CARBON FIBER STRUCTURAL COMPOSITES AS THERMISTORS

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Introduction

A thermistor is a thermometric device consisting of a material (typically a semiconductor) whose electrical resistivity decreases with increasing temperature. They are distinct from thermocouples, which are based on the Seebeck effect.

This paper provides a new class of thermistors, which involve carbon fiber structural composites instead of semiconductors. The advantages of the composites are low cost, mechanical rugged and processability into various shapes and sizes (as small as a coin or as large as a bridge). The processability into large sizes means that a composite structure is inherently able to sense its own temperature, without the need for embedded or attached sensors. This makes the structure intrinsically smart. Compared to the use of embedded or attached sensors, the intrinsically smart structure has the advantages of low cost, high durability, large sensing volume (everywhere rather than just here and there) and absence of mechanical property degradation (which occurs in the case of embedded sensors).

Concrete is a cement-matrix composite that is important for civil structures. The addition of short fibers as an admixture is known to decrease the drying shrinkage and increase the flexural toughness [1-3]. In the case of the fibers being carbon fibers, the fiber addition also increases the flexural strength and renders the composite the ability to sense its own strain [4-8]. The strain sensing ability is due to the effect of strain on the volume electrical resistivity of the composite. The Seebeck effect has been reported in carbon fiber cement-matrix composites [9]; it allows the cement-matrix composites to serve as temperature sensors. However, the use of the Seebeck effect for temperature measurement requires Seebeck voltage measurement, such that the voltage drops in the electrical leads and other parts of the circuit are not included. This requirement makes it more complicated to make use of the Seebeck effect in a structure in practice than the thermistor effect (i.e., the decrease of the resistivity with increasing temperature), which relates to resistance measurement rather than voltage measurement. The thermistor effect has not been previously reported in cement-matrix composites, although studies of the electrical resistivity have been made [10-14].

Continuous carbon fiber polymer-matrix composites are widely used for lightweight structures, such as aircraft, sporting goods and even automobiles and wheel chairs. Continuous fibers are not used in cement-matrix composites due to the high cost of continuous fibers compared to short fibers, the impossibility of having continuous fibers in a concrete mix, and the importance of low cost for a concrete to be industrially viable. For polymer-matrix structural composites, continuous fibers rather than short fibers are used, because continuous fibers are much more effective for reinforcing than short fibers. The thermistor effect has been previously reported in short fiber polymer-matrix composites [15], but not in continuous fiber polymer-matrix composites.

The thermistor effect is not only useful for application in temperature sensing, it is relevant to the study of the electrical conduction mechanism, which relates to the structure of the composite. The sensitivity of a thermistor for temperature sensing is described by the activation energy of the electrical conduction, as obtained from the negative slope of the Arrhenius plot of the logarithm of the electrical conductivity versus the reciprocal of the absolute temperature. The activation energy reflects the energy for the hopping of the charge carrier in the composite.

This paper describes the thermistor effect in short carbon fiber cement-matrix composite and continuous carbon fiber polymer-matrix composite. The former was found to be associated with an activation energy that is similar to the values for semiconductors, whereas the latter was found to be associated with a lower activation energy. Hence, the former is superior to the latter for thermistor application. However, the latter is more amenable to practical implementation, because the continuous fibers serve as electrical leads, so that both thermistors and leads are built-in to a continuous fiber composite.

Conclusion

Carbon-fiber silica-fume cement paste was found to be an effective thermistor. The electrical resistivity decreased with increasing temperature (1-45°C), with an activation energy of electrical conduction (electron hopping) of 0.4 eV, which is comparable to those of semiconductors (typical thermistor materials) and higher than that of carbon fiber polymer-matrix composites. Without carbon fibers, or with latex in place of silica fume, the activation energy is much lower and the resistivity is higher. The voltage range for linear current-voltage characteristic is narrower when fibers are present than when fibers are absent. Linearity occurred up to 8 V for carbon-fiber silica-fume cement paste at 20°C.

An epoxy-matrix continuous carbon fiber composite comprising two crossply laminae was a thermistor array. Each junction between crossply fiber tow groups of the adjacent laminae was a thermistor, while the fiber groups served as electrical leads. The contact electrical resistivity of the junction decreased reversibly upon heating, due to the electron hopping between the laminae. The fractional change in contact resistivity provided an indication of temperature. The contact resistivity decreased with increasing pressure during composite fabrication, due to increase in pressure exerted by fibers of one lamina on those of the other lamina. The magnitude of the fractional change in contact resistivity per degree C increased with increasing curing pressure (fiber volume fraction), due to the increase in interlaminar stress with increasing fiber volume fraction and the consequent increase in activation energy. A crossply junction is much better than a unidirectional junction as a thermistor, due to the absence of interlaminar stress in the latter.

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