Electrical Percolation Effect on Electromechanical Behavior of CNT Nanocomposites

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ABSTRACT

Electrical resistance responses of multi-walled carbon nanotubes (MWCNT) reinforced polypropylene (PP) nanocomposites under mechanical tensile loading are studied in this paper. A standard tensile test was conducted while the electrical resistance was measured using 2-probe method. From our previous works on the CNT/PP nanocomposites, the percolation threshold of electrical conductivity is around 3.8 wt% of CNT. The influence of this percolation threshold on the electrical resistance upon mechanical loading was investigated. The results will be discussed and compared.

Keywords: percolation threshold, multi-walled carbon nanotubes, nanocomposites, electrical conductivity, mechanical loading.

INTRODUCTION

It is well known that polymers are naturally insulators; combined with CNTs, they become conductive and make them even more attractive due to this additional property on top of their other interesting properties such as light weight, high strength, machinability, and optical properties, among the others. In our previous work [1], we have shown that PP-MWCNT composites produced using injection molding had a percolation threshold of electrical conductivity around 3.8 wt% of CNT.

During the electrical resistance measurement, two techniques can be used. The first, called the two-point probe technique, is an electrical potential method, which is made of two single-terminal electrodes attached to the surface of the conductive structure. A DC *or* AC source current is then applied through the two electrodes and the resulting voltage across the same electrodes is measured. The electrical resistance between these two electrodes is then calculated based on the Ohm's law. The second, called the four-point probe technique, is an electrical impedance method, which uses separate pairs of electrodes for current-sourcing and voltage-sensing. That is, the outer and inner terminals of the electrodes are used as current and voltage contacts, respectively. The key advantage of the four-point probe technique over the traditional two-point probe technique is that by separating current-sourcing and voltage-sensing terminals, the four-point probe technique eliminates the impedance contributions of the wiring and contact resistances. On the other hand, when space is limited, such as the 1-D strip specimens commonly used in laboratory tests, the two-point probe technique can be applied more conveniently than the four-point probe technique.

Since carbons are both piezoresistive and electric conductive, they have been considered as candidates for sensing purposes [2-4]. Most of those studies were carried out on carbon fiber composites and proved to be efficient. Among the others, Chung and her associates [5-15] have conducted extensive research in the area of self-sensing/self-monitoring/self-diagnosing of carbon based system. Pham et al. [16] developed carbon nanotube polymer composite films that can be used as strain sensors with tailored sensitivity. The films were fabricated by either melt processing or solution casting of poly (methyl)methacrylate)(PMMA)with MWNT. However, little work has examined the effect of mechanical loading on electrical conductivity of CNT polymer composites. For the CNT-PP nanocomposites used in this study, melt-mixed CNT-PP concentrate was diluted with neat PP in the injection molding process. This letdown of pelletized masterbatches is a very common practice for handling fine particles during injection molding. In this paper, the influence of tensile loading on the electrical resistance of the CNT-PP nanocomposites is investigated for the volume fractions of CNTs above the percolation threshold of electrical conductivity. This will provide a general guidance for selecting appropriate CNT-PP nanocomposites for sensing applications.

EXPERIMENTS

To fabricate the nanocomposites, a CNT-PP masterbatch (concentrate) was dispersed in polypropylene base material using a 55-ton reciprocating screw injection molding machine (Cincinnati Milacron-Fanuc, Model: Robo 55R-22) The polypropylene (BP Amoco's Acclear 8449) was a random copolymer with a melt index of 12g/10min. The MWNT masterbatch was obtained from Hyperion Catalysis (grade: MB 3020-01) and contained about 20 wt% MWNTs. The mixture of PP masterbatch with virgin PP was used to get the ratio of 2%, 3.5%, 4.5%, 5%, 7%, 10% and 12% weight percentage of CNT. Test specimens were injection molded using three injection velocities: low (1 in/s), medium (4 in/s) and high (7 in/s); other processing parameters such as melting temperature, mold temperature, packing pressure, and back (plastication) pressure were controlled to produce the consistent homogeneous specimens.

For mechanical loading, mechanical tensile tests were conducted using an INSTRON universal testing machine; strain were recorded using an extensometer. A mechanical load was applied at a standard strain rate of 0.01/min. Again for each type of sample, three specimens have been tested and compared for consistency.

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Standard 2-Probe method was used to measure the electrical resistance of the nanocomposites. Since the percolation threshold has been evaluated to be around 4% weight CNT, only specimen with CNT weight percentages higher than the percolation threshold were tested since they are more conductive and have a potential for sensing capability. The CNT weight percentages of 5, 7, 10 and 12 are chosen for electrical resistance measurement under tensile loading.

Once the specimen is ready, electric current is applied to the specimen through an electrical circuit powered by a DC power source; the DC source was used for the tests for its simplicity. Nevertheless, it is worthwhile to note that in real-life practice AC source in 1 kHz is commonly used to avoid inaccuracy caused by polarization. The electrical data were then recorded using Labview software.

Figure 1: Specimen in the INSTRON machine with the extensometer and the electrical probes.

RESULTS AND DISCUSSIONS

During the mechanical loading, the electrical resistance of the system was obtained from the 2-probe measurement as described above; at the same time, the stress-strain curves were obtained form the tensile tests data. Figure 2 shows the stress-strain of the three MWCNT-PP composites with 5 wt% CNT.

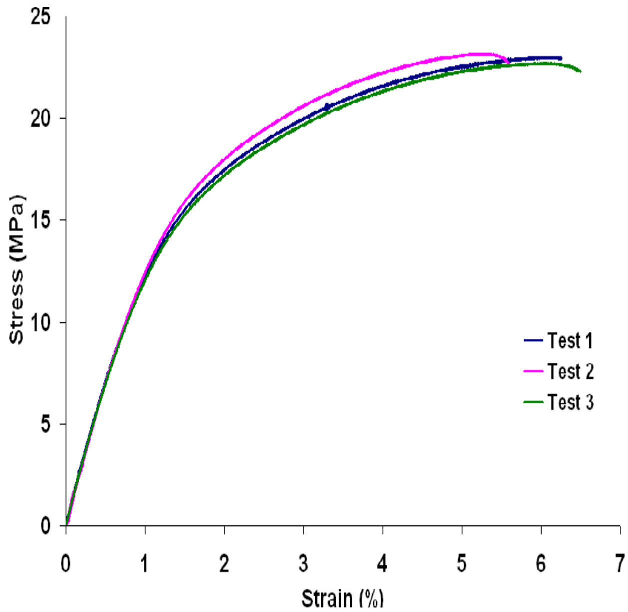

Figure 2: Stress-Strain curves for 5wt %MWCNT-PP composite specimens

The resistance change was also measured using 2-probes method. The change in resistance was not clearly pronounced for 5wt% of CNTs. This could results to the fact that with 5%CNT, the conductivity of the composite specimen is still at the lowest level to highly sense the electrical resistance change. Figure 3 below shows the change in electrical resistance due to the strain change.

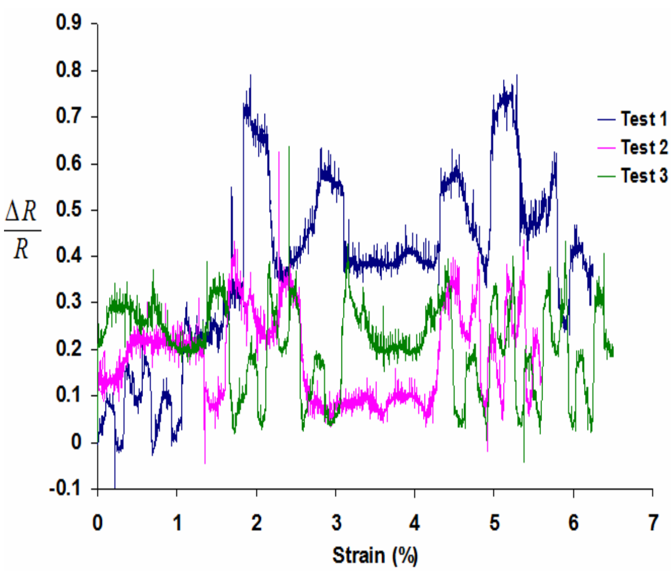

Figure 3: Electrical resistance change due to strain change for 5 wt% MWCNT-PP composite specimens

The same tests were also carried out on the composites specimens with 7% CNT.

Figure 4 shows the stress-strain curves for the composites specimens with 7% CNT.

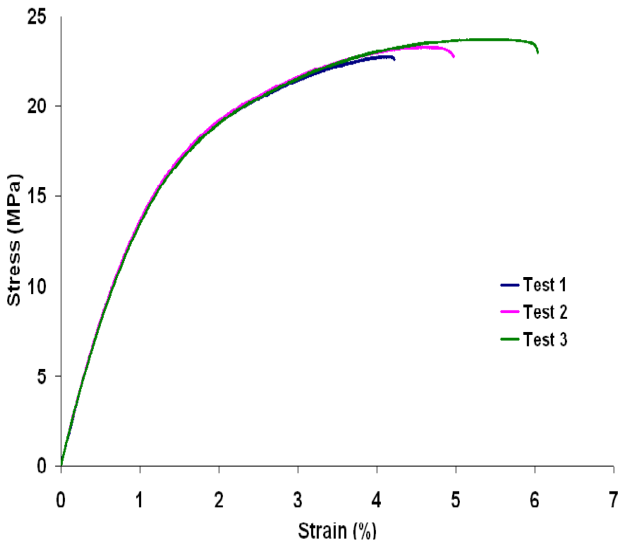

Figure 4: Stress-Strain curves for 7 wt% MWCNT-PP composite specimens

The electrical resistance change was more pronounced in this case even though an obvious pattern was not clearly presented. It is illustrated in Figure 5 below.

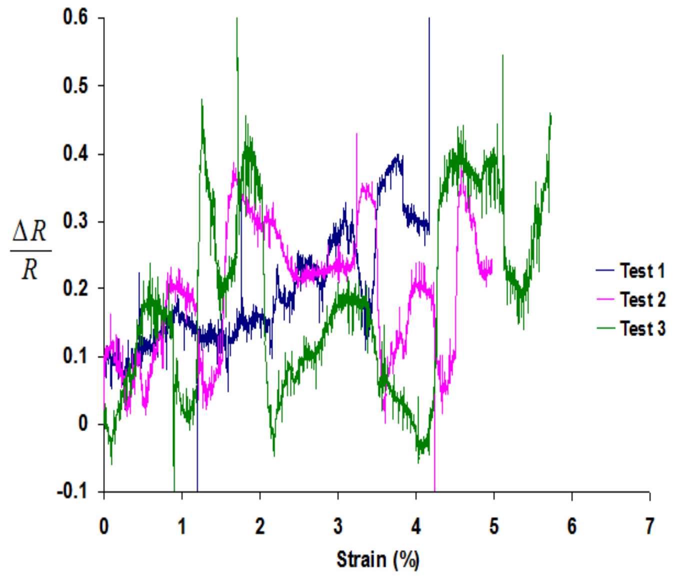

Figure 5: Electrical resistance change due to strain change for 7 wt% MWCNT-PP composite specimens

For the PP nanocomposites with CNT weight percentages of 10% and 12%, the resistance change sensitivity to mechanical loading was more pronounced and clear patterns could be observed. Figures 6 and 7 show the stress-strain and resistance change curves for the composites specimens with 10% CNT respectively.

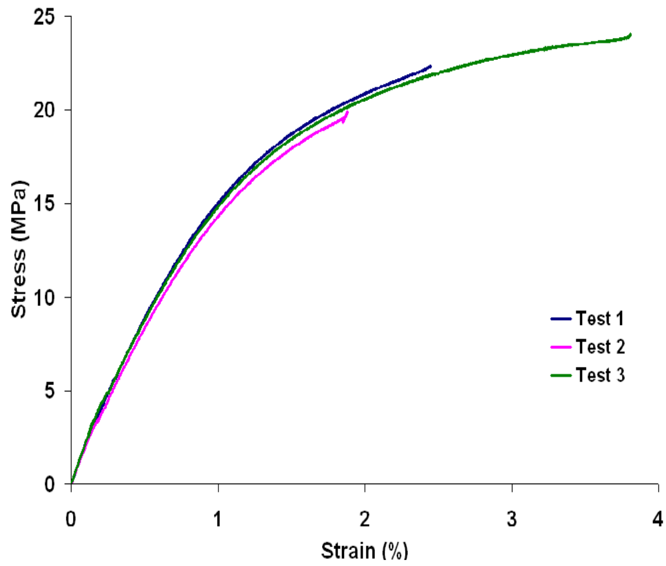

Figure 6: Stress-Strain curves for 10 wt% MWCNT-PP composite specimens

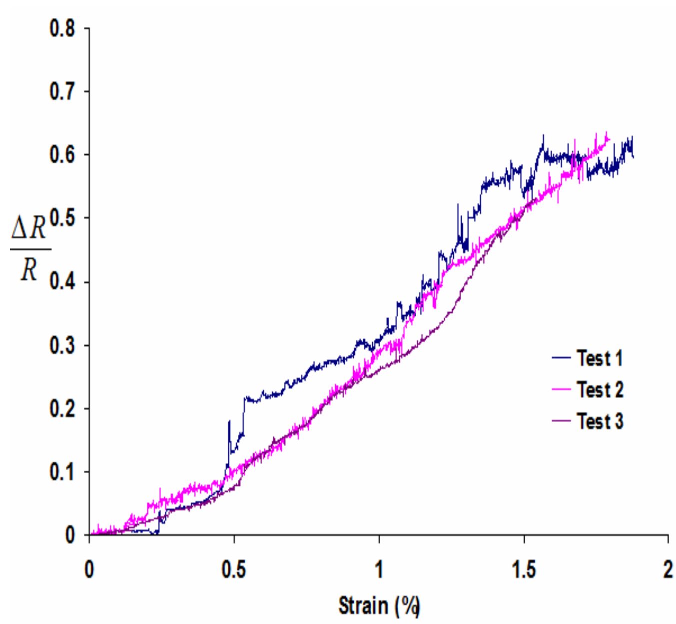

Figure 7: Electrical resistance change due to strain change for 10 wt% MWCNT-PP composite specimens

Form figure 7 above, we can realize the increase in sensitivity to strain change by the change of electrical resistance. It can be noted that the change has a clear pattern compared to the CNT percentages of 5% and 7%.

The same increase in sensitivity was also presented for the PP nanocomposites with 12 wt% CNTs. Figure 8 shows stress-strain curves for the PP-MWCNT composites with 12 wt%.

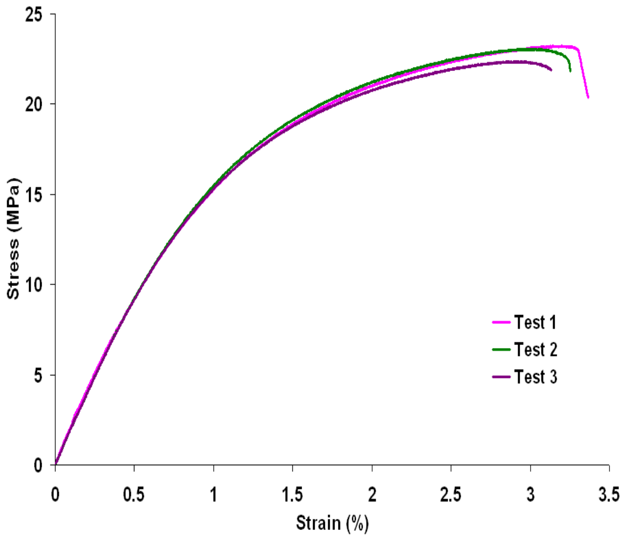

Figure 8: Stress-Strain curves for 12 wt% MWCNT-PP composite specimens

Figure 9 illustrates the resistance change sensitivity to strain change for the PP nanocomposites with 12 wt% CNT. Similarly to the 10 wt% MWCNT-PP composite specimens, the resistance change sensitivity is more pronounced.

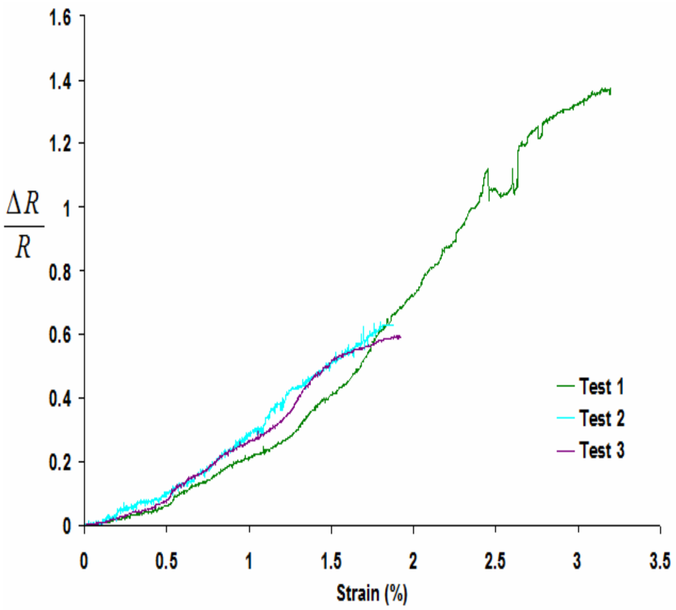

Figure 9: Electrical resistance change due to strain change for 12%MWCNT-PP composite specimens

CONCLUSIONS

The CNT-PP nanocomposites were produced by injection molding. The composites specimens showed electrical resistance change sensitivity to strain change. The level of sensitivity varies with the CNT wt%; it is less pronounced in composites with 5 wt% and 7 wt% CNT. The reason might be that the CNT weight contents are still too close to the percolation threshold of about 3.8 wt%. The sensitivity became more pronounced for nanocomposites with 10 wt% and 12 wt% CNT which shows the proportional increase of electrical resistance with increasing straining.

The above results are promising for potential use of CNT-PP nanocomposites for sensing applications. This additional property will add to the already existing advantageous range of properties of CNT nanocomposite and makes it more attractive for engineering applications.

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