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Computational multiscale modeling and characterization of piezoresistivity in fuzzy fiber reinforced polymer composites

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ABSTRACT

In this paper, the piezoresistive response (i.e. the change of resistance under the application of strain) of polymer composites reinforced by a novel material known as fuzzy fibers is characterized by using single tow piezoresistive fragmentation tests and modeled by using a 3D computational multiscale model based on the finite element analysis. In the characterization work, the fuzzy fiber tow is embedded in a dog-bone specimen infused by epoxy, with resistance and displacement measured simultaneously to obtain its piezoresistive response. An approximately linear and stable piezoresistive response is observed within the fuzzy fiber tow region yielding gauge factors on average of 0.14. Using a 3D multiscale mechanical–electrostatic coupled code and explicitly accounting for the local piezoresistive response of the anisotropic interphase region, the piezoresistive responses of the overall fuzzy fiber reinforced polymer composites are studied parametrically in an effort to provide qualitative guidance for the manufacture of fuzzy fiber reinforced polymer composites. It is observed from the model that the fuzzy fiber reinforced polymer composites with cylindrically orthotropic carbon nanotube interphase regions are dominated by the electrical tunneling effect between the nanotubes and can yield very large gauge factors while fuzzy fibers with randomly oriented carbon nanotubes in the interphase region yield smaller gauge factors as the material is electrically saturated by the carbon nanotubes. Finally, the modeling efforts provide plausible reasons for the observed small gauge factors in experiments in the form of a combination of high concentration randomly oriented carbon nanotube interphase regions separated by sparse nanotube regions along the fuzzy fiber length.

1. Introduction

The fuzzy fiber material (Bower et al., 2000; Thostenson et al., 2002; Zhu et al., 2003; Zhang et al., 2005; Ci et al., 2005; Mathur et al., 2008; Garcia et al., 2008; Sager et al., 2009; Yamamoto et al., 2009, 2012; Wood et al., 2012; Sebastian et al., 2014) is an engineering material that has a carbon, glass, ceramic, or alumina structural fiber core, with dense CNT "forest" coated on the fiber surface, as observed in Fig. 1. In the fuzzy fiber reinforced polymer composites (FFRPC), the CNTs on the structural fiber surface form a multifunctional interphase region, which can provide enhanced load transfer, damage resistance, higher thermal and electrical conductivities, and electromechanical coupling in the form of piezoresistivity. For example, it is found that fuzzy fibers coated with randomly oriented MWCNTs and aligned MWCNTs can have 71% and 11% increase respectively in interfacial shear strength over the unsized and untreated fibers (Sager et al., 2009). It is measured that FFRPC with alumina-fiber cores have a high electrical conductivity of >100 S/m and an enhancement of thermal conductivity (~1 W/m K) (Yamamoto et al., 2012). Sebastian et al. (2014) integrated fuzzy fiber sensors into composite structures to explore their internal sensing abilities. It is found that the fuzzy fiber sensors with a gauge factor of 1.6–2.3, which is similar to conventional strain gauges, can provide sensing over large sections and in locations not accessible to conventional strain gauging techniques. The multi-functionality of the interphase region makes FFRPC good candidates for multifunctional applications such as structural health monitoring, electromagnetic shielding, fire resisting and deicing (Yamamoto et al., 2012; Sebastian et al., 2014). In this paper we are focused on modeling and characterization of the piezoresistive response of FFRPC, which is believed to be governed by the piezoresistive response of the nanocomposite interphase. It has been found that in the small strain range, with a small wt% loading of single-walled carbon nanotubes (SWCNTs) or multi-walled carbon nanotubes (MWCNTs), linear, reversible and path

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independent piezoresistive response has been observed in a range of polymer nanocomposites including Polycarbonate (Zhang et al., 2006), PMMA (Kang et al., 2006b), Polyimide (Kang et al., 2009), Epoxy (Wichmann et al., 2009), and PSF (Bautista-Quijano et al., 2010) among others. The maximum gauge factors (<10) are achieved at a concentration just above or a few times larger than the percolation threshold concentration (Kang et al., 2006b, 2009; Bautista-Quijano et al., 2010; Oliva-Aviles et al., 2011; Ferreira et al., 2012), which makes CNT-polymer nanocomposites very attractive in the manufacturing of high gauge-factor lightweight strain gauges (Watkins et al., 2004; Loh et al., 2005; Veedu et al., 2006; Kang et al., 2006a,b, 2009; Zhang et al., 2006; Boger et al., 2008; Wichmann et al., 2009; Song et al., 2009; Gao et al., 2009; Thostenson et al., 2009; Yamamoto et al., 2012). In contrast to the customary surface strain measurements, FFRPC strain gauges have the potential to be directly embedded in structural composites during composite processing to provide internal strain sensing (Veedu et al., 2006; Boger et al., 2008; Yamamoto et al., 2012). In order to aid in the design of FFRPC strain gauges with tailored sensitivities, it is necessary to develop an understanding of the underlying mechanisms which govern the macroscale piezoresistive response.

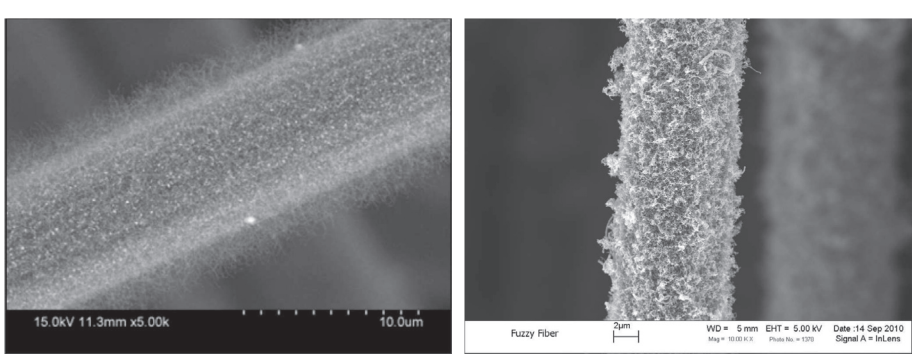
Currently several mechanisms, which may potentially account for the observed overall piezoresistivity of the nanocomposites, have been identified. For example, the electrical tunneling effect (electron hopping) is a phenomenon allowing electrons to be transported between CNTs that are close enough to one another thereby forming conductive paths through the normally insulating polymer matrix (Simmons, 1963; Fuhrer et al., 2000; Budlum and Lu, 2001; Li et al., 2007; Xia and Curtin, 2007; Li and Chou, 2008; Li et al., 2008; Theodosiou and Saravanos, 2010; Hu et al., 2012). The electrical tunneling effect has been observed to be highly sensitive to the distances of adjacent CNTs. When distance between two neighboring CNTs is increased by several nanometers, the electrical conductivity in the conductive path between the two CNTs corresponding to electron tunneling is sharply reduced, returning to the insulating matrix value at the maximum electrical tunneling distance. An additional mechanism is associated with the CNTs themselves which have been shown to have a considerable inherent piezoresistive effect (Rochefort et al., 1999; Peng and Cho, 2000; Tombler et al., 2000; Cao et al., 2003; Dharap et al., 2004; Stampfer et al., 2006; Megalini et al., 2009; Theodosiou and Saravanos, 2010). It has been observed both experimentally and in modeling that mechanical deformation of CNTs can directly lead to significant changes in their conductance (Peng and Cho, 2000), indicating CNTs are themselves good strain sensors due to inherent piezoresistivity. In both of the electrical tunneling effect and the inherent piezoresistive effect of the CNT, the mechanical and electrostatic properties are one-way coupled, i.e. the mechanical properties can greatly influence the electrostatic properties, but not vice versa. In order to obtain the overall piezoresistive response of the nanocomposites, and in turn the FFRPCs, it is crucial to account for the local piezoresistive response in light of multiple mechanisms, especially given the dependence on dispersion.

To date, modeling efforts in the literature have been focused on obtaining the effective mechanical and the effective electrostatic, i.e. the effective electrical conductivity under steady state conditions, properties of FFRPC (Kundalwal and Ray, 2011, 2012; Chatzigeorgiou et al., 2012; Seidel et al., 2014). For example, Chatzigeorgiou et al., 2012 applied a hierarchical analytic composite cylinders method (CCM) to obtain the overall effective mechanical properties of the composites reinforced by radially aligned fuzzy fibers. The impact of the CNT length and volume fraction on the overall composite properties is studied. In contrast, Kundalwal and Ray (2011, 2012) used the Mechanics of Materials (MOM) approach and the Mori–Tanaka (MT) method respectively for obtaining the effective mechanical properties of the fuzzy fiber reinforced composites. In (Chatzigeorgiou et al., 2012; Kundalwal and Ray, 2011, 2012), it was found that due to the radial growing of CNTs, the transverse effective properties of this composite are significantly improved. In a similar manner as in Chatzigeorgiou et al. (2012)) and Seidel et al. (2014) studied the effective electrostatic properties of FFRPC by using a hierarchical electrostatic CCM model and a finite element model (FEM) respectively. However, to our knowledge, no efforts have been found in the literature for modeling the piezoresistive, i.e. the mechanical-electrostatic coupled response of FFRPC.

In this paper, single tow piezoresistive fragmentation testing is conducted for characterization of the piezoresistive response of FFRPC. Correspondingly, a 3D computational multiscale mechanical-electrostatic coupled model is constructed to model the same process. The detailed experimental and modeling work are introduced in Sections 2 and 3 respectively.

2. Single tow piezoresistive fragmentation testing

The fuzzy fiber tows being tested were manufactured in the University of Dayton Research Institute, with glass fiber as the structural fiber core, as seen in Fig. 2. Within one fuzzy fiber tow, it is estimated that there are roughly 600 single fuzzy fibers. By measuring multiple places of different fuzzy fiber structural cores



(a) (b)

Fig. 1. Fuzzy fiber material: (a) A single fuzzy fiber with densely-packed and predominantly radially oriented CNTs on the surface indicative of a potentially cylindrically orthotropic interphase wherein the CNTs are aligned in the radial direction of the glass fiber. (b) A single fuzzy fiber with densely-packed and randomly oriented CNTs on the surface indicative of an effectively isotropic interphase.