Smart Mater. Struct. **5** (1996) 243–246. Printed in the UK

TECHNICAL NOTE

A piezoresistive carbon filament polymer-matrix composite strain sensor

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Received 13 June 1995, accepted for publication 26 November 1995

Abstract. The relationship between strain and the fractional increase in electrical resistance ($\Delta R/R_0$) of piezoresistive polyether-sulfone-matrix composite strain sensors was found to be much more linear and less noisy when the electrically conducting filler was 0.1 μm diameter carbon filaments rather than the conventionally used 10 μm diameter carbon fibers. For the fiber composite, the non-linearity manifested itself as $\Delta R/R_0$ increasing reversibly with increasing compressive strain—an effect opposite to and occurring on top of piezoresistivity. This effect was absent from the filament composite. Furthermore, the percolation threshold was lower for the filament composite than for the fiber composite. For both filament and fiber composites, $\Delta R/R_0$ became more negative as cycling progressed up to $\sim$10 cycles and then stabilized though the effect was more significant for the latter.

1. Introduction

Piezoresistive strain sensors are usually in the form of a composite with an electrically non-conducting matrix and a conducting filler. Upon tension, increase in the separation between adjacent filler units causes the composite's volume electrical resistivity to increase; upon compression, decrease in the separation causes the resistivity to decrease. In this way, strain sensing is provided [1–4]. Because of the need for the composite to strain under tension or compression, the matrix cannot be too brittle. Therefore, the matrix is commonly a polymer rather than a ceramic. The fillers used by various previous workers include carbon fibers of diameter $\sim$ 10 μm [1, 2], carbon black [2–4] and metal particles [4].

A shortcoming of piezoresistive strain sensors is the non-linearity between the resistivity change and the strain. Little attention has been paid to the alleviation of this problem via the design of the composite. In this paper, through the replacement of the conventionally used 10 μm diameter carbon fibers with 0.1 μm diameter carbon filaments as the filler, this problem was greatly alleviated.

2. Experimental details

The composites' matrix was polyether sulfone (PES), a thermoplastic of volume resistivity > 10^{10} Ω cm and provided a Victrex PES 4100P by ICI. The carbon fibers of 10 μm diameter were of length 1 mm and volume resistivity 10^{-3} Ω cm, and were provided as Carboflex by Ashland Petroleum Co., Ashland, KY. The carbon filaments of 0.15 μm diameter were of length > 100 μm, as provided as ADNH by Applied Sciences Inc., Cedarville, OH. The carbon filaments had a bent morphology, resembling cotton wool, as shown by the scanning electron microscopy photographs in figure 1. In contrast, the carbon fibers were straight. In this work, the term 'filaments' refers to fibers of diameter $\sim$0.15 μm and the term 'fibers' refers to fibers of diameter $\sim$10 μm.

The composites were fabricated by mixing the polymer powder (100–150 μm size) and the filler with water in a blender, drying the wet mix at 120 °C, and subsequent hot pressing in a steel mold at 310 °C (processing temperature for PES, as recommended by ICI) and 13.4 MPa for $\sim$30 min.

The electrical resistance R was measured using the four-probe method while cyclic tension or cyclic tension–compression was applied in the load control mode. A precaution was made to prevent buckling during compression. Silver paint was used for electrical contacts. The four probes consist of two outer current probes and two inner voltage probes. The resistance R refers to the sample resistance between the inner probes. The distance between the inner probes was 25 mm. The samples were of size 80 × 8 × 3 mm. The resistance was measured along the stress axis. The current (DC) used was 0.5–1.0 mA; the voltage used was 2.0–2.4 V. The displacement

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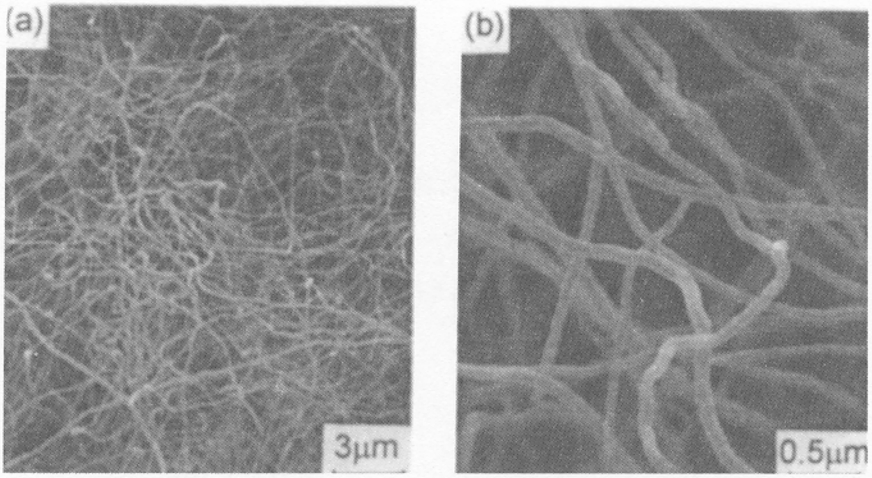

Figure 1. Scanning electron microscopy photographs at two different magnifications of carbon filaments.

rate was 1.0 mm min^{-1}. The strain was measured by a strain gage, which was of a type that could withstand repeated strain up to >1% without irreversibly changing its resistance. Testing was conducted by using a hydraulic materials testing system (MTS 810). Tensile testing was similarly performed, except that R was not measured.

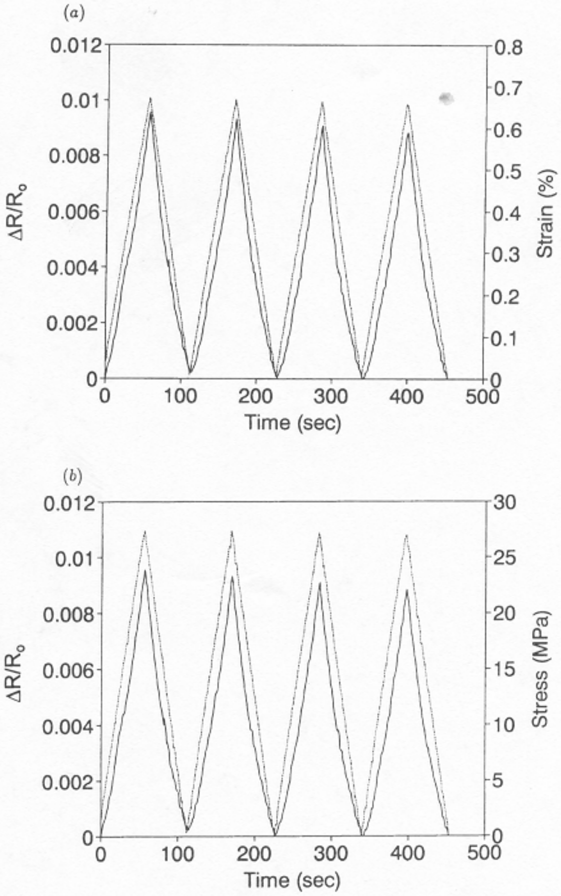

Figure 2. The variation of $\Delta R/R_0$ (solid line), strain (dashed line, (a)) and stress (dashed line (b)) with time during cyclic tensile loading for a PES-matrix composite containing 7 vol.% carbon filaments.

3. Results and discussion

Figure 2 shows the strain (a), stress (b) and fractional resistance increase ($\Delta R/R_0$) obtained simultaneously during cyclic tension for a composite with 7 vol.% carbon filaments. Because of the small strains involved, $\Delta R/R_0$ is essentially equal to the fractional increase in resistivity. Figure 3 shows the strain and $\Delta R/R_0$ obtained at a similar strain amplitude for a composite with 13 vol.% carbon fibers. (With 7 vol.% fibers, the composite was quite high in electrical resistivity, as shown in table 1, so 13 vol.% fibers was used. The percolation threshold was lower for filament composites than for fiber composites, as shown by the data in table 1). The relationship between $\Delta R/R_0$ and strain was far more linear in figure 2(a) than in figure 3. In figure 3, $\Delta R/R_0$ decreased slightly upon tension, probably due to fiber straightening, before abruptly increasing upon further tension due to piezoresistivity; $\Delta R/R_0$ increased slightly toward the end of each cycle (due to fiber buckling) and then decreased at the beginning of the following cycle (due to fiber straightening) before increasing abruptly with increasing strain due to piezoresistivity. In contrast, figure 2(a) does not exhibit this abnormality. Moreover, in figure 3, $\Delta R/R_0$ became more and more negative as cycling progressed.

Figure 4 and 5 show similar results for these two composites obtained during cyclic tension–compression at similar strain amplitudes. Not only is figure 5 far more non-linear than figure 4, but it also exhibits a portion in the compression part of each cycle in which $\Delta R/R_0$ increases reversibly upon compression. This portion essentially does not exist in figure 4. Since piezoresistivity is such that $\Delta R/R_0$ decreases upon compression, this abnormal effect is attributed not to the change in separation between the fibers, but probably to the change in degree of straightness of the fibers. Upon compression beyond the point at which the adjacent fibers touch one another, the fibers decrease in degree of straightness due to fiber buckling, thus causing the resistivity to increase reversibly. Figure 3 also shows

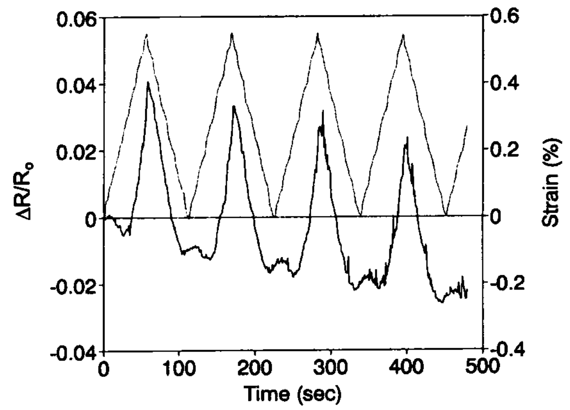

Figure 3. The variation of $\Delta R/R_0$ (solid line) and strain (dashed line) with time during cyclic tensile loading for a PES-matrix composite containing 13 vol.% carbon fibers.

Table 1. The volume electrical resistivity of PES-matrix composites with various volume fractions of carbon filaments and carbon fibers.

	Electrical resistivity (Ω cm)	
Filler vol.%	Filaments	Fibers
3	112	—
7	3.78	678
13	0.37	16.9
19	0.12	—

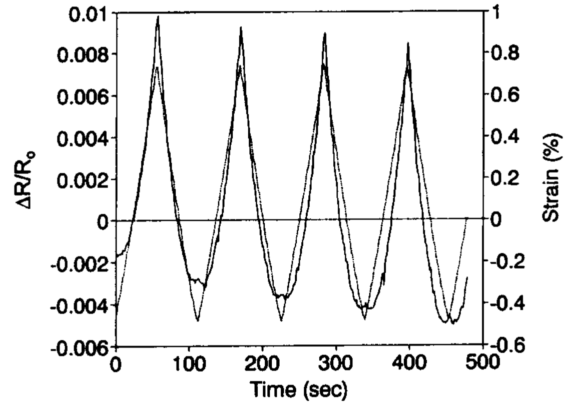

Figure 4. The variation of $\Delta R/R_0$ (solid line) and strain (dashed line) with time during cyclic tensile–compressive loading for a PES-matrix composite containing 7 vol.% carbon filaments.

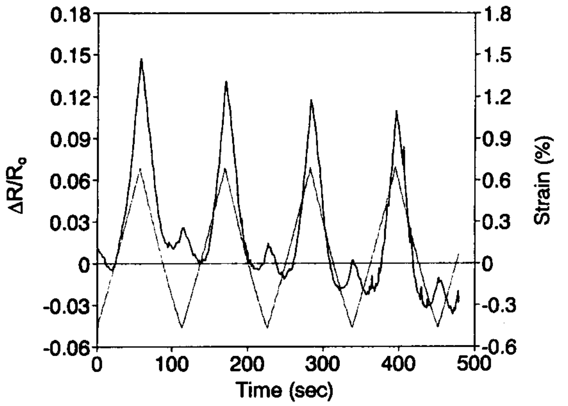

Figure 5. The variation of $\Delta R/R_0$ (solid line) and strain (dashed line) with time during cyclic tensile–compressive loading for a PES-matrix composite containing 13 vol.% carbon fibers.

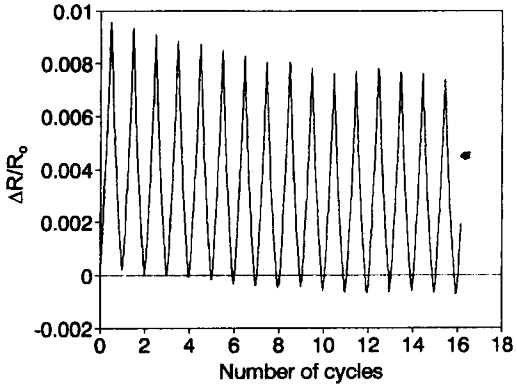

Figure 6. The variation of $\Delta R/R_0$ with cycle number during cyclic tensile loading for a PES-matrix composite containing 7 vol.% carbon filaments (the same as figure 2 except for more cycles). Strain amplitude, 0.7%.

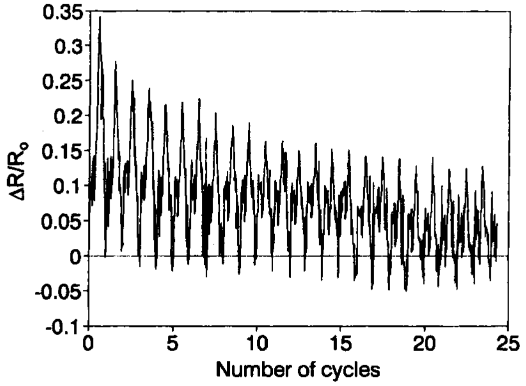

Figure 7. The variation of $\Delta R/R_0$ with cycle number during cyclic tensile loading for a PES-matrix composite containing 13vol.% carbon fibers. Strain amplitude, 0.8%.

this effect, though to a much smaller extent due to the zero compressive strain amplitude. The absence of this effect from figure 4 is due to the bent morphology of the filaments and the resulting absence of filament buckling. That the filament composite does not show the abnormal effect while the fiber composite does, in spite of their similar tensile modulus values (table 2), indicates that this abnormal effect is not due to specimen buckling under compression.

As in figures 2 and 3, figures 4 and 5 exhibit the trend in which $\Delta R/R_0$ becomes more and more negative as cycling progressed. This trend levels off after about 10 cycles for both composites, as shown in figures 6 and 7. It is attributed to the decrease in the matrix film thickness at the junction of the filaments or fibers as the cycling progressed (before reaching 10 cycles). A decrease in this thickness led to a decrease in the contact resistivity between the filaments or fibers and thereby a decrease in the volume resistivity of the composite. Comparison of figures 6 and 7 shows that the extent of decrease was larger for the fiber composite

Table 2. Tensile properties of PES-matrix composites.

Filler	Ultimate strength (MPa)	Youngs' modulus (GPa)	Strain at break (%)
7% carbon filaments[a]	47.6 ± 3.4	3.8 ± 0.1	1.3 ± 0.1
7% carbon fibers[b]	53.8 ± 2.4	4.1 ± 0.3	1.8 ± 0.2
13% carbon fibers[b]	51.3 ± 2.8	3.6 ± 0.2	1.7 ± 0.2

[a] Four specimens tested.

[b] Two specimens tested.

(figure 7) than the filament composite (figure 6) at similar strain amplitudes. This is reasonable since the fibers are more robust than the filaments.

Comparison of figure 2(a) with figure 3, figure 4 with figure 5 and figure 6 with figure 7 shows that, at similar stress amplitudes, the noise in the variation of $\Delta R/R_0$ with strain is smaller for the filament composite than the fiber composite.

Table 2 gives the tensile properties of some of the composites of table 1. Comparison of the composites with carbon filaments and carbon fibers at the same volume fraction (7%) shows that the carbon fibers are a more effective reinforcement than the carbon filaments. However, increasing the carbon fiber volume fraction from 7% to 13% degraded the tensile properties slightly. Nevertheless, the differences in tensile properties for the various composites in table 2 are too small to be of much concern to the use of the composites as sensors.

4. Conclusions

(i) The relationship between $\Delta R/R_0$ and strain during cyclic loading of carbon filament PES-matrix composite was found to be much more linear and less noisy than carbon fiber PES-matrix composite.

(ii) For the fiber composite, the non-linearity manifested itself as $\Delta R/R_0$ increasing reversibly with increasing compressive strain and is probably due to the tendency of the fibers to reversibly change in their degree of straightness upon cyclic loading; this effect is opposite to and occurs on top of piezoresistivity, which is the dominant mechanism for the strain sensing ability. For the filament composite, this side effect is absent, probably because of the inherently bent morphology of the filaments.

(iii) The percolation threshold is lower for filament composites than fiber composites, so the filler volume fraction needed is lower for the former.

(iv) For both filament and fiber composites, $\Delta R/R_0$ became more negative as cycling progressed up to ~10 cycles, though the effect was more significant for the latter. This effect is probably due to the decrease of the matrix film thickness at the filament–filament or fiber–fiber junction as cycling progressed. After ~10 cycles, $\Delta R/R_0$ does not vary from cycle to cycle.

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