PIEZORESISTIVITY IN CONTINUOUS CARBON FIBER POLYMER-MATRIX AND CEMENT-MATRIX COMPOSITES

Sihai Wen, Shoukai Wang and D.D.L. Chung
Composite Materials Research Laboratory
State University of New York at Buffalo
Buffalo, NY 14260-4400, USA

Introduction

Piezoresistivity is a phenomenon in which the electrical resistivity of a material changes with strain, which relates to stress. This phenomenon allows a material to serve as a strain/stress sensor. Applications of the stress/strain sensors include pressure sensors for aircraft and automobile components, vibration sensors for civil structures such as bridges and weighing-in-motion sensors for highways (weighing of vehicles). The first category tends to involve small sensors (e.g., in the form of cement paste or mortar) and they will compete with silicon pressure sensors. The second and third categories tend to involve large sensors (e.g., in the form of precast concrete or mortar) and they will compete with silicon, acoustic, inductive and pneumatic sensors.

Piezoresistivity studies have been mostly conducted on polymer-matrix composites with fillers that are electrically conducting. These composite piezoresistive sensors work because strain changes the proximity between the conducting filler units, thus affecting the electrical resistivity. Tension increases the distance between the filler units, thus increasing the resistivity; compression decreases this distance, thus decreasing the resistivity.

Previously investigated composite piezoresistive materials include polymer-matrix cmposites containing continuous carbon fibers [1-6], carbon black [7-9], metal particles [8], short carbon fibers [9,10], cement-matrix composites containing short carbon fibers [11-16], and ceramic-matrix composites containing silicon carbide whiskers [17]. The sensing of reversible strain had been observed in polymer-matrix and cement-matrix composites [1-8,10-16].

Piezoresistivity in a structural material, such as a continuous fiber polymer-matrix composite, is particularly attractive, since the structural material becomes an intrinsically smart material that senses its own strain without the need for embedded or attached strain sensors. Not needing embedded or attached sensors means lower cost, greater durability, larger sensing volume (with the whole structure being able to sense) and absence of mechanical property degradation (which occurs in the case of embedded sensors).

Piezoresistivity has been previously reported in continuous carbon fiber epoxy-matrix composites [1-6], which are important for lightweight structures. Tensile strain in the fiber direction of a composite results in reversible increase in the resistivity in the through-thickness direction (perpendicular to the fiber layers in the composite) [3,4], as measured by the four-probe method. This is due to the increase in the degree of fiber alignment and the consequent decreased chance of fibers of adjacent layers touching one another. Tensile strain in the fiber direction also results in reversible decrease in the resistance in the fiber direction, as measured by using the four-probe method in which two current (outer) and two voltage (inner) contacts are around the entire perimeter of the composite at four planes that are perpendicular to the fiber direction [1,2,4]. This was attributed to the increase in the degree of fiber alignment [1,2,4], just as the phenomenon observed in the through-thickness direction. However, by using the two-probe method in which the common current/voltage contacts are at the ends of the fibers in the composite, the resistance in the fiber direction was observed to increase reversibly upon tension in the fiber direction [5]. Ref. 5 attributed this phenomenon to the dimensional changes during tension.

The opposite trends described above in the change in resistance in the fiber direction upon tensile strain in the fiber direction [1,2,4,5] are due to the difference in electrical contact configurations, so a study of the effect of electrical contact configuration is needed. The four-probe method [1,2,4] is in general better than the two-probe method [5], due to the elimination of the contact resistance from the measured resistance. Moreover, practical implementation of strain sensing (particularly strain distribution sensing) is more convenient when the contacts do not have to be at the ends of the fibers. However, having the current contacts at the ends of the fibers [5] ensures that current goes through all the fibers. Therefore, this paper extends previous work [1,2,4,5] provide a systematic comparison of the results obtained on the same composite with four contact configurations, namely (i) four-probe method with all four contacts around the entire perimeter at four planes that are perpendicular to the fiber direction, (ii) four-probe method with two voltage contacts around the entire perimeter at two planes that are perpendicular to the fiber direction and two current contacts at the fiber ends, (iii) two-probe method with both contacts around the entire perimeter at two planes that are perpendicular to the fiber direction, and (iv) two-probe method with both contacts at the fiber ends.

Due to the electrical conductivity of carbon fibers and the slight conductivity of the cement matrix, measurement of the DC electrical resistance of a carbon fiber cement-matrix composite provides a way to detect damage. Fiber breakage obviously causes the longitudinal resistance to increase irreversibly. Fiber-matrix bond degradation obviously increases the transverse resistance, but it also increases the longitudinal resistance when the electrical current contacts are on the surface (e.g., perimetrically around the composite in a plane perpendicular to the longitudinal direction). When the transverse resistivity is increased, the electrical current has more difficulty in penetrating the entire cross-section of the specimen, thereby resulting in an increase in the measured longitudinal resistance. Note that the electrical resistivity of carbon fibers is 10^{-4} Ω.cm, whereas that of cement paste is 10^{5} Ω.cm.

Although piezoresistivity has been reported in short fiber cement-matrix composites, it has not been previously reported in continuous fiber cement-matrix composites. This paper addresses piezoresistivity in continuous carbon fiber cement-matrix and polymer-matrix composites.

Conclusion

Piezoresistivity in continuous unidirectional carbon fiber epoxy-matrix composites was observed upon tension in the fiber direction. The phenomenon involved the volume resistivity of the composite in the fiber direction decreasing reversibly upon tension, due to an increase in the degree of fiber alignment, as observed by using the four-probe method. Use of the two-probe method resulted in measurement of the contact resistance rather than the volume resistance. The contact resistivity increased reversibly upon tension, but the phenomenon is not true piezoresistivity and is not suitable for practical use for strain sensing due to the need to have the electrical contacts at the fiber ends.

Piezoresistivity with gage factor up to +60 was observed in continuous carbon fiber cement-matrix composites with fiber volume fractions in the range from 2.6 to 7.4%. The electrical resistance in the fiber direction, as measured using surface electrical contacts, increases upon tension in the same direction. The resistance increase is mostly reversible, such that the irreversible portion increases with the stress amplitude. The effect is attributed to fiber-matrix interface degradation, which is partly irreversible. At higher strains at which the modulus is decreased, the resistance increases with strain abruptly, due to fiber breakage. The tensile strength of the composites is (88 ± 1)% of the calculated value based on the Rule of Mixtures. The tensile modulus (84 ± 1)% of the calculated value based on the Rule of Mixtures.

References

[1] Wang X, Chung DDL. Smart Mater Struct 1996;5:796.

[2] Wang X, Chung DDL. Smart Mater Struct 1997;6:504.

[3] Wang X, Chung DDL. Polymer Composites 1997;18(6):692.

[4] Wang X, Chung DDL. Composites: Part B, 1998;29B(1): 63.

[5] Irving PE, Thiagarajan C. Smart Mater Struct 1998; 7: 456.

[6] Muto N, Yanagica H, Miyayama M, Nakatsuji T,. Sugita M, Ohtsuka Y. J Ceramic Soc Jpn. (Int. Ed.) 1992;100: 582.

[7] Kost J, Narkis M, Foux A. J Appl Polymer Science 1984;29:3937-3946.

[8] Radhakrishnan S, Chakne S, Shelke PN. Mater Lett 1994; 18:358-362.

[9] P.K. Pramanik, D. Khastgir, S.K. De and T.N. Saha, J. Mat. Sci. **25**, 3848-3853 (1990).

[10] Taya M, Kim WJ, Ono K. Mechanics of Materials 1998;28 (1/4): 53-59.

[11] Chen P, Chung DDL. Smart Mater Struct 1993; 2: 22-30.

[12] Chen P, Chung DDL. Composites, Part B 1996; 27B: 11-23.

[13] Chen P, Chung DDL. ACI Mater J 1996; 93(4): 341-350.

[14] Fu X, Chung DDL. Cem Conc Res 1996; 26(1): 15-20.

[15] Fu X, Ma E, Chung DDL, Anderson WA. Cem Concr Res 1997; 845-852.

[16] Fu X, Lu W, Chung DDL. Cem Concr Res 1998; 28(2): 183-187.

[17] Ishida A, Miyayama M, Yanagida H. J Am Ceramic Soc 1994; 77(4): 1057-1061.

[18] Fu X, Lu W, Chung DDL. Carbon 1998; 36(9): 1337-1345.

[19] Saito K, Kawamura N, Kogo Y. 21st Int. SAMPE Technical Conf., 796-802 (1989).