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Piezoresistivity in Silicon Carbide Fibers

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Abstract. The polycrystalline β-SiC fiber of diameter 14 μm (without a carbon core) is piezoresistive under tension, with gage factor 5. The resistivity increases linearly and reversibly with strain in the elastic regime. The fiber of diameter 140 μm (with a carbon core) is not piezoresistive, due to the carbon core controlling the electrical resistance.

Keywords: silicon carbide, fiber, piezoresistivity, electrical resistivity, electrical resistance

Introduction

Silicon carbide fiber is a ceramic fiber that is an important continuous reinforcement for high temperature structural composites, particularly ceramic-matrix composites. In contrast to carbon fiber, SiC fiber is more oxidation resistant and thus more resistant to high temperatures. However, the brittleness of the SiC fiber makes the fiber prone to damage upon mechanical loading. For the purpose of hazard mitigation, it is desirable to monitor nondestructively the health of the SiC fiber. As damage commonly occurs upon loading, it is also desirable to monitor nondestructively the elastic strain of the fiber. In addition, strain monitoring allows recording of the load history. As strain occurs during vibration, strain monitoring also allows vibration sensing, which is needed for structural vibration control. Thus, this paper is focused on the sensing of strain in SiC fiber.

The sensing of strain in a composite material is conventionally achieved by embedding sensors (such as optical fibers [1] or tungsten fibers [2]) in the composite. The embedded sensor is intrusive, as its presence tends to cause degradation of the mechanical and thermal properties of the composite. Furthermore, embedded sensors are hard to be repaired and durability is an issue. In contrast, this paper uses the reinforcing fiber (i.e., SiC fiber) itself as the sensor, thereby alleviating the problems mentioned above.

Using the fiber itself as the strain sensor involves attaching wires (probes) for current and voltage measurement. The method allows the sensing of the overall strain between the two voltage probes. If it is necessary to sense the stress concentrations or the strain distribution, more wires (probes) are needed to obtain the strains at different locations.

The use of carbon fiber structural composites to sense their own strain has been previously reported [3–9], but the use of SiC fiber or its composites for sensing strain has not been previously reported. On the other hand, the SiC fiber has been previously reported to be a thermistor for temperature sensing [10, 11].

The effect of strain on the resistance can be due to the change in dimensions, though it can also be due to a change in the resistivity. If the resistivity is changed, the effect is known as piezoresistivity and the gage factor (fractional change in resistance per unit strain) exceeds 2. Piezoresistivity is a phenomenon that is practically used for strain (pressure) gages [12–14]. Piezoresistive materials include silicon [15–22], diamond [23–31], carbon [32–35], oxides [36–40], perovskite ceramics [41–45], metals [46, 47], polymers [48–50], composites [3–9, 51–55], compound semiconductors [56, 57] and SiC [58–62]. In the case of SiC, piezoresistivity has been observed in α-SiC (hexagonal) and β-SiC (cubic) in monocrystalline and polycrystalline film form, which is suitable for devices. In contrast, this paper

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addresses β-SiC in fiber form, which is suitable for structural composites.

The continuous SiC fibers studied in this work are in two forms, which are both commercially available. In one form, the entire fiber is SiC and the diameter is small (around 10–20 μm). The other form has a carbon core along the axis of the SiC fiber and the diameter is large (around 100–200 μm). Piezoresistive measurements were made on both forms of SiC fiber.

Experimental Methods

The thin form of SiC fiber is Hi-Nicalon ceramic fiber from Nippon Carbon Co., Ltd. (Tokyo, Japan). It is made by pyrolysis of a polymeric precursor fiber and is homogeneously composed of ultrafine β-SiC crystallites that have little preferred orientation, in addition to an amorphous mixture of silicon and carbon. The fiber properties are shown in Table 1.

The thick form of SiC fiber is SCS-6 from Textron Specialty Materials (Lowell, MA). It is fabricated by chemical vapor deposition on a continuous carbon fiber of diameter 33 μm. The overall fiber has diameter 140 μm. The fiber properties are also shown in Table 1. The β-SiC crystallites are radial in orientation.

This work involved single fiber electromechanical testing, i.e., measuring the electrical resistance during static and cyclic tension [4]. The DC resistance was measured by using the four-probe method, using silver paint for the electrical contacts.

For the thin SiC fiber work, the outer two contacts (110 mm apart) were for passing a current (0.9 μA), as provided by a DC power supply; the inner two contacts (90 mm apart) were for voltage measurement (Fig. 1). A standard resistor of 10 MΩ was connected in series with the single fiber. A Keithley 2001 multimeter was used to measure the voltages between the two inner contacts and across the standard resistor. The voltage across the standard resistor divided by the known resistance of the resistor gave the current. The voltage between the two inner contacts divided by the current gave the resistance of the part of the fiber between the two inner contacts. Next to the two inner contacts, the single fiber was attached vertically with adhesive (88 mm apart) to a piece of paper with an oblong hole cut in it (Fig. 1). Prior to vertical tension application, the paper was cut horizontally along the dashed lines shown in Fig. 1.

Table 1. Properties of SiC fiber

	Thin type	Thick type
Diameter (μm)	14	140
Density (g/cm^3)	2.74	3.0
Tensile strength (GPa)	2.80	3.45
Tensile modulus (GPa)	270	400
Electrical resistivity (Ω·cm)	1.4	/
Thermal expansion (25–500°C) (°C^{-1})	3.5×10^{-6}	/
Specific heat (50°C) (J/g·°C)	0.67	/

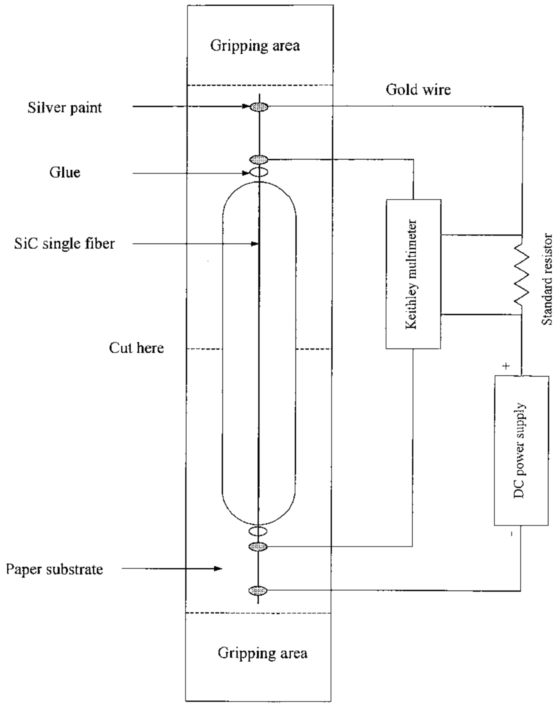

Fig. 1. Configuration for single fiber (14 μm diameter) electromechanical testing. The single fiber (solid vertical line) is adhered to a sheet of paper using a glue (open circles) such that the points of adhesion are 88 mm apart. The four silver paint electrical contacts (dotted circles) are such that the outer contacts are 110 mm apart and the inner contacts are 90 mm apart. The sheet of paper has an oblong hole cut in its middle.

For the thick SiC fiber work, the outer two contacts were 60 mm apart and the inner two contacts were 45 mm apart. The single fiber was embedded at both ends in epoxy, which served as end tabs. The exposed fiber length was 70 mm.

For both types of fiber, the tension was under load control, as provided by a screw-type mechanical testing system (Sintech 2/D). The crosshead speed was 0.1 mm/min. The strain was obtained from the crosshead displacement; its accuracy is supported by its consistency with the load, fiber diameter and fiber modulus.

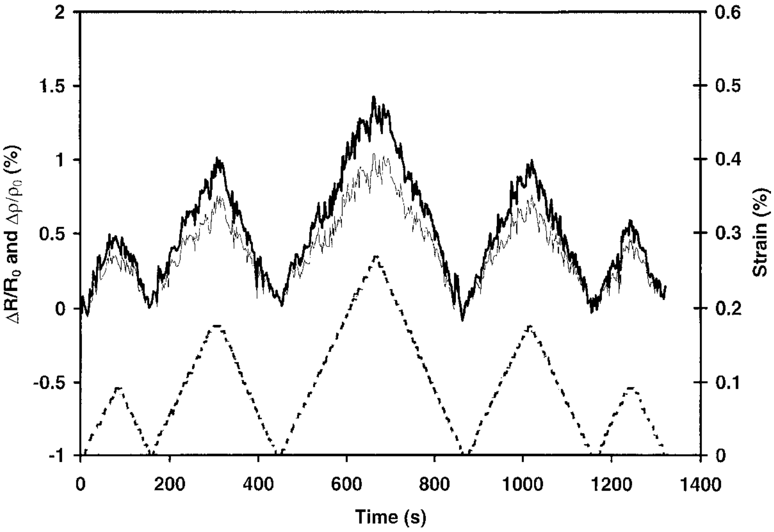

Fig. 2. Fractional change in electrical resistance (thick solid curve) vs. time, fractional change in resistivity (thin solid curve) vs. time, and strain (dashed curve) vs. time during repeated tensile loading of fiber of 14 μm diameter. The strain amplitude was stepped up and then stepped down.

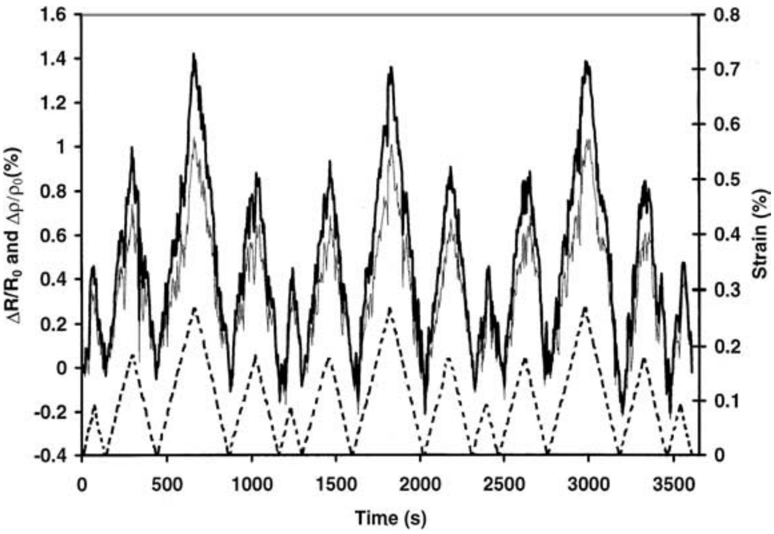

Fig. 3. Fractional change in electrical resistance (thick solid curve) vs. time, fractional change in resistivity (thin solid curve) vs. time, and strain (dashed curve) vs. time during repeated tensile loading of fiber of 14 μm diameter. The strain amplitude was stepped up and down for three times.

Results and Discussion

Thin Type of SiC Fiber

Figures 2 and 3 show the fractional change in resistivity (obtained by assuming that the Poisson ratio is 0.2), fractional change in resistance, and strain during repeated tensile loading at varying strain amplitudes within the elastic regime. The strain returns to zero at the end of each cycle. In Fig. 2, the strain amplitude was increased in two steps and then decreased in two steps. In Fig. 3, the strain amplitude was stepped up and down for three times. The resistivity increases reversibly upon tension in every loading cycle. The resistivity varies quite linearly with strain. The fractional change in resistivity per unit strain is 3.6. The gage factor (fractional change in resistance per unit strain) is 5.0. The baseline of the resistance or resistivity shifts down slightly as cycling progresses. This shift is not due to polarization, which causes the resistivity to shift upward slightly, as shown by continuous resistance measurement in the absence of stress. The observed downward shift is due to some irreversible effect of the stress on the resistivity of the fiber.

The gage factor previously reported for monocrystalline β-SiC films is negative (e.g., −32 [58, 63, 64]), but is positive for polycrystalline β-SiC films [65]. The β-SiC fiber used in this work is polycrystalline and the gage factor is positive. The piezoresistivity in monocrystalline SiC films is attributed to the change in carrier mobility (intervalley electron transfer [60]) in response to strain. In the case of the SiC fiber of this work, the piezoresistivity is probably related to a reversible microstructural change which occurs upon tension and which causes the resistivity to increase, as suggested by the multi-phase polycrystalline structure of the SiC fiber.

The temperature of the fiber may increase because of Joule heating and the temperature change may affect the electrical resistance of the fiber [66]. However, calculation shows that the temperature increase due to such a low current (0.9 μA) is negligible (less than 0.36°C).

The piezoresistivity observed in this work is not associated with a high gage factor. Nevertheless, the effect is substantial and linear and enables the use of the SiC fiber as a tensile strain/stress sensor. The piezoresistivity of a composite in which the SiC fiber is a component is not expected to be the same as that of the SiC fiber itself. Nevertheless, information on the piezoresistivity of the SiC fiber itself is basic to the understanding of the piezoresistivity of the composite.

Thick Type of SiC Fiber

Figure 4 shows the corresponding result for the thick type of SiC fiber. The resistance increases reversibly upon tension, whereas the resistivity does not change upon tension. The observed effect is attributed to dimensional changes.

As the resistivity of carbon is around 10^{-3} Ω·cm and that of SiC is around 1 Ω·cm, the resistance of the fiber is approximately equal to the resistance of the carbon core, in spite of the small diameter of the carbon core relative to the overall fiber diameter. It has been previously reported that the gage factor upon tension is 2 for a single carbon fiber [67]. Hence, our observation on the thick type of SiC fiber reflects the behavior of the carbon core. It should be noted that the calculation of the gage factor does not involve the fiber diameter.

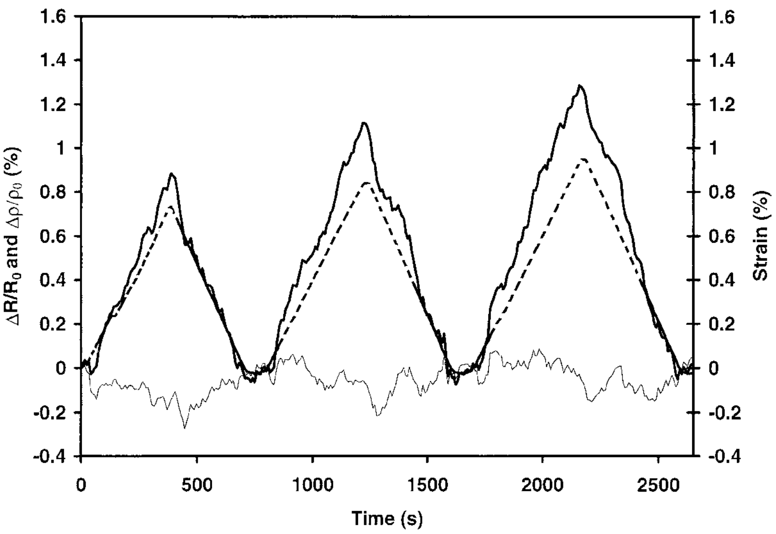

Fig. 4. Fractional change in electrical resistance (thick solid curve) vs. time, fractional change in resistivity (thin solid curve) vs. time, and strain (dashed curve) vs. time during repeated tensile loading of fiber of 140 μm diameter.

Comparison of Results for Thin and Thick Types of SiC Fiber

The gage factor is much higher for the thin type than the thick type of SiC fiber. The electromechanical behavior of the thin type reflects the piezoresistive behavior of SiC, whereas that of the thick type reflects the resistive behavior of the carbon core. The behavior of the thick type is not piezoresistivity, since the resistivity essentially does not change with stress. For practical application in strain/stress sensing, the thin type of fiber is more attractive, due to the relatively large gage factor.

Conclusion

The polycrystalline β-SiC fiber of diameter 14 μm (without a carbon core) is piezoresistive under tension, with gage factor 5. The resistivity increases linearly and reversibly with strain in the elastic regime, thus allowing the use of the fiber as a strain/stress sensor. The fiber of diameter 140 μm (with a carbon core) is not piezoresistive, due to the carbon core controlling the electrical resistance.

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