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Material Behaviour

Motion of carbon nanotubes based polymer nanocomposites subjected to multi-directional deformation

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A B S T R A C T

Interesting behavior is observed in the electrical resistance across the thickness of glass fibers/epoxy/carbon nanotubes (CNTs) laminate when the laminate is subjected to uniaxial stress along its length. Normally, when a tensile stress is applied along the length of the laminate, Poisson coupling would result in a decrease in the thickness of the laminate. One may expect that this would give rise to smaller electrical resistance across the thickness of the laminate due to the smaller dimension. However, the opposite is observed, ie., an increase in electrical resistance across the thickness. Additional experiments with loading along different directions were imposed on the laminate and electrical resistance was measured. An explanation is provided for this behavior. The results from these simple experiments and the proposed explanation can provide insight into the effect of the motion of the nanostructure on the macro electrical resistance behavior of polymer composite structures containing CNTs when the structure is subjected to multi-directional deformation.

1. Introduction

Polymer matrix composites are increasingly used in the aerospace industry. When carbon nanotubes (CNTs) are added to polymeric materials such as epoxy, the electrical conductivity of the polymeric material increases. The electrical conductivity relies on two mechanisms: One is the conductivity along the connecting networks of CNTs by electron transfer. The other is the electron tunneling conductivity by the jumping of electrons across the gap (made of polymeric material) from one nanotube to the adjacent nanotube when these gaps are small enough [1–3]. Utilizing this, CNTs have been incorporated into polymer matrix composites by many researchers to enhance the electrical conductivity of the matrix material [4–8]. This approach was exploited to measure strains along the x direction (length direction of the laminate) [9–12], or even to detect damage in the laminate [13–17]. What has been revealed is that, for a laminate subjected to lengthwise uniaxial tension stress, the electrical resistance between points along the length of the sample increases. This corresponds to increase in axial strain. This can be explained by the increase in the tunneling resistance and/or by the loss of a number of electrical contacts between the CNTs. One may use the increase in electrical resistance as an indicator for strain. Up to now, most investigations on the correspondence between strain and change in electrical resistance has been omnidirectional, relating to the change in electrical resistance in a certain direction due to the strain along that same direction. For example, if a tensile strain is imposed along the x direction of a laminate, one observes that the electrical resistance in the x direction increases. The production of a tensile strain in the x direction is performed by the imposition of a uniaxial tensile stress in the x direction. However the imposition of a uniaxial tensile stress along the x direction also produces a compressive strain along the y direction (width) and along the z direction (thickness), due to Poisson coupling. This indicates that the application of a uniaxial stress can produce multi-directional deformation. It is of interest to find out what is the change in electrical resistance of the sample in the transverse direction (for example, along the z direction) when a uniaxial stress is applied along the x direction. In a previous publication [18], we showed that the application of a uniaxial stress along the x direction produces electrical resistance

Abbreviations: ATTS, Average Through-Thickness Strain; TTER, Through-Thickness Electrical Resistance; MWCNTs, Multiwalled Carbon Nanotubes; ERC, Electrical Resistance Change; ERM, Electrical Resistance Measurement.

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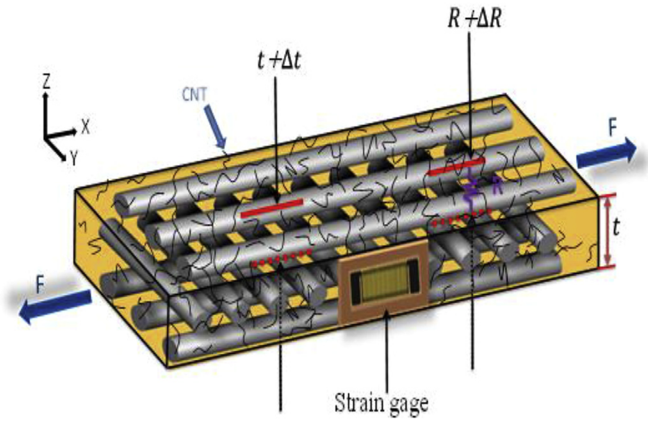

Fig. 1. Schematic illustration of cross ply glass fibers/epoxy/CNTs composite laminate showing out-of plane deformation and change in through-thickness electrical resistance while it is loaded.

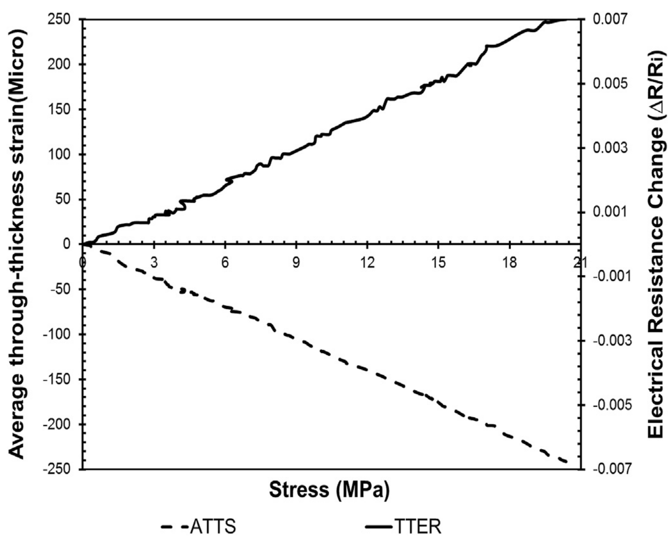

Fig. 2. Variation of ATTS measured by strain gage and TTER versus tensile stress along the length of sample (initial TTER at the edge of sample: 165,510 Ω).

change along the z direction that is proportional to the strain along the z direction. However, the sign was opposite and was unexpected. We found that, with the application of a uniaxial stress along the x direction, there is a reduction in thickness (compressive strain) along the thickness direction. We expected that the change in electrical resistance along the z direction should be negative (meaning reduction in electrical resistance). The reason for this expectation is that a reduction in the thickness direction would bring the CNTs closer, thus would increase the number of electrical contacts and/or reduce the tuneling gaps. However, the opposite is observed (electrical resistance along the thickness direction actually increases). Further work was carried out to investigate this phenomenon. This paper presents the results of this further investigation, and an explanation is provided to describe this behavior.

2. Experimental work

2.1. Materials

Multiwalled carbon nanotubes (MWCNTs) with 95% purity, diameters of 2–20 nm and lengths of 1 μm to more than 10 μm were produced by Bayer Material Science. Unidirectional S-glass fibers, Epon 862 and EPIKURE W were purchased from ACP Composites Company and Miller-Stephenson Chemical Company, respectively.

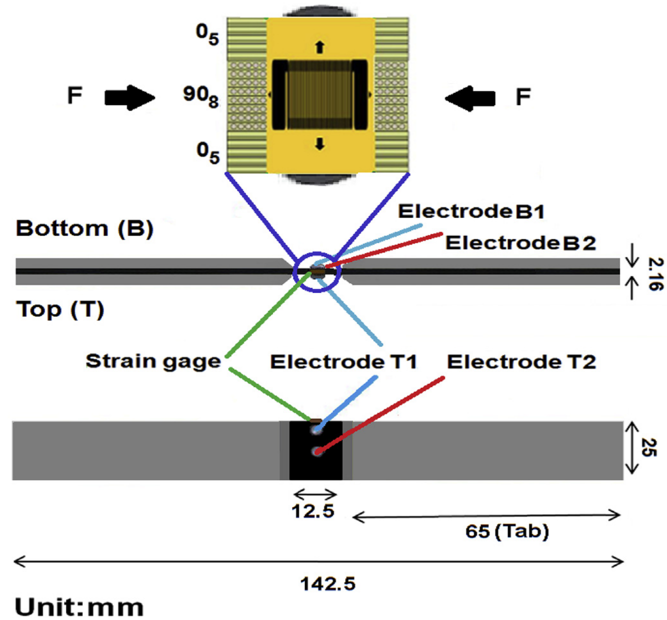

Fig. 3. Schematic illustration of lengthwise compression sample details.

2.2. Fabrication of composite laminates

Laminate with lay-up sequence [$0_5/90_8/0_5$] made of glass fibers/epoxy/MWCNTs was found to give the largest average through-thickness strain (ATTS) using classical lamination theory. This laminate has 18 layers (2.16 mm) which is sufficiently thick to allow the application of a small strain gage to measure ATTS [18]. The [$0_5/90_8/0_5$] glass fibers/epoxy/MWCNTs laminates were prepared by incorporating 0.3 wt% MWCNTs (as an optimal quantity of MWCNTs) [16] into the epoxy resin mixed with curing agent (26.4 wt %). The dispersion of 0.3 wt% MWCNTs in epoxy matrix was performed using three-roll milling (EXAKT 80E, EXAKT Technologies Inc). The laminates of modified epoxy and glass fibers were produced by hand lay-up. An Autoclave was used to cure the plates.

2.3. Sample specification, arrangement of electrical connections and strain gage

This was described in Ref. [18] and is repeated here for completeness. ASTM D 3039 was employed for sample preparation. Electrical contact points made from silver-epoxy paste were mounted on the top (T) and bottom (B) surfaces of the [0_5, 90_8, 0_5] sample with dimensions (250 mm × 25 mm × 2.16 mm). Then, electrodes were prepared by attaching wires to silver-epoxy paste on both surfaces of the sample for electrical resistance measurement (ERM). A conventional metallic strain gage (L1E-350K-PC06-LE) produced by MFL Company [19] was bonded to the edge of the laminate to measure the ATTS over a 90° layer localized at the mid thickness of the [0_5, 90_8, 0_5] laminate due to its gage length limitation placed at the mid thickness of the laminate [18].

2.4. Through-thickness electrical resistance (TTER) measurement

TTER measurement was performed by two-probe method using an Agilent digital multimeter (34401A). Electrical resistance change (ERC) is defined by: