PIEZORESISTIVITY-BASED SENSING IN CONTINUOUS CARBON FIBER POLYMER-MATRIX COMPOSITE

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Abstract

Continuous carbon fiber epoxy-matrix composite exhibits various types of piezoresistivity, which is valuable for strain/stress sensing and is investigated in this work by using a commercially manufactured quasi-isotropic composite. The negative piezoresistivity associated with the increase of the through-thickness resistivity upon longitudinal tension and decrease in the through-thickness resistivity upon longitudinal compression is practically attractive for strain sensing and is attributed to the decrease in the degree of contact between fibers of adjacent laminae upon longitudinal tension. This effect is stronger, more reversible and less prone to causing minor damage for the tension case than the compression case. The positive piezoresistivity associated with the through-thickness resistivity decreasing upon through-thickness compression results in the longitudinal resistivity decreasing upon through-thickness compression and is useful for the sensing of through-thickness stress, which is relevant to fastening stress monitoring. The positive piezoresistivity associated with the longitudinal resistivity increasing upon longitudinal tension is negligibly weak, if any, independent of the number of laminae. The previously reported negative piezoresistivity associated with the longitudinal resistivity decreasing upon longitudinal tension does not occur for a commercially manufactured composite in which the fibers are well aligned.

Introduction

Piezoresistivity is a phenomenon in which the electrical resistivity of a material changes with strain. It is practically useful for providing strain sensing through electrical resistance measurement. Strain sensing is to be distinguished from damage sensing (Chung, in press). Strain causes reversible effects, whereas damage causes irreversible effects.

The resistance R is related to the resistivity ρ, the length ℓ in the direction of resistance measurement and the cross-sectional area A perpendicular to the direction of resistance measurement, i.e.,

$$R = \rho \ell / A \qquad (1)$$

The fractional change in resistance is given by the equation

$$\delta R/R = \delta\rho/\rho + (\delta\ell/\ell)(1-\nu_{12}-\nu_{13}), \qquad (2)$$

where ν_{12} and ν_{13} are values of the Poisson ratio for the transverse and through-thickness strains respectively.

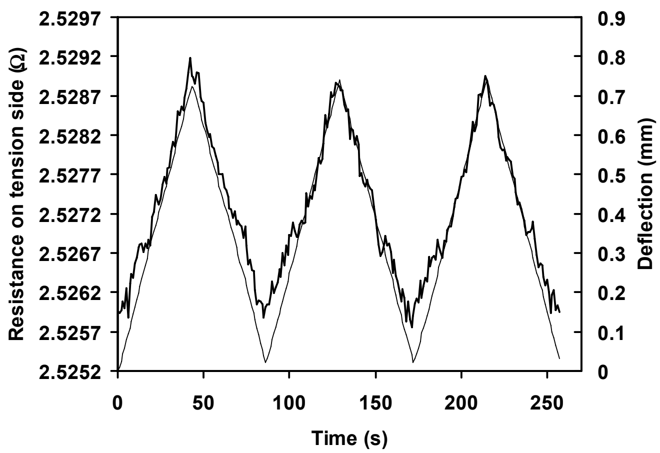
Positive piezoresistivity refers to the behavior in which the resistivity increases with increasing strain, i.e., $(\delta\rho/\rho) / (\delta\ell/\ell) > 0$. Negative piezoresistivity refers to the behavior in which the resistivity decreases with increasing strain, i.e., $(\delta\rho/\rho) / (\delta\ell/\ell) < 0$. Piezoresistivity is usually positive, because elongation tends to change the microstructure in such a way that the resistivity becomes larger in the direction of elongation.

For the purpose of effective strain sensing, a large fractional change in resistance per unit strain is desired. Thus, the severity of piezoresistivity is commonly described in terms of gage factor, which is defined as the fractional change in resistance per unit strain. Eq. (2) shows that the gage factor depends both on the fractional change in resistivity per unit strain and the Poisson ratio. A positive value of the gage factor does not necessarily mean that the piezoresistivity is positive, but a negative value of the gage factor necessarily means that the piezoresistivity is negative.

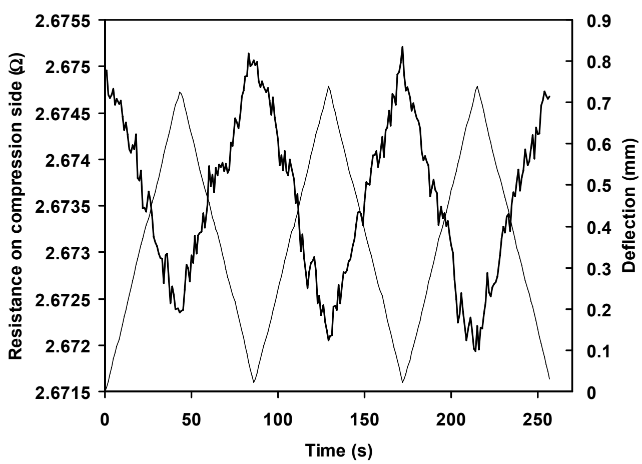
In order to attain a large fractional change in resistance at a particular strain, positive piezoresistivity is more desirable than negative piezoresistivity that exhibits the same magnitude of the fractional change in resistivity. When the strain is small, as is the case when the piezoresistive material is a stiff structural material, the fractional change in resistance is essentially equal to the fractional change in resistivity. Under this circumstance, positive and negative piezoresistivities are equally desirable for providing a large magnitude of the fractional change in resistance. From the viewpoint of the scientific origin, negative piezoresistivity is more intriguing than positive piezoresistivity.

Piezoresistivity in continuous carbon fiber polymer-matrix composites

Continuous carbon fiber polymer-matrix composites are important for lightweight structures. A form of negative piezoresistivity in these materials entails the resistivity in the through-thickness direction (i.e., the direction perpendicular to the laminae, which refer to the fiber layers) of the composite increasing upon uniaxial tension in the longitudinal direction (Wang et al., 1998; Wang and Chung, 1998). Due to the Poisson effect, the through-thickness direction undergoes shrinkage during the longitudinal tension. As a result, the piezoresistivity in the through-thickness direction is negative. This negative piezoresistivity results in decrease in the extent of penetration of the electric current that is applied on the surface on the tension surface of a composite specimen under flexure, thereby causing the tension surface resistance to increase upon flexure (Fig. 1(a)) (Wang and Chung, 2006; Zhu and Chung, in press). As the through-thickness resistivity decreases upon longitudinal compression, this negative piezoresistivity results in increase in the extent of penetration of the electric current that is applied on the surface on the compression surface under flexure, thereby causing the compression surface resistance to decrease upon flexure (Fig. 1(b)).



(a)



(b)

Figure 1. Resistance (thick curve) during flexural deflection (thin curve) cycling of a quasi-isotropic carbon fiber epoxy-matrix composite at a maximum deflection of 0.724 mm (stress amplitude of 129.7 MPa). (a) Tension surface resistance. (b) Compression surface resistance. (Wang, S. and Chung, 2006).

Another form of negative piezoresistivity involves the longitudinal resistivity decreasing upon uniaxial tension in the longitudinal direction (Wang et al., 1998; Wang and Chung, 1998). However, this phenomenon is not observed when the composite consists of only a single lamina; the piezoresistivity is weakly positive rather than being negative, whether surface sanding is conducted (Todoroki and Yoshida, 2004 and 2005) or not (Gordon et al., 2004) prior to electrical contact application. For composites with multiple laminae, this form of negative piezoresistivity is larger for composites that contain fibers that are less perfectly aligned during fabrication (Wang et al., 1998). For a commercially manufactured composite in which the fibers are well aligned, this form of negative piezoresistivity does not occur (Wang, S. and Chung, in press).

Yet another form of negative piezoresistivity in these composites involves the longitudinal resistance decreasing upon compression in the through-thickness direction (Leong et al. 2006; Wang, D. and Chung, in press) (Fig. 2). Due to the Poisson effect, slight extension occurs in the longitudinal direction, so the piezoresistivity is negative in the longitudinal direction. This effect is due to the squeezing of the fibers in the through-thickness direction causing the though-thickness resistivity to decrease. A decrease in the through-thickness resistivity helps conduction in the longitudinal direction, because it promotes the ability of the longitudinal current to detour from a longitudinal fiber to another in case of an imperfection in the first fiber. Sensing of the through-thickness stress can be attained by measuring the surface resistance in the direction of the surface fibers or by measuring the volume resistance in essentially any in-plane direction. Such stress sensing is relevant to fastening condition monitoring.

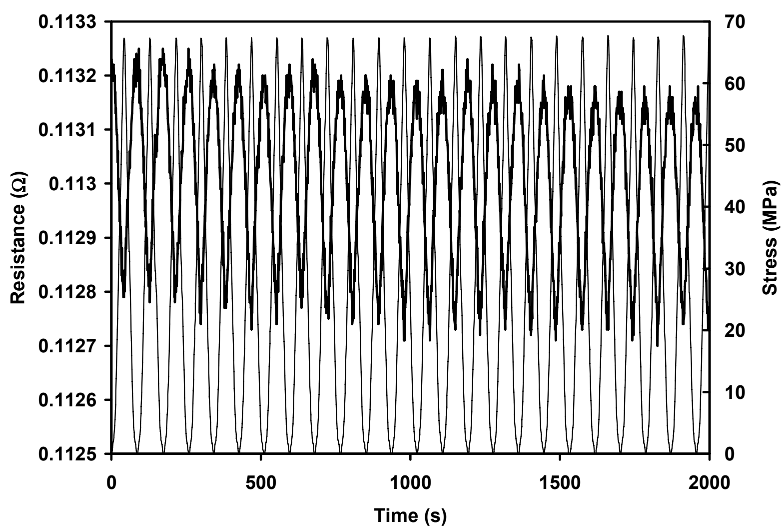


Figure 2. Variation of the longitudinal volume resistance (at the stressed region) (thick curve) with time and of the through-thickness compressive stress (thin curve) with time during through-thickness stress cycling of a quasi-isotropic carbon fiber epoxy-matrix composite at a fixed stress amplitude of 67 MPa. (Wang, D. and Chung, in press))

Conclusion

Piezoresistivity in carbon fiber epoxy-matrix composites allows such composites to sense their own strain and stress through electrical resistance measurement. The negative piezoresistivity in the form of the through-thickness resistivity increasing upon longitudinal tension is particularly effective for strain/stress sensing. This effect also allows sensing under flexure, as the tension surface resistance increases upon flexure, while the compressive surface resistance decreases upon flexure. This effect is due to the decrease in the degree of the tension surface current penetration upon flexure and the increase in the degree of compressive surface current penetration upon flexure. The negative piezoresistivity in the form of the longitudinal resistance decreasing upon compression in the through-thickness direction is valuable for through-thickness stress sensing. The previously reported negative piezoresistivity associated with the longitudinal resistivity decreasing upon longitudinal tension does not occur for a commercially manufactured composite in which the fibers are well aligned.

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