

Reverse Piezoelectric Behavior of Carbon Fiber Thermoplastic-Matrix Composite

ZHEN MEI, VICTOR H. GUERRERO, DANIEL P. KOWALIK
and D. D. L. CHUNG

*Composite Materials Research Laboratory
State University of New York at Buffalo
Buffalo, NY 14260-4400*

The reverse piezoelectric effect was observed in the through-thickness direction of a continuous carbon fiber nylon-6 matrix composite. The piezoelectric coupling coefficient was 2.2×10^{-6} m/V, as determined up to an electric field of 261 V/m. The effect was largely reversible upon turning off the field and was unaffected by field reversal. It is attributed to the electric dipoles in the nylon-6 matrix.

INTRODUCTION

The reverse piezoelectric effect refers to the phenomenon in which strain results from the application of an electric field due to electric polarization in the material that is undergoing strain. This phenomenon is widely used for actuators, which are needed for machines, smart structures, and, in general, the conversion of electrical energy to mechanical energy. This effect is well known in ceramics (e.g., lead zirconate titanate) which exhibit the distorted perovskite structure. Such ceramics are commonly embedded in a polymer-matrix structural composite in order to provide actuation (strain, stress or both) (1–3). The use of the piezoelectric effect for actuation is to be distinguished from the use of a composite laminate comprising layers of materials that are very different in the coefficient of thermal expansion (CTE) (4); upon heating, the CTE mismatch causes curvature and thus actuation.

Although the embedment of a piezoelectric material in a composite is quite common, it results in degradation of the mechanical properties of the composite. Moreover, the embedment can only occur here and there (not everywhere), thus limiting the volume with the actuation ability. The development of a structural composite that is itself piezoelectric, without the need for embedment, would alleviate the problems mentioned above. One method of attaining this is to use piezoelectric fibers as the reinforcement in the composite (1, 3). However, fine piezoelectric fibers with acceptable mechanical properties are far from being well developed. Their high cost is another problem. Another method is to use conventional reinforcing fibers (e.g., carbon fibers) while exploiting the polymer matrix for the reverse piezoelectric effect. Due to some ionic character in the covalent bonds, some polymers

are expected to polarize in response to an electric field, thereby causing strain. The polarization is enhanced by molecular alignment, which is in turn enhanced by the presence of the fibers. The latter method involves widely available fibers and matrix and is thereby attractive economically and practically. This paper is concerned with the latter method.

In this work, nylon-6 is used as the polymer matrix, because of the partially ionic character of covalent bonds that involve C = O and N – H. Furthermore, nylon-6 is one of the most common thermoplastic matrices for fibrous composites. The reinforcing fibers used in this work are carbon fibers, which are widely used for lightweight structures, such as aircraft and sporting goods. In contrast to glass fibers, carbon fibers are electrically conducting, thus facilitating the application of an electric field across the polymer matrix in the interlaminar region.

EXPERIMENTAL METHODS

The thermoplastic polymer was nylon-6 (PA) in the form of unidirectional carbon-fiber (CF) prepregs supplied by Quadra Corp. (Portsmouth, Rhode Island; QNC 4162). The fibers were 34–700 from Grafil, Inc. (Sacramento, California). The fiber diameter was 6.9 μm . The fiber weight fraction in the prepreg was 62%. The glass transition temperature (T_g) was 40–60°C and the melting temperature (T_m) was 220°C for the nylon-6 matrix. The prepreg thickness was 250 μm .

The prepreg was cut to size 76 \times 38 mm. Then 108 plies of the prepreg were stacked in a steel mold, together with a copper foil at the top and another copper foil at the bottom of the stack. The stack was heated to 260°C at a heating rate of 10°C/min and a pressure of 2.0 MPa. Then it was consolidated by hot pressing at 260°C and 2.0 MPa for 30 min. After demolding, the

specimen was cut and polished to size $64 \times 34 \times 21$ mm. The copper foils served as electrical contacts for applying a DC electric field (up to 261 V/m) in the through-thickness direction of the resulting laminate, which was 21 mm thick. The electric field was applied by using a DC voltage source.

The strain in the through-thickness direction was measured by using a resistive strain gage attached to the middle of one of the four sides that were parallel to the through-thickness direction. As the applied electric field might cause Joule heating, which would in turn might cause thermal expansion, the temperature was monitored by using a T-type thermocouple, which was positioned immediately next to the strain gage. The measured temperature and the calculated coefficient of thermal expansion (CTE) of the composite were used to calculate the contribution of thermal expansion to the measured strain. The longitudinal CTE of the composite was given by (5)

$$\alpha_1 = \frac{V_f \alpha_{f1} E_{f1} + V_m \alpha_m E_m}{V_f E_{f1} + V_m E_m} \quad (1)$$

where V_f = fiber volume fraction,

V_m = matrix volume fraction,

α_{f1} = longitudinal CTE of fiber = $0.7 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$,

α_m = matrix CTE = $83 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$,

E_{f1} = longitudinal Young's modulus of fiber = 317 GPa, and

E_m = Young's modulus of matrix = 2.0 GPa.

From Eq 1, $\alpha_1 = 1.02 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$.

The transverse CTE of the composite was given by (5)

$$\alpha_t = V_f \alpha_{ft} \left(1 + V_{f1} \frac{\alpha_{f1}}{\alpha_{ft}} \right) + V_m \alpha_m (1 + \nu_m) - (V_f \nu_f + V_m \nu_m) \alpha_t \quad (2)$$

where α_{ft} = transverse CTE of fiber = $10 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$,

ν_f = Poisson ratio of fiber = 0.2, and

ν_m = Poisson ratio of matrix = 0.33.

From Eq 2, $\alpha_t = 48 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$.

The strain and temperature were simultaneously monitored while a constant electric field of various values was applied for a chosen length of time and then either turned off or reversed in polarity. The calculated thermal expansion strain was subtracted from the measured strain in order to obtain the strain due to the reverse piezoelectric effect. From the slope of the plot of the strain due to the piezoelectric effect versus the electric field, the piezoelectric coupling coefficient was determined.

RESULTS

Figure 1 shows the variation of the measured strain with time, that of the temperature with time, and that of the calculated thermal expansion strain (based on the measured temperature) with time during application of an electric field of 261 V/m for 1 min, followed by an extended period of no applied field. The temperature rose during current application, due to Joule heating. However, the thermal expansion strain was small compared to the measured strain. Both measured strain and thermal expansion strain increased as the electric field was maintained and decreased gradually (with a long tail) when the field was turned off.

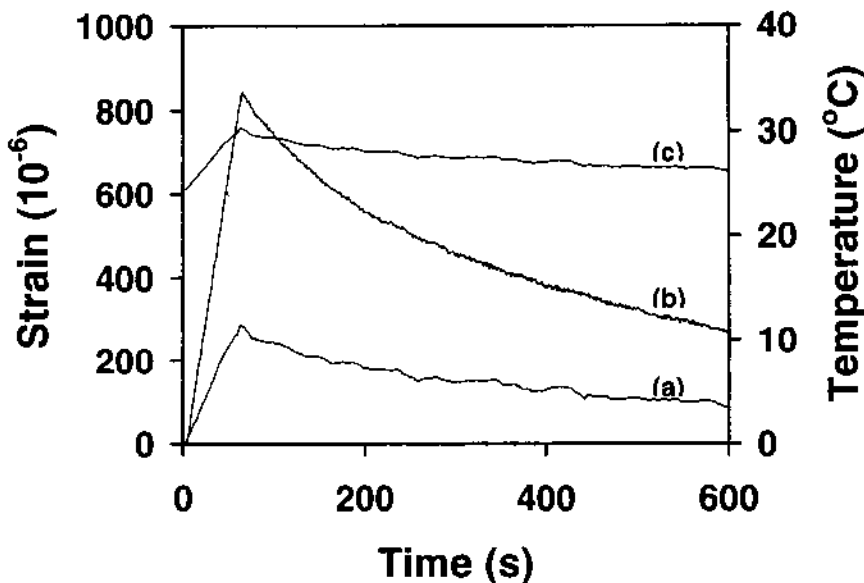


Fig. 1. Variation of the measured strain and the calculated thermal expansion strain (based on the measured temperature) with time. An electric field of 261 V/m was maintained for 1 min, followed by an extended period of no applied field. (a) Calculated thermal expansion strain. (b) Measured strain. (c) Temperature.

Plots like Fig. 1 were obtained for various values of the electric field. The piezoelectric strain (measured strain minus the thermal expansion strain) is shown in Fig. 2 as a function of the electric field. From the slope of this plot (quite linear), the piezoelectric coupling coefficient was determined to be 2.2×10^{-6} m/V.

The measured strain increased with the time of electric field (261 V/m) application quite linearly in Fig. 1, where the time of field application was up to 1

min. However, when the time of field application was 10 min, the slope of the curve of measured strain versus time of field application decreased with increasing time, suggesting a saturation effect (Fig. 3).

Figure 4 shows results obtained during cyclic field application. In each cycle, a field of 208 V/m was applied for 1 min, followed by turning off the current for 5 min. The measured strain greatly exceeded the calculated thermal expansion strain, as in Fig. 1. The measured strain was mostly reversible in each cycle.

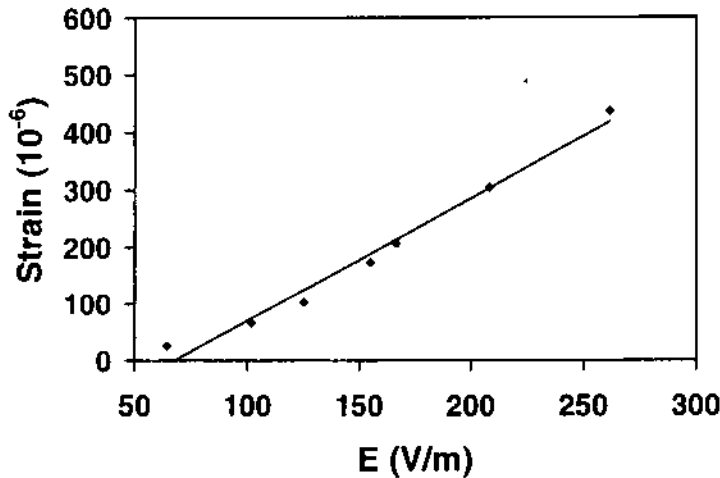


Fig. 2. Plot of piezoelectric strain (measured strain minus the thermal expansion strain) vs. electric field.

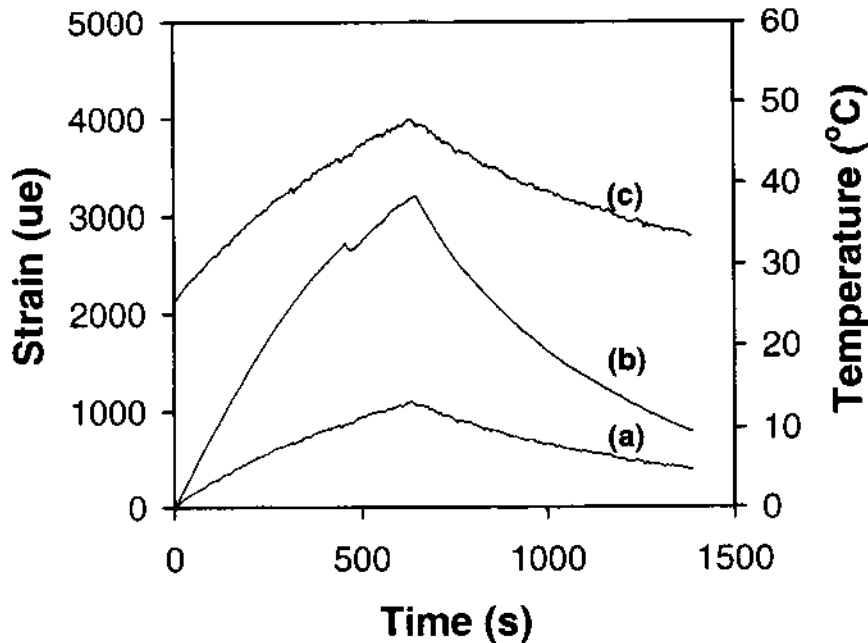


Fig. 3. Variation of the measured strain and the calculated thermal expansion strain (based on the measured temperature) with time. An electric field of 208 V/m was maintained for 10 min, followed by an extended period of no applied field. (a) Calculated thermal expansion strain. (b) Measured strain. (c) Temperature.

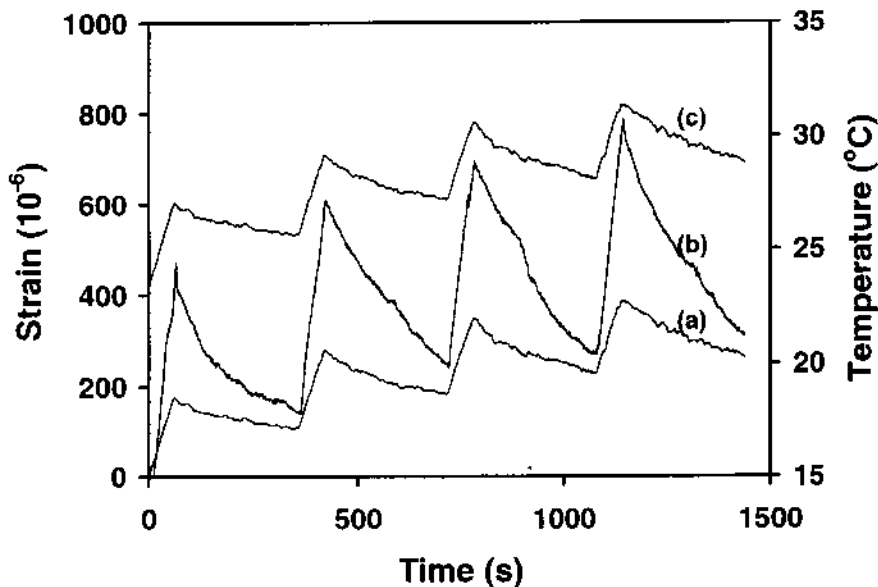


Fig. 4. Variation of the measured strain and the calculated thermal expansion strain (based on the measured temperature) with time during cyclic field application. In each cycle, an electric field of 208 V/m was maintained for 1 min, followed by turning off the current for 5 min. (a) Calculated thermal expansion strain. (b) Measured strain. (c) Temperature.

as shown upon turning off the current in each cycle. However, the temperature change was quite irreversible for the length of time in which the current was off. As a result, the calculated thermal expansion strain was also quite irreversible. Similar results were obtained for lower field values, except that the strains and temperature increased with increasing field.

Figure 5 shows results obtained during field direction switching while the magnitude of the field was kept constant. A field of 102 V/m was applied for 1 min, followed by changing the direction of the field for

1 min. Then the field was turned off. Both before and after switching, the measured strain increased with time. In other words, the switching had no effect on the strain.

DISCUSSION

The reverse piezoelectric effect is attributed to electric dipole orientation change during electric field application. Because of geometric hindrance and the extent of orientation of a dipole relative to the electric field, not all dipoles contributed to the reverse piezoelectric effect

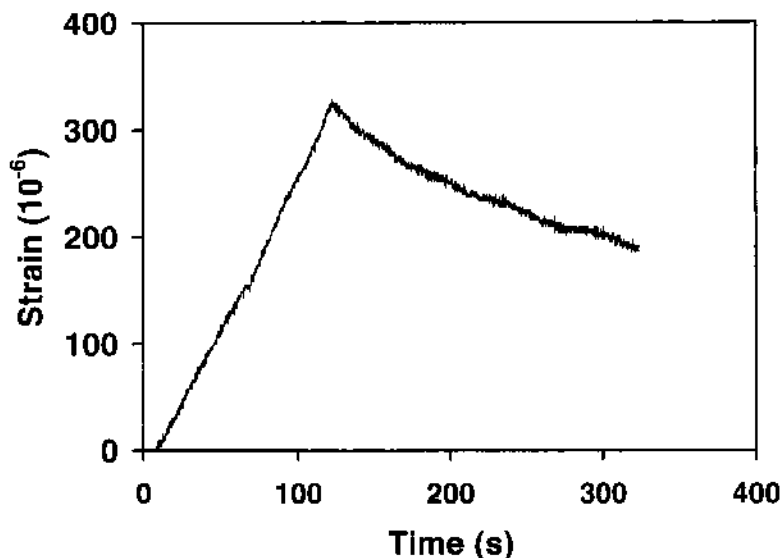


Fig. 5. Variation of the measured strain with time. An electric field of 102 V/m was maintained for 1 min, followed by changing the field direction for 1 min. Then the electric field was turned off.

for a given field direction. A reversal of the field direction is believed to result in a different set of dipoles responding to the field. As a result, the piezoelectric effect was unaffected by field reversal.

The piezoelectric coupling coefficient is high compared to values for conventional ceramic piezoelectric materials (e.g., 1×10^{-10} m/V for BaTiO₃). This is due to the difference in mechanism behind the effect. The high value is attractive for actuation, as it means that a smaller electric field is needed for the same strain. However, the effect is limited to the through-thickness direction of the laminate.

CONCLUSION

The reverse piezoelectric effect was observed in the through-thickness direction of a continuous carbon fiber nylon-6 matrix composite. The piezoelectric coupling coefficient was 2.2×10^{-6} m/V, as determined up to an electric field of 261 V/m. The effect was

largely reversible upon turning off the field and was unaffected by field reversal. It is attributed to the change in orientation of some of the electric dipoles in the polymer molecules in response to the electric field.

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