ELECTROMECHANICAL BEHAVIOR OF CARBON FIBER

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Introduction

The electromechanical behavior of carbon fibers is relevant to the potential use of carbon fibers as a strain/stress sensor in a smart composite structure. This behavior pertains to the reversible increase of the electrical resistance of a fiber upon tensile strain, as previously observed for a bare low-modulus carbon fiber (including the fiber of this work) and shown to be mainly due to dimensional change rather than resistivity change [1-6]. As carbon fibers are commonly used in a polymer (e.g., epoxy) matrix rather than being bare, the electromechanical behavior of a carbon fiber in a polymer matrix needs to be studied before the fiber can be used as a sensor in a polymer-matrix composite. This paper extends our previous work on a bare carbon fiber [6] to the case of a carbon fiber embedded in epoxy. It has been reported that a carbon fiber in epoxy increases its electrical resistivity during the curing of the epoxy due to the residual compressive stress resulting from the shrinkage during curing and thermal contraction during cooling of the epoxy [5]. Since the residual compressive stress in the fiber is expected to decrease upon subsequent tension of the fiber, this observation suggests that the electromechanical behavior of a carbon fiber in epoxy may be different from that of a bare carbon fiber. However, Ref. 5 reported the same electromechanical behavior for bare carbon fiber and carbon fiber in epoxy. As the residual compressive stress in a fiber increases with increasing curing temperature [5], a higher curing temperature than Ref. 5 was used in this work. Consequently, the fiber resistivity increased by 10% after curing of epoxy in this work, whereas it increased by only 0.5% after room temperature curing in Ref. 5. Thus, upon subsequent tension of the fiber in cured epoxy, we observed decrease of the fiber resistance due to reduction of the residual compressive stress, whereas Ref. 5 observed increase of the fiber resistance (as in the case of the bare fiber). Hence, a new electromechanical effect was observed in this work.

Experimental

The carbon fiber used was 10E-Torayca T-300 (unsized, PAN-based), of diameter 7 μm, density 1.76 g/cm^3, tensile modulus 221 ± 4 GPa, tensile strength 3.1 ± 0.2 GPa and ultimate elongation 1.4%. The electrical resistivity was (2.2 ± 0.5) x 10^{-3} Ω.cm. The epoxy used was EPON(R) resin 9405 together with curing agent 9470, both from Shell Chemical Co., in weight ratio 70:30.

The DC electrical resistance of a carbon fiber embedded in epoxy before and after the curing of the epoxy (at 180°C, without pressure, for 2 h), as well as during subsequent tensile loading at a crosshead speed of 0.1 mm/min, was measured. A single fiber was embedded in epoxy for a length of 60 mm and an epoxy coating thickness of 5 mm, such that both ends of the fiber protruded and were bare in order to allow electrical contacts to be made on the fiber using silver paint. Four contacts were made. The outer two contacts were for passing a current, whereas the inner two contacts (80 mm apart) were for measuring the voltage.

Results and Discussion

Measurement of the electrical resistivity of carbon fiber before curing of epoxy (6 samples) and after both curing and subsequent cooling (6 samples) showed that the resistivity increased by ~ 10% after curing and subsequent cooling.

Fig. 1 shows the fractional change in

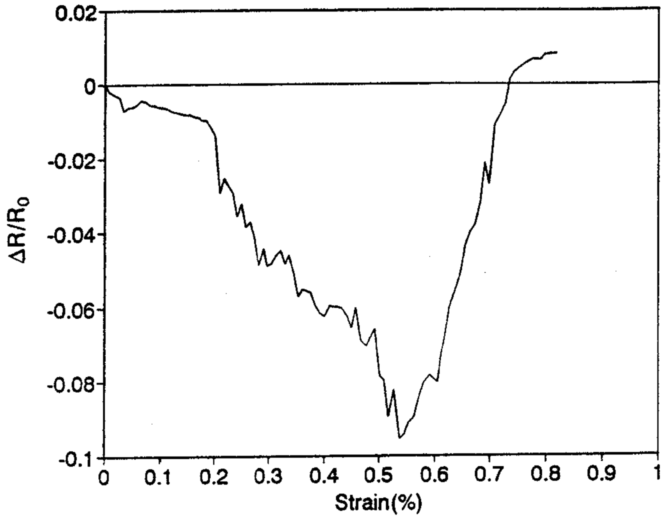

Fig. 1 $\Delta R/R_0$ of single carbon fiber in epoxy under tension.

resistance ($\Delta R/R_0$) of fiber in cured epoxy upon static tension up to fracture. The $\Delta R/R_0$ decreased by up to ~10% upon tension to a strain of ~0.5% and then increased upon further tension. The initial decrease in $\Delta R/R_0$ is attributed to the reduction of the residual compressive stress in the fiber. The later increase in $\Delta R/R_0$ is attributed to fiber damage.

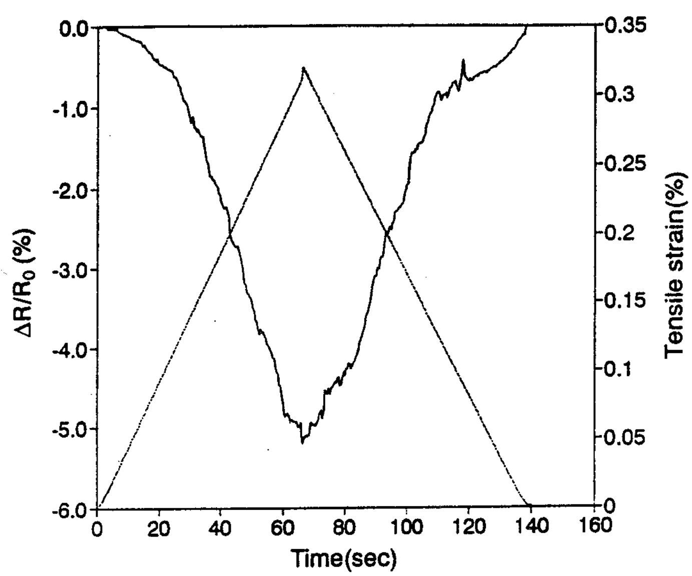

Fig. 2 Plots of $\Delta R/R_0$ vs. time and strain vs. time during tensile loading and unloading for single carbon fiber in epoxy. Solid curve: $\Delta R/R_0$ vs. time. Dashed curve: tensile strain vs. time.

Fig. 2 shows the $\Delta R/R_0$ of fiber in cured epoxy upon tensile loading to a strain of ~ 0.3% and upon subsequent unloading. The $\Delta R/R_0$ decreased upon loading and increased back to the initial value upon unloading, indicating the reversibility of the electromechanical effect.

The $\Delta R/R_0$ per unit strain for the electromechanical effect of Fig. 2 is -17. In contrast, $\Delta R/R_0$ per unit strain for the electromechanical effect associated with a bare carbon fiber and due to dimensional changes is 2. The large magnitude of $\Delta R/R_0$ per unit strain (called strain sensitivity or gage factor) for the new electromechanical effect of this paper makes this effect technologically attractive for use of a carbon fiber polymer-matrix composite as a strain sensor [7].

Conclusions

A new electromechanical effect was observed in a single carbon fiber embedded in epoxy. This effect involves the resistivity of the fiber decreasing reversibly upon tension. It is due to the reduction of the residual compressive stress in the fiber. The residual stress is due to the shrinkage of the epoxy during curing and during subsequent cooling. (Epoxy has a higher coefficient of thermal expansion than carbon.) The effect is opposite from that of a bare carbon fiber, which reversibly increases in resistivity upon tension due to dimensional changes.

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