Composite Interfaces, Vol. 11, No. 1, pp. 95–103 (2004)

Letter

Piezoresistivity in unidirectional continuous carbon fiber polymer-matrix composites: single-lamina composite versus two-lamina composite

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Received 15 May 2003; accepted 18 June 2003

Abstract—Piezoresistivity in unidirectional carbon fiber epoxy-matrix composites was studied by measurement of the electrical resistance of single-lamina and two-lamina composites in the longitudinal (fiber) direction during elastic tensile loading and unloading in the same direction. The piezoresistive effect was reversible. The resistivity increased slightly with longitudinal tensile strain for the single-lamina composite, but decreased with strain for the two-lamina composite. The gage factor was around +2 and −6 for single-lamina and two-lamina composites, respectively. The very weak piezoresistivity in the single-lamina composite was probably due to decrease in the extent of fiber–fiber contact upon tension. The relatively strong piezoresistivity in the two-lamina composite was probably due to increase in the degree of fiber alignment upon tension.

Keywords: Composite; polymer; carbon fiber; electrical resistance; piezoresistivity.

1. INTRODUCTION

Piezoresistivity refers to the change in electrical resistivity with strain [1]. The phenomenon is useful for strain sensing. It is particularly valuable when a structural material exhibits piezoresistivity, because this allows the structural material to sense its own strain for the purpose of structural vibration control and hazard mitigation. In other words, the structural material becomes self-sensing, with elimination or reduction of the need for embedded or attached sensors, which suffer from high cost, poor durability, limited sensing volume and, in the case of embedded sensors, degradation of the mechanical properties.

Continuous carbon fiber polymer-matrix composites are the dominant advanced composites for lightweight structures, such as aircraft, satellites and sporting goods. Piezoresistivity has been reported in these materials [2–8]. For both unidirectional and crossply composites with multiple laminae, the resistivity in the longitudinal (fiber) direction decreases reversibly upon tension and the phenomenon is attributed to an increase in the degree of fiber alignment [2–5, 7]. Consistent with this origin is the observation that the through-thickness resistivity increases reversibly upon longitudinal tension [3–5]. In other words, the chance of fibers in adjacent laminae to touch one another is diminished when the fibers are more aligned, thus causing the through-thickness resistivity to increase. On the other hand, the transverse direction shows negligible piezoresistivity, i.e. the transverse resistivity increases only slightly upon transverse tension; the transverse resistance increases reversibly upon transverse tension merely due to dimensional changes [9].

The notion mentioned above that the piezoresistivity in the longitudinal direction is due to an increase in the degree of fiber alignment upon tension needs more substantiation. For this purpose, this paper provides a comparative study of the longitudinal piezoresistivity for a single-lamina composite and a two-lamina composite. The fibers within the same lamina are more aligned than those of different laminae, due to the manual process of stacking one lamina over another during the fabrication of a two-lamina composite. Hence, the inherent degree of fiber alignment is higher for a single-lamina composite than a two-lamina composite. A higher inherent degree of fiber alignment is associated with weaker piezoresistivity, as shown by comparison of the piezoresistivity of composites with multiple laminae and various inherent degrees of fiber alignment [2].

The use of the four-probe method rather than the two-probe method is necessary for observation of the longitudinal piezoresistivity, which involves the resistivity decreasing upon tension [7]. The use of the two-probe method is misleading, as the contact resistance (rather than the specimen volume resistance) dominates the measured resistance and it increases reversibly upon tension [6, 7]. The four-probe method is used in this work.

2. EXPERIMENTAL

Both single-lamina and two-lamina composites were fabricated from unidirectional carbon fiber epoxy-matrix prepregs provided by Zoltek Materials Group, San Diego, CA (Table 1). The two-lamina composite was unidirectional and made by hand lay-up. Consolidation and curing were conducted by applying pressure (0.62 MPa) and heat (up to $121 \pm 2°C$ at a rate of $2°C/min$, subsequent holding at temperature for 3 h and then furnace cooling to room temperature).

The composite specimens were of size 178 × 12 mm. The thickness was 0.15 and 0.31 mm for the single-lamina and two-lamina composites respectively. The volume fraction of fibers in the composites was 42%, as determined from the composite density, which was $1.43\ g/cm^3$ for both single-lamina and two-lamina composites. Glass fiber reinforced epoxy end tabs for gripping the specimens during subsequent tension were applied near both ends on both sides of each piece, such that the inner edges of the end tabs on the same side were 89 mm apart (Fig. 1). Three specimens of each type were tested.

Table 1.
Carbon fiber and epoxy matrix properties (according to Zoltek Materials Group, San Diego, CA)

Fortafil 555 continuous carbon fiber (PAN-based)	
Diameter	6 μm
Density	1.8 g/cm^3
Tensile modulus	231 GPa
Tensile strength	3.80 GPa
Ultimate elongation	1.64%
Electrical resistivity	1.67×10^{-3} Ω cm
Filaments per tow	80,000
Twist	None
Zoltek C2002 epoxy	
Processing temperature	121 °C
Flexural modulus	99.9 GPa
Flexural strength	1.17 GPa
T_g	129 °C
Density	1.15 g/cm^3

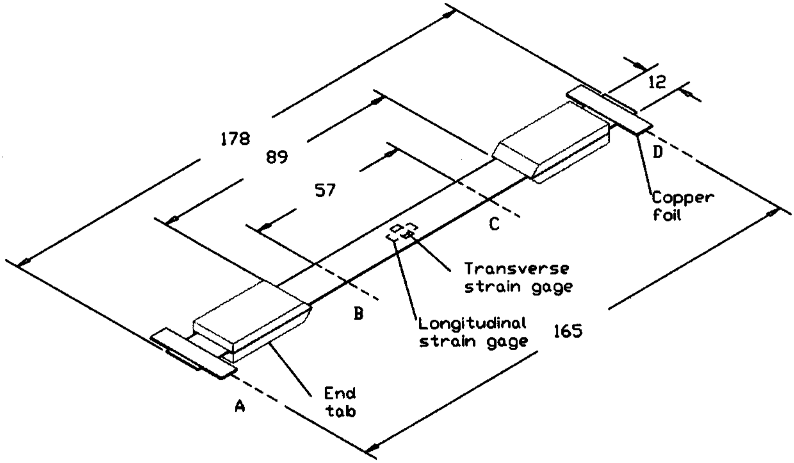

Figure 1. Specimen configuration. A, B, C and D are the electrical contacts used in the four-probe method. A and D are for passing current; C and D are for voltage measurement. All dimensions are in mm.

The electrical resistance R was measured in the fiber (longitudinal) direction while cyclic tension was applied in the same direction. For each specimen, the stress amplitude was increased in steps, such that at least 9 cycles were conducted at each of three steps. All stresses were in the elastic regime. Silver paint was used for electrical contacts. The four probes (A, B, C and D in Fig. 1) consisted of two outer current probes (A and D) and two inner voltage probes (B and C). The measured resistance is the specimen volume resistance between the inner probes. The two inner probes in the form of silver paint in conjunction with copper wires were around the whole perimeter of the specimen in two parallel planes that were perpendicular to the fiber direction, such that they were 57 mm apart. The two current probes were at the two ends where the matrix had been removed by burning, such that the burnt regions protruded from the outer edges of the end tabs and the current contacts were not gripped during subsequent tensile testing. Silver paint was applied to the fibers that had been exposed by burning. Then the silver-painted regions were wrapped by copper foil to which copper wires were subsequently soldered for passing current during piezoresistivity testing. The distance between the current probes was 165 mm.

Two strain gages of type EA-06-120LZ-120, produced by Measurements Group, Inc., with strain limit 3% and gage factor 2.060 ± 0.5% (at 24°C), were attached to the centers of the two largest opposite faces of each specimen (Fig. 1) for measuring the longitudinal and transverse strains separately. A Keithley 2001 multimeter was used for DC resistance measurement. The displacement rate was 0.25 mm min^{-1}. A screw-action mechanical testing system (Sintech 2/D, MTS Systems Corp., Marblehead, MA) was used for cyclic tensile loading in the fiber direction.

3. RESULTS

The volume electrical resistivity of the composites in the fiber direction was $(3.03 \pm 0.04) \times 10^{-3}$ and $(2.65 \pm 0.01) \times 10^{-3}$ Ω cm for the single-lamina and two-lamina composites respectively, as measured using the four-probe method mentioned above prior to loading. That the resistivity was slightly lower for the two-lamina composite may be due to slight differences in the curing conditions. Nevertheless, the similarity in resistivity between the single-lamina and two-lamina composites suggests that the microstructure is similar for the two composites. The resistivity calculated by using the nominal resistivity of the fibers and the Rule of Mixtures was 4.4×10^{-3} Ω cm — quite close to the measured values.

The tensile strength was 730±30 and 736±17 MPa for the single-lamina and two-lamina composites respectively. The value calculated by using the nominal tensile strength of the fibers and the Rule of Mixtures was 1440 MPa. That the measured value was much lower than the calculated value is due to the fiber waviness and the limited degree of fiber alignment in the composite.

Upon longitudinal tension, the longitudinal strain reversibly increases in magnitude, becoming more positive, while the transverse strain reversibly increases in magnitude, becoming more negative, as expected from the Poisson effect. The stress is linearly related to the longitudinal and transverse strains for all the stress amplitudes used. The Poisson ratio is shown in Table 2 for the single-lamina and the two-lamina composites at different strain amplitudes.

Upon longitudinal tension, the longitudinal resistance and resistivity (calculated from the resistance and the longitudinal and transverse strains) of the single-lamina composite increase reversibly, whereas those of the two-lamina composite decrease reversibly. The behavior is the same for all three specimens of each type. Figures 2 and 3 show the reversible changes in resistivity upon cyclic strain variation for

Table 2.
Value of the gage factor for a typical single-lamina composite and a typical two-lamina composite: the composites correspond to those of Figs 2 and 3

No. of laminae	Strain amplitude (%)	Poisson ratio	Gage factor
1	0.04	0.50	3.5
1	0.11	0.45	1.8
1	0.15	0.39	1.8
2	0.06	0.46	−6.0*
2	0.15	0.40	−5.5*
2	0.21	0.36	−5.1*

* Relatively large data scatter.

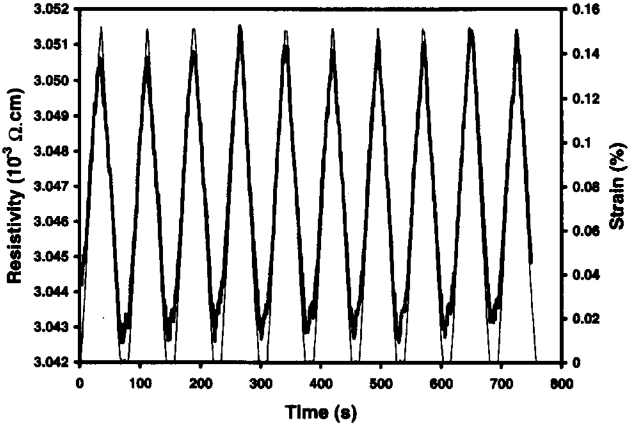

Figure 2. Resistivity *vs.* time (thick curve) and strain *vs.* time (thin curve) during cyclic strain variation for the single-lamina composite.

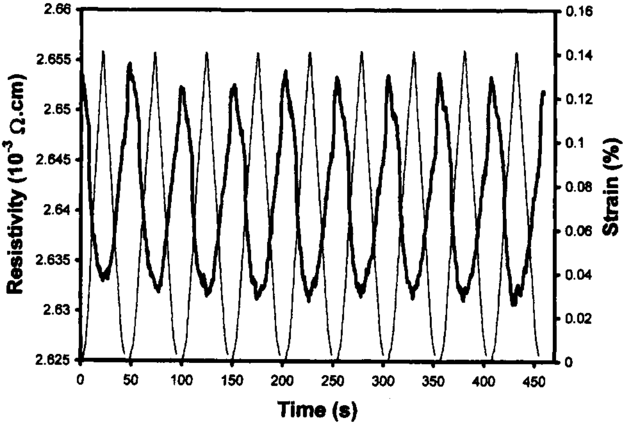

Figure 3. Resistivity *vs.* time (thick curve) and strain *vs.* time (thin curve) during cyclic strain variation for the two-lamina composite.

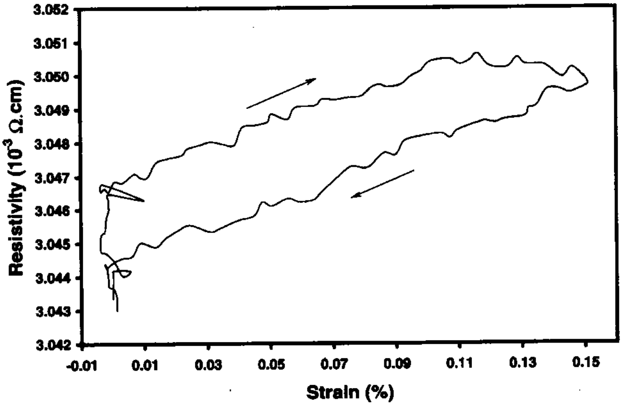

Figure 4. Resistivity *vs.* strain for the single-lamina composite during loading and unloading.

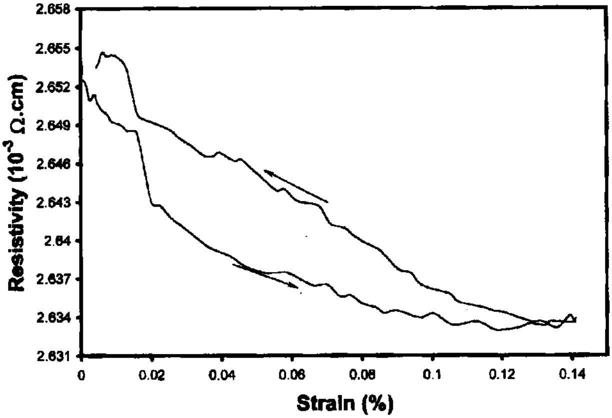

Figure 5. Resistivity *vs.* strain for the two-lamina composite during loading and unloading.

single-lamina and two-lamina composites respectively. In the case of the single-lamina composite, the resistivity shows an irreversible decrease at the end of the first strain cycle, as observed for a strain amplitude of 0.15% (Fig. 2) as well as lower strain amplitudes (as low as 0.04%). The strain is longitudinal in this paper unless noted otherwise. For the two-lamina composite, no irreversible behavior was observed (Fig. 3).

The gage factor (fractional change in resistance per unit strain) is listed in Table 2 for both single-lamina and two-lamina composites. The gage factor is positive for the single-lamina composite because the resistance increases with strain; it is negative for the two-lamina composite because the resistance decreases with strain. There is some dependence of the gage factor on the strain amplitude, but the trend is not sufficiently clear with the data available.

Figures 4 and 5 show the variation of the resistivity with strain for single-lamina and two-lamina composites, respectively. The second strain cycle at a certain strain amplitude step is shown in each case. Hysteresis was observed in both cases. The resistivity is higher upon loading than upon subsequent unloading at the same strain in the case of the single-lamina composite (Fig. 4), but is lower upon loading than upon subsequent unloading in the case of the two-lamina composite (Fig. 5). The dependence of the resistivity on strain is non-linear in both cases.

4. DISCUSSION

The trend of the resistivity decreasing with strain, as observed for the two-lamina composite, is consistent with the previous report for an eight-lamina unidirectional composite [2] and for a twelve-lamina crossply composite [5].

The trend of the resistance increasing with strain, as observed for the single-lamina composite, is expected for the scenario in which the resistance change is due to the changes in dimensions. If the resistance change is purely due to dimensional changes, the gage factor ranges from +1.4 (for $\nu = 0.2$) to +2.0 (for $\nu = 0.5$), as shown by simple calculation. The gage factor obtained for the single-lamina composite ranges from +1.8 to +3.5. The increase of the resistivity with strain is not large (Fig. 4); the reversible effect is attributed to a subtle and reversible change in the microstructure of the composite. The nature of the microstructural change has not been identified, but it may be related to a reversible decrease in the extent of fiber–fiber contact. A decrease in the extent of fiber–fiber contact can cause the volume resistivity of the composite to increase, because not all the fibers are perfect and current detour to an adjacent fiber through the fiber–fiber contact alleviates the negative effect of an imperfect fiber on the volume resistivity of the composite. The resistivity of the fiber itself increases irreversibly upon damage, as previously observed in a single carbon fiber [10]. However, the low levels of stress and strain used in this paper and the reversible nature of the observed resistivity increase suggest that the observed resistivity increase in the single lamina composite is not due to the change in fiber resistivity.

The decrease in resistivity with strain, as observed for the two-lamina composite, obviously cannot be explained by dimensional changes. It is probably partly due to an increase in the degree of fiber alignment, as previously mentioned for eight-lamina [2, 7] and twelve-lamina [5] composites. The gage factor was −5 for an eight-lamina composite that involved four electrical contacts that were similar to those of this work [7]. The gage factor of the two-lamina composite of this work is about the same in both sign and magnitude.

The resistivity is higher upon loading than upon unloading for a single-lamina composite (Fig. 4). This is consistent with the irreversible decrease in the resistivity after the first strain cycle at a strain amplitude step (Fig. 2). This phenomenon suggests that the decrease in fiber–fiber contact that occurs upon loading is followed by a disturbance upon unloading. The disturbance is such that it causes an increase in the extent of fiber–fiber contact relative to that in the state prior to loading. The disturbance is particularly significant after the first loading cycle.

The resistivity is slightly lower upon loading than upon unloading for a two-lamina composite (Fig. 5). However, there is no irreversible resistivity change after unloading for any loading cycle (Fig. 3). The slight hysteresis is probably because the increase in the degree of fiber alignment upon loading results in a decrease of the extent of fiber–fiber contact.

The values of the Poisson ratio (ν_{12}) are high, particularly for the single-lamina composite. The high values reflect the anisotropy of the composites and the relative ease for shrinkage in the direction perpendicular to the fibers. They are consistent with the value of 0.5 previously reported for a 24-lamina unidirectional composite [10].

That the Poisson ratio decreases with increasing strain for both single-lamina and two-lamina composites is because the extent of fiber–fiber contact in the transverse direction increases with longitudinal strain and the contact makes further transverse shrinkage more difficult.

In spite of the high Poisson ratio of the single-lamina composite and the consequent large extent of transverse shrinkage, the resistivity increases upon loading. Thus, the Poisson effect appears to be unable to mask the effect of fiber alignment and the consequent decrease in the extent of fiber–fiber contact. Nevertheless, due to these opposing effects (one effect to increase the fiber–fiber contact and the other to decrease the contact), the piezoresistivity is very weak in the single-lamina composite.

The Poisson effect in both the transverse direction (ν_{12}) and the through-thickness direction (ν_{13}) may contribute to the piezoresistivity in the two-lamina composite. However, its contribution is minor compared to the contribution by the increase in the degree of fiber alignment. This is because of the increase in the through-thickness resistivity during longitudinal tension, as previously reported for composites with multiple laminae [3–5]. The Poisson effect would have caused the through-thickness resistivity to decrease upon longitudinal tension.

The data scatter for the gage factor is much larger for the two-lamina composite than the single lamina composite. This is consistent with (i) the contribution of the increase in the degree of fiber alignment to the cause of the piezoresistive effect of the two-lamina composite and (ii) the variation of the initial degree of fiber alignment among the two-lamina composite specimens.

Although the single-lamina and two-lamina composites are similar in the longitudinal volume resistivity and in the Poisson ratio, they are very different in the piezoresistive behavior. This piezoresistivity difference supports the notion that the large piezoresistive effect in the two-lamina composite is due to an increase in the degree of fiber alignment upon longitudinal tension. However, further analysis is needed to fully confirm this notion

As practical composite laminates involve multiple laminae, the relatively large piezoresistive effect of the two-lamina composite of this work is useful in practical applications, whereas the weak piezoresistive effect of the single-lamina composite is not useful in practical applications. Nevertheless, information on the single-lamina composite is useful for fundamental understanding of the piezoresistive behavior of multiple-lamina composites.

Piezoresistivity testing can be considered a new nondestructive method of studying the micromechanics of composite materials. The method is nondestructive, since the testing can be conducted in the elastic regime, as in this work. The gage factor provides a quantitative and concise description of the piezoresistive effect.

5. CONCLUSION

The piezoresistive effect in carbon fiber epoxy-matrix composites is reversible and is such that the resistivity increases slightly with longitudinal tensile strain for a single-lamina composite (gage factor around +2) but decreases with strain for a two-lamina composite (gage factor around −6). The increase in resistance with strain in the single-lamina composite is mainly due to dimensional changes; the slight increase in resistivity is probably due to a reversible decrease in the extent of fiber–fiber contact. The decrease in resistivity with strain in the two-lamina composite is probably due to reversible increase in the degree of fiber alignment.

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