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Variation in electrical conductivity of conductive polymer composites under shock wave

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ABSTRACT

The piezoresistive effect is an important property of conductive polymer composites (CPCs), but the conductive behavior of the composite under shock wave of high pressure and high strain rate, including incident wave and reflected wave, needs to be further studied. To characterize such a system, we study the variation in electrical conductivity of a conductive polymer composite under shock waves, including loading wave and unloading wave, in this paper. The polymer matrix is polyamide-6 with carbon nanotubes and stainless steel fibers are the fillers. The data indicate that the resistivity decreases under the loading shock wave, but sharply increases due to the unloading shock wave. Scanning electron microscopy (SEM) reveals that this resistivity increase is due to damage by the unloading wave and subsequent failure of many micro-conductive channels in the material.

1. Introduction

Recently, considerable attention has been given to conductive polymer composites (CPCs) (Spitalsky et al., 2010; Deng et al., 2014), and some new progress has been achieved on the conductive behavior, resistance–temperature characteristics, and thermal/mechanical properties of CPCs.

In fact, such CPCs utilize piezoresistive effect due to tunnel effect which exists in conductive fillers. Therefore the electrical properties of composites are influenced by mechanical loading. For instance, Taya et al. (1998) analyzed the electrical behavior of a conductive short fiber/elastomer matrix composite. They found that the decrease in conductivity was due to the degeneration of initially percolating networks under a finite strain. Vidhate et al. (2009) examined the electrical conductivity of polyvinylidene fluoride/carbon nanotube conductive composite using quasi-static loading experiments. They found that the stress–time and resistance–time histories were synchronous but that the resistance peak value decreased with increased cycles. This is attributed to charge storage in the nanocomposite under cyclic loading. Soltani and Katbab (2010) examined the variation in nanocomposite conductivity based on room temperature vulcanizing silicone rubber (RTVSR)/graphite nanosheets. They found that there exists a sharp negative pressure coefficient of resistance at 0.7–10 MPa. Wang and Chung (1997) and Wang et al. (1999) measured the conductivity of a single carbon fiber embedded in epoxy via tensile tests. The experiment showed that the resistivity of the fiber decreased reversibly upon tension—this was attributed to accompanying reduction in residual compressive stress of the fiber. This finding provides a new method for measuring the residual stress along the fiber direction. Wang and Chung (2000) also tested the resistivity of a carbon fiber polymer–matrix composite and a carbon–carbon composite. They found that the fiber breakage and matrix cracking irreversibly increases the resistivity. Utilizing an

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equivalent electrical circuit method, Zhu and Chung (2007) suggested a new model for calculating the surface resistance of a conductive polymer. Their data showed that the theoretical model is consistent with the experimental observation if the magnitude of the average longitudinal strain on the surface is less than 0.003. Kishimoto et al. (2011) studied the alumina/carbon-black composite ceramics and established the dependence of conductivity on pressure. They found that the resistance of the material decreased linearly with increasing applied pressure. Rausch and Mader (2010) proposed a new approach for monitoring GF reinforced composites. This technology that may give rise to interphase sensors for CNT-coated GF reinforced composites. By using this method, the onset of GF breakage and the initial failure in the reinforcing fibers can be identified. Barnossa et al. (2009) investigated the conductivity of chemically synthesized polypyrrole (PPy) thin films. They observed that the film thickness and the gas pressure affect the electrical conductivity. Todoroki et al. (2009) measured the applied strain of carbon fiber reinforced plastics (CFRPs) based on electrical conductivity changes. The results indicate that the change in the conductivity in the fiber direction is not directly proportional to the measured unidirectional strain of the carbon fibers. This is due to the influence of electric current in the transverse direction.

All studies mentioned above were carried out on the electrical behavior of conductive polymer composites under quasi-static loading or low frequency period loading. However, the variation in the conductive behavior of composites under dynamic loading is different from that under quasi-static and low frequency period loading. Nellis et al. (2001) measured the electrical conductivity of polybutene under shock pressures and found that the connectivity between nanoparticles increases rapidly with an associated rapid increase in electrical conductivity. Fukushige et al. (2006) proposed a perforation hole detection system suitable for monitoring the impact of space debris. This technology may be applied to any size and volume resistivity across rectangular resistance films. Lei et al. (2012) investigated the variation of a conductive composite resistance by revised SHPB experimental technology.

Importantly, the inertial effect on the electrical properties of conductive polymer composite materials under dynamic loading must be taken into account. Here, the effect of shock waves on the electrical properties of conductive polymer composites is studied using a one-stage light-gas gun. A new dynamic high-resistance meter detects the rapid variation in conductivity within three microseconds. The propagation of the loading and unloading waves in the specimen is analyzed in terms of stress wave theory. We find that resistivity decreases first due to the loading wave, and then rapidly increases due to the unloading wave.

2. Experimental

2.1. Sample preparation

Polyamide-6 (nylon 6) was supplied by Nanjing Dellon Plastics Alloy Co. with the following properties: 1.8% water at 24 h, 23 °C), density of 1.13 g/cm^3, tensile strength of 72 MPa, elongation of 80%, flexural strength of 90 MPa, flexural modulus of 2.5 GPa, charpy impact strength of 6 kJ/m^2, surface resistance of $10^{13}\,\Omega$, and dielectric strength of 20 kV/mm. In order to improve the conductivity and mechanical behavior, stainless steel fiber (SSF) and carbon nanotubes were selected as conductive fillers. The stainless steel fiber (SSF) was obtained from Hunan Huitong Advanced Materials Co. with a diameter of 12 μm, length of 5 mm and resistivity of 6.07 kΩ m. Industrial multi-wall carbon nanotubes (CNT) (p/n TNIM6) were obtained from Chengdu Organic Chemical Co. (Chinese Academy of Sciences). The CNTs are 85% pure and had an outer diameter of 20–40 nm, length of 10–30 μm, tap density of 0.16 g/cm^3, and a true density of ~2.1 g/cm^3.

The CNT, SSF, and PA6 composite material was manufactured by blending, melting, and injection molding, respectively. The content of SSF was 12 wt%, and the CNT was 1 wt%, and was used to improve conductivity. The specimen numbered "112", which shape is circular plate. Its diameter is 51.50 mm, and the thickness, l_s, is 3.24 mm. Silver was coated on both surfaces of a sample to improve electrical contact. The initial resistance between two surfaces (in thickness direction) is 15.21 Ω. The distribution of SSF and CNT in specimen was shown in Fig. 1.

2.2. Experimental methods

A one-stage light-gas gun test examined the piezoresistivity of the material under intense impact loading. The details of the gas gun test were plotted in Figs. 2 and 3 showed an electrical circuit used in the test (Fig. 3(a)), the details of the system used in the test (Fig. 3(b)), a photo of the specimen fixed in the target (Fig. 3(c)), and a photo of a flyer plate for producing impact pressure (Fig. 3(d)).

In the case of high pressure and high strain rate, measuring piezoresistivity is difficult due to the sharp variation in the resistance (in microseconds). To effectively detect the resistance variation, a new dynamic high-resistance meter (NBUBLC2010) was designed by authors in this study. Fig. 3(a) plots the corresponding electrocircuit used for the measurement.

From the electrical circuit, the relationship between the resistance of the sample, R_x, and the output voltage, $U_{out}^{(s)}$, can be expressed as follows:

$$R_x = R_c U_{out}^{(s)} / \left(U_s - U_{out}^{(s)}\right) \tag{1}$$

where R_c is the resistance of the series connection resistor and U_s is the voltage of power source. It is obvious from Eq. (1) that R_x can be determined if $U_{out}^{(s)}$ is measured. It should be pointed out that R_x is the resistance between the two surfaces of the sample. For numerical stability, we used line contact (not point contact) to detect its value (shown in Fig.3(c)).

The pressure applied to the specimen by a flyer plate was measured by means of the change of resistance of manganin gauge. In this study, the calibration on the relation between the impact pressure, p, and the change of resistance of manganin gauge, ΔR_g, has been