when nanotubes are separated by a small gap. Initial results on the piezoresistive response of CNT yarns integrated or embedded in polymeric matrices forming monofilament composites where the yarns are constrained are also available[5]. This study includes experimental results on the piezoresistive response of polymer-embedded CNT yarns (CNT yarn monofilament composites) and the comparison with that of free CNT yarns subjected to various loading conditions. Some of the most relevant parameters that affect the piezoresistive response of free CNT yarns including the strain rate and strain level are also considered in this study.

Materials and Methods

The CNT yarn used in this study is a one-thread yarn grown from a vertically aligned CNT array at The Nanoworld Laboratories, University of Cincinnati. The as-spun CNT array was approximately 350–400 µm in height with a distribution of one up to six or seven walls. The array was spun into yarn at about 2000 rpm-twisting rate achieving an angle of twist of approximately 30º. Densification was achieved with acetone yielding a CNT yarn's diameter of about 25–30 µm.

The CNT yarns were integrated into polymeric samples using EPON™ Resin 862 (Diglycidyl Ether of Bisphenol F) epoxy resin and Epikure W curing agent, both from Miller-Stephenson Chemical Co. (Danbury, CT, USA). The polymeric samples with the integrated CNT yarns were subjected to tension and four-point bending. The mechanical response of the samples was determined in a loading machine (MTS[TM] Criterion 43 electromechanical with a 30-kN-capacity load cell) and the electrical response was recorded by an electrical data acquisition system (PXI-4072 Inductance–Capacitance–Resistance, LCR, reader unit mounted in a National Instruments

PXI-1033). The data acquisition rates of both the LCR and the MTS system were 1 Hz. Strain rates of 0.0005, 0.003 and 0.006 min^{-1} were considered in this study.

Results and Discussion

The relative resistance change of both the free CNT yarn and the CNT yarn monofilament composites as a function of the strain in the CNT yarn was considered to compare their piezoresistive responses under uniaxial tension and bending. For the samples tested to a maximum strain of 0.1% at a strain rate of 0.003 min^{-1}, the gauge factor (slope of relative resistance change versus strain curve) of the CNT yarn monofilament composites under pure bending and pure tension were approximately 15.2 and 2.7, respectively, compared to 0.1 of the free CNT yarn. A gauge factor of 30.7 was recorded for the CNT yarn monofilament composites under bending versus 0.2 for the free CNT yarn when tested up to a maximum strain of 0.1% at a strain rate of 0.006 min^{-1} (Figure 1). The gauge factor increased from the free CNT yarn to the CNT yarn monofilament composite and it increased much more significantly under bending at higher strains. However, the strain rate does not affect the value of the gauge factor in a CNT yarn monofilament composite as much in a free CNT yarn[5]. This may be attributed mainly to the fact that the fiber volume fraction increases due to the constraint imposed on the CNT yarn by the polymer medium and could lead to a lateral contraction. Thus, there is an increased CNT density in the medium compared to the case of the free CNT yarn.

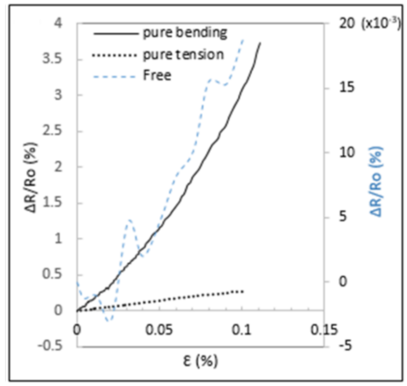

Figure 1. Relative resistance change curves of free CNT yarns and CNT yarn monofilament composite

Conclusions

The piezoresistive response of CNT yarn monofilament composites was determined to mimic the piezoresistive response of CNT yarn sensors that are integrated in polymers or composites. Their piezoresistive response is much more sensitive than that of the free CNT yarns. Higher sensitivity was observed at higher strain rates with gauge factors increasing with increasing strain levels.

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