Electromechanical Behavior of Hybrid Carbon/Glass Fiber Composites with Tension and Bending

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ABSTRACT: To understand the smart (i.e., good memory) characteristics of hybrid composites of carbon fibers (CFs) and glass fibers (GFs) with epoxy resin as a matrix, the changes in the electrical resistance of composites with tension and on bending were investigated. The electrical resistance behavior of composites under tension changed with the composition of the CF/GF, as well as with the applied strain. The fractional electrical resistance increased slowly with increasing strain within a relatively low strain region. However, with further loading it increased stepwise with the strain according to the fracture of the CF layers. The strain sensitivity of the samples increased with increasing CF weight percentage, and the samples incorporating more than 40 wt % CF showed a strain sensitivity higher than 1.54 for a single CF. The changes in the fractional electrical resistance with bending were not so dominant as those with tension. This difference was attributed to the action of two cancelling effects, which are the increasing and decreasing fractional electrical resistance due to tension and compression with bending, respectively. On recovery from a large applied bending, the fractional electrical resistance decreased slowly with unloading because of the increase of contacts between the fibers that resulted from the reorganization of ruptured CFs during the recovery. Even the composites incorporating a relatively small CF content showed an irreversible electrical resistance with both tension and bending. However, the strain sensitivity being larger with tension than with bending is ascribed to the difference in their mechanical behaviors. © 2002 John Wiley & Sons, Inc. J Appl Polym Sci 83: 2447–2453, 2002

Key words: electromechanical behavior; hybrid composites; carbon fiber; glass fiber; electrical resistance; tension and bending

INTRODUCTION

Carbon fiber (CF) reinforced composites have been widely used in the aerospace, automotive, and other industries because of their high specific modulus and strength. However, because the composite structures are susceptible to repeated loading or straining in service, damage-sensing techniques are required to prevent fatal damage during and after loading. The methods of sensing the strain have included installations of sensors such as piezoelectric or optical fiber inside the composites, an acoustic emission method, and an electrical resistance technique.[1–6] The electrical resistance technique is a useful candidate for assessing the damage in composites because it can monitor the degree of damage in the composite structures in real time during or after various loadings.[7,8]

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Table I Properties of Samples Used in Study

Samples	Tensile Strength (MPa)	Tensile Modulus (GPa)	Compressive Strength (MPa)	Compressive Modulus (GPa)	Interfacial Laminar Shear Strength (MPa)
CF prepreg	1780	140	800	120	100
GF fabric prepreg	303	54	303	—	—

Research on changes of the electrical resistance in CF-reinforced composites was reported recently. Schulte and Baron[9] showed that the variation in the electrical resistivity of CF-reinforced composites during tensile and fatigue loading could be taken as a damage analogue. According to Wang and Chung,[10] the unidirectional CF-reinforced epoxy composite could sense its own strain in the fiber direction because its longitudinal electrical resistance decreases reversibly and its transverse resistance increases reversibly with longitudinal tension. Muto et al.[2] suggested that a CF/glass fiber (GF) hybrid composite was preferred over the electrical resistance technique because it did not experience brittle failure and therefore prevented fatal fractures.

The conducting properties of CFs seem to play an important role in sensing the variation of the electrical conductivity as an indicator of rupture of fibers in CF-reinforced composites. Therefore, the increase in the electrical resistance of a composite on loading is regarded as primarily arising from the increase in the number of ruptured CFs when loaded. However, the influence of other factors such as the fiber properties, fiber type, fiber volume fraction, fiber alignment, and laminate stacking sequence cannot be excluded. Among these, the electrical resistance changes due to fiber contacts and elongation of the fiber itself were throughly investigated. The contribution of fiber elongation to electrical resistance was obtained by investigating a linear relationship between the electrical resistance and strain for a single CF.[11] Wang et al. reported that the degree of neatness of the fiber alignment was related to the irreversible electrical resistance in CF composites under longitudinal cyclic tension.[8] However, the evaluation of fiber contacts is complex because the number of contacts between fibers varies with the alignment of the fiber bundle.[12] We also recently reported on the contribution of the following factors for changes of the electrical resistance with tension: the number of ruptured fibers, the degree of fiber contacts, and the strain of the fiber itself using the mixed bundles of CFs and GFs with no matrix resin.[13] Each contribution to the changes of the electrical resistance was obtained theoretically and experimentally. The influence of the number of ruptured fibers was the strongest whereas the effect of the fiber strain was relatively weak. The contribution of the fiber contacts was not large within the strain range where the fiber rupture began to occur, but it was significant beyond the fiber rupture strain. It could be evaluated by comparing the electrical resistances between the fiber bundles and a single CF. On the other hand, in the fiber-reinforced composite with matrix resin, the effects of the fiber contacts may be regarded as insignificant, at least below the strains where fibers began to rupture, because of the very low conductivity of the matrix resin. However, the situation becomes different when the number of ruptured fibers increases because the ruptured fiber ends may affect the electrical resistance. In particular, different fiber contacts are expected according to the types of loading such as the tensile loading and bending.

In this article the electrical resistance change of hybrid composites composed of CF and GF with epoxy resin as a matrix was investigated as a function of bending and tension.

EXPERIMENTAL

Unidirectional CF prepreg (TZ-307, Taekwang Industrial Co.) and plain-woven GF fabric prepreg (ER2310, Hankuk Fiber Co.) were used in this study; their mechanical properties are shown in Table I. The CF/GF hybrid composite laminates were prepared in an autoclave using CF prepreg and GF fabric prepreg with an epoxy resin as the matrix. There were 7–12 layers composed of CF and GF that were used in preparing each composite in order to preserve a flat surface of the sample during curing.

The electrical resistance change of the composites in the longitudinal CF direction was measured during tension and bending via a two-terminal dc method,[4] using a multidisplay digital multimeter (Metex M-4640A) with personal computer interference. The distance between the electrical contacts was 120 mm and silver paint was used for all electrical contacts. The electrical resistance during tension and bending was recorded in real time on the computer as a function of time, and fractional electrical changes were computed. The fractional electrical resistance ($\Delta R/R_0$) was defined as a fraction of the change in the electrical resistance relative to the electrical resistance of the unloaded sample (i.e., $\Delta R = R - R_0$).

The elongation of the samples was accomplished by applying both static and dynamic tensile loading with an Instron tensile tester.[14] The static loading was done with a constant elongation rate of 0.5–200 mm/min up to the breaking of the sample, but most measurements were performed at a rate of 0.5 mm/min with a gauge length of 50 mm. A 5-mm notch was made at the midpoint of the composite to prevent slippage during elongation. Two sets of experiments were carried out for the dynamic testing. In the first set the samples were loaded at a rate of 0.5 mm/min and then instantaneously unloaded. This was done cyclically with a progressive increase in strain. During loading and recovery the electrical resistance and the deflection were recorded as a function of time. The second set of experiments was performed in the same way as the first set except the loading was at a constant strain for all cycles.

The load–deflection experiments for samples of 5-mm width and 70-mm length were carried out by a three-point bend test using an Instron tensile tester. The samples were supported at two points equidistant from the center and loaded at the center at a constant deflection rate of 1.5 mm/min.

RESULTS AND DISCUSSION

Figure 1 shows a plot of the stress and fractional electrical resistance versus the applied strain for pure CF composite upon the application of a constant elongation up to the point of fracture. The fractional electrical resistance of the sample initially increases very slightly with increasing strain. The decrease of stress and increase of electrical resistance around the strain of 1.6% are both due to the notch in the sample. When further strained close to the breaking point, the fractional electrical resistance increases stepwise near a strain of 4.2%. This effect is ascribed to the fracture of the CF layers. At the same time, an abrupt decrease of stress around a strain of 4.2% is seen. This indicates that the changes in the stress and electrical resistance corresponded closely to each other. The dramatic increase in the fractional electrical resistance at a strain of 4.8% is due to the macroscopic rupture of the sample. Therefore, the fractional electrical resistance of the composite is dependent on the magnitude of the applied strain. Their relation may be described by a strain sensitivity[11] that is defined as the fractional electrical resistance per unit strain. The strain sensitivity in a range of relatively low strains around 1% was 2.50, and in the region ranging from 2.0 to 4.0% it was 6.26.

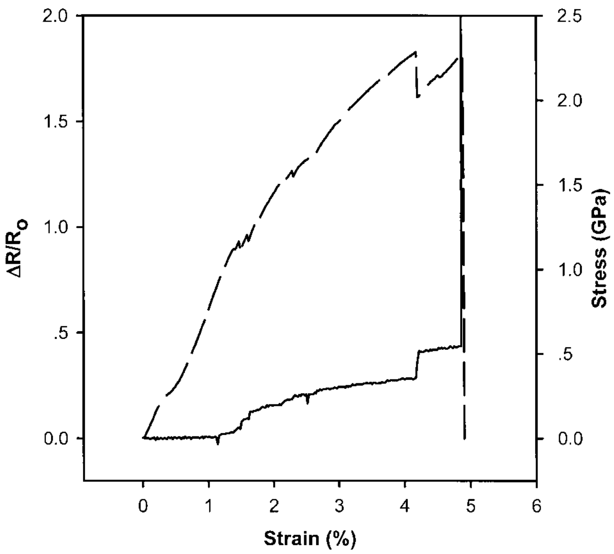

Figure 1 The (—) fractional electrical resistance and (- - -) stress of pure CF composite versus the strain in the tensile loading.

In hybrid composites of CF and GF the electrical resistance change is affected by the composition of the CF/GF, as well as the applied strain. Figure 2 shows the fractional electrical resistance versus the applied strain for three kinds of hybrid composites with different CF/GF compositions. All samples show a slow increase in the fractional electrical resistance in a relatively low strain region, which is similar to the pure CF composite. On further loading a stepwise increase in the electrical resistance is seen that is attributable to the fracture of CF layers. Finally, the electrical resistance increased infinitely with the complete breaking of the GFs. Here it may be noted that

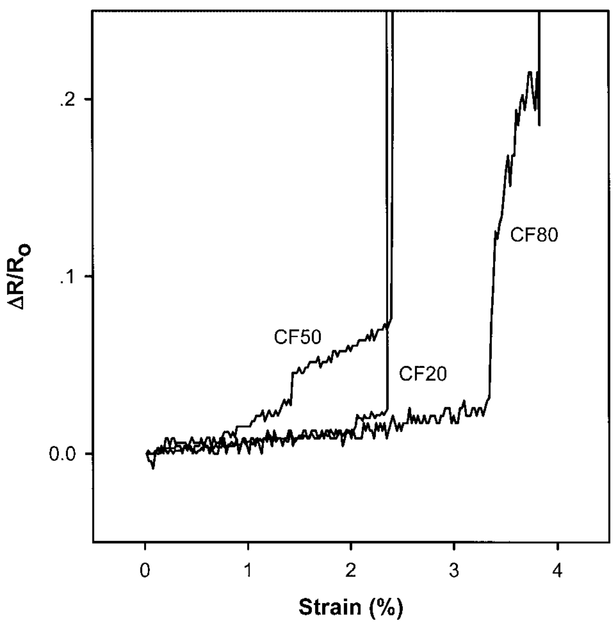

Figure 2 The fractional electrical resistance of various composites versus the strain in the tensile loading.

the presence of GF in the CF composites should give rise to the hybrid effect in the mechanical properties. Similarly, the hybrid effect can be shown from the electrical resistance behavior.

The strain sensitivity of the composites in the low strain region is plotted as a function of the CF weight fraction in Figure 3. The strain sensitivity increased with increasing CF weight fraction. In our previous report the strain sensitivity for CF/GF bundles with no polymeric matrix decreased with increasing CF weight percentage. Such a difference in the strain sensitivity between fiber-reinforced composites and fiber bundles is regarded to result primarily from the degree of contacts between the CFs. The contribution of the contact points in a CF bundle to the electrical resistance change is quite large. However, in composites it is not so large because the composite also includes the epoxy matrix, which has low electrical conductivity. This implies that the fiber contact problem in composites may be less sensitive than that in fiber bundles. Therefore, the fractional electrical resistance ($\Delta R/R_0$) for fiber composites can be obtained by assuming that the electrical resistance change of a single CF is proportional to the linear relation to the strain of CF and there is no electrical resistance change due to the fiber contacts. The following can be written within the small strain range[4,12]:

$$\Delta R/R_0 = (1 + 2\nu)\varepsilon + n_f/(n - n_f) \qquad (1)$$

where ν and ϵ are Poisson's ratio and the applied strain, respectively, and n_f and n denote the number of ruptured CFs and total number of CFs, respectively. The strain sensitivity of pure carbon monofilament can be computed as 1.54 using only the first term of the right side in eq. (1) and $\nu = 0.27$.[15] However, the strain sensitivity of pure CF composite within the strain of 1.5%, where the number of ruptured CFs is not so high, was experimentally determined to be 2.50 as discussed previously. Therefore, the difference between the two values should be ascribed to the effects of fiber rupture and fiber contacts. In spite of this, a difference of 0.96 is too high to attribute to the effect of fiber rupture only. Therefore, it should be considered that the contribution of the contacts of ruptured fibers to the electrical resistance cannot be ignored in a high strain region, even in the fiber composites. As a result, the hybrid composites with a CF content of more than 40 wt % could have a strain sensitivity higher than 1.54.

Figure 4 shows the $\Delta R/R_0$ for various CF composites as a function of time with cyclical tensile loading and unloading under a progressive increase in the applied strain. The fractional electrical resistance of the composites increases upon loading, leaving an irreversible residual electrical resistance upon subsequent unloading at each cycle. As the number of cycle increases, the irreversible electrical resistance increases gradually. This is because a successive rupture of fibers follows each subsequent loading. Such a trend of a fractional resistance change for the hybrid composite

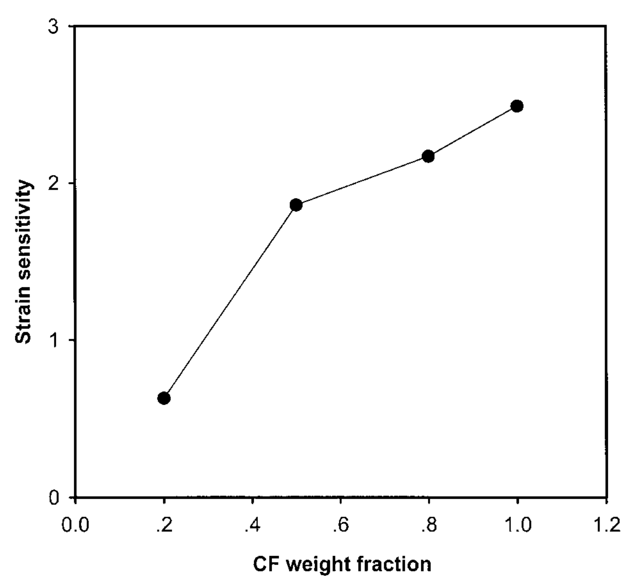

Figure 3 The strain sensitivity versus the CF weight fraction of composites under tension.

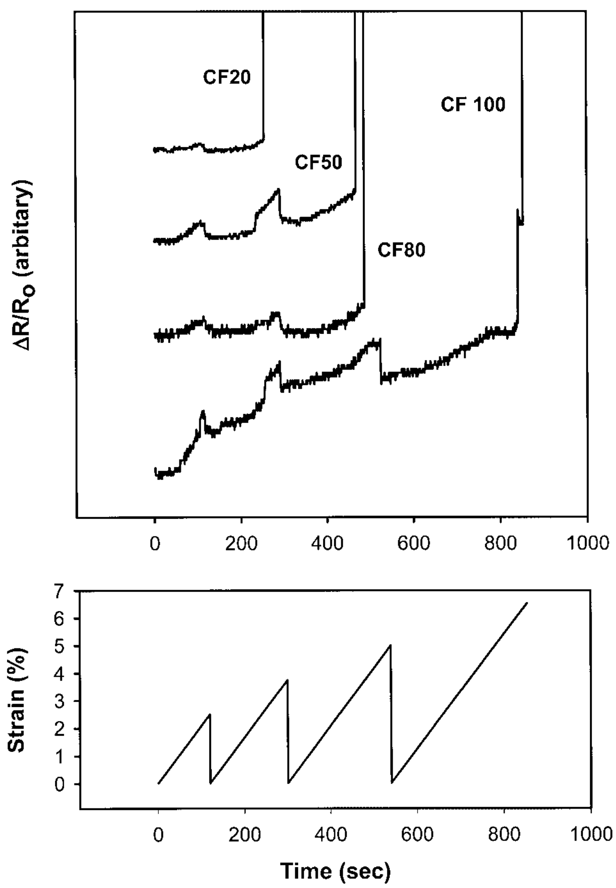

Figure 4 The changes in the fractional electrical resistance of composites versus time during cyclic tensile loading with a progressive increase in the strain.

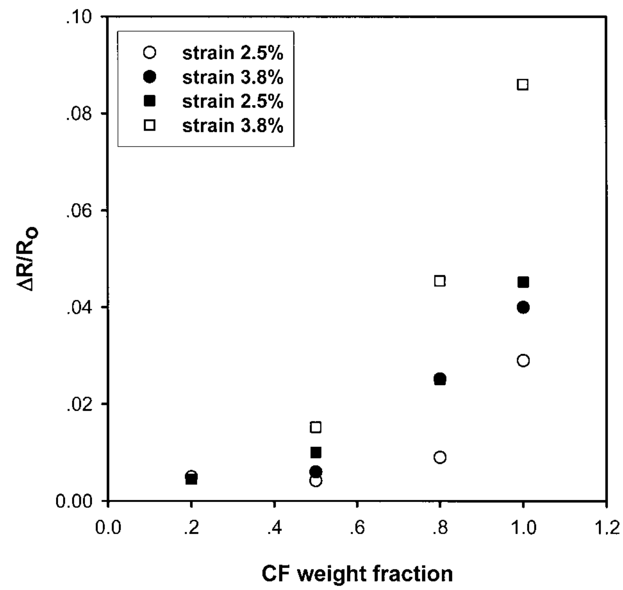

Figure 5 The total and irreversible electrical resistances of composites versus the CF weight fraction during tensile loading.

is similar to that for the pure composite, although their breaking strain decreased with decreasing CF weight percentage. Figure 5 shows the change in the fractional electrical resistance with tension as a function of the CF weight fraction and strain. As the CF fraction increases, the total fractional electrical resistance and the irreversible part both increase after bending recovery. Consequently, the presence of an irreversible electrical resistance plays the role of imparting samples with a good memory effect of the previous loading history.

The electrical resistance changes of composites with bending were obtained and compared with the results with tension. Figure 6 shows the electrical resistance change of the pure CF composite when bending. As the bending deflection of the sample increases, the load increases gradually; on further deflection, the load drops sharply near the rupture of the composite. However, the fractional electrical resistance change on bending is not so dominant compared to the tensile loading. Only a small increase of the electrical resistance is shown with bending. Such a difference in the electrical change should be ascribed to the difference in the deformation mechanism of composites under tension and bending. That is, the electrical resistance at the inner side of a bent sample on bending decreases due to the action of compres-

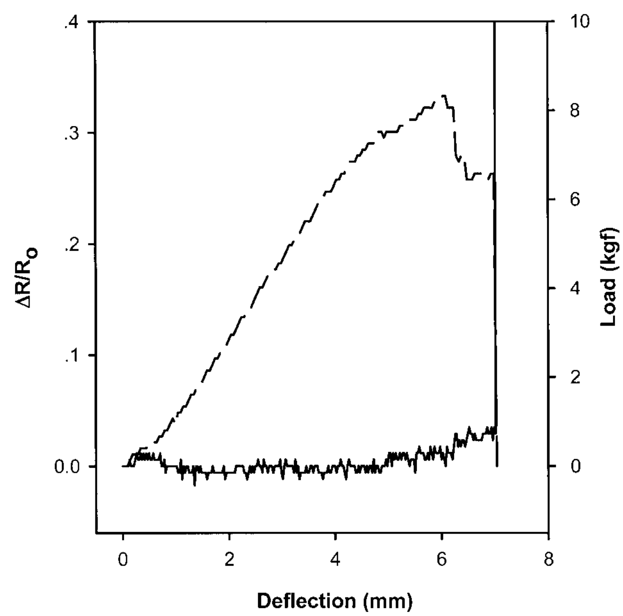

Figure 6 The (—) fractional electrical resistance and (- - -) stress of pure CF composite versus the strain during bending.

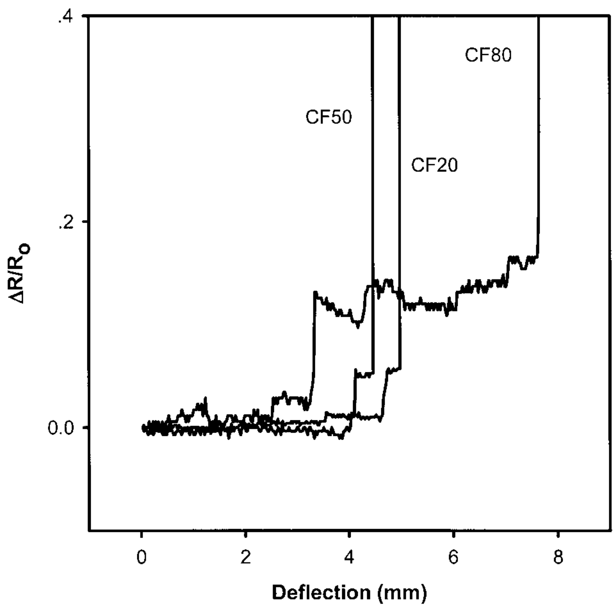

Figure 7 The fractional electrical resistance of various composites versus the deflection during bending.

sion, whereas that at the outer side of the sample increases by the action of tension because the fibers elongate. Therefore, the total electrical resistance with bending does not change so significantly because of the action of the two canceling effects of increasing and decreasing resistance. Figure 7 shows the results of the electrical resistance change for various CF/GF composites. However, the fractional electrical resistance near the final rupture of the composites increases infinitely.

On the other hand, the electrical resistance change under bending may also be dependent on the CF composition, the thickness of the laminate, and the combination method of the CF and GF layers. Figure 8 shows the electrical resistance change of a 50/50 CF/GF composite under repeated bending and recovery. The electrical resistance change with time is related to the applied deflection. In a low deflection region, the change in the fractional electrical resistance is relatively small and the maximum electrical resistance tends to decrease with the number of repeated reflection cycles. However, in a somewhat higher deflection, as shown in Figure 9, the pattern of the electrical resistance change was quite different. Upon recovery from the applied deflection, the fractional electrical resistance decreases very slowly. This may reflect the difference in the deformation mechanism due to tension and bending similar to that discussed in the explanation of Figure 8: the fiber contact change at bending recovery occurs according to the reorganization of the ruptured CFs. Such an effect becomes larger as the deflection increases. In spite of this, there was an irreversible value of the fractional electrical resistance that depended on the applied deflection, as shown in Figure 10. Consequently, it is considered that the hybrid CF/GF composites show smart characteristics when bent and when under tension because of the presence of an irreversible change in the electrical resistance.

CONCLUSION

The change in the electrical resistance of hybrid CF/GF fiber composites when under tension and bending was investigated and the following conclusions were obtained.

The fractional electrical resistance of composites under tension was affected by the composition of the CF/GF, as well as the applied strain. The slow increase in the fractional electrical resistance was shown in a relatively low strain region; on further loading, a stepwise increase in the resistance was shown, which was due to the fracture of CF layers. The strain sensitivity of the

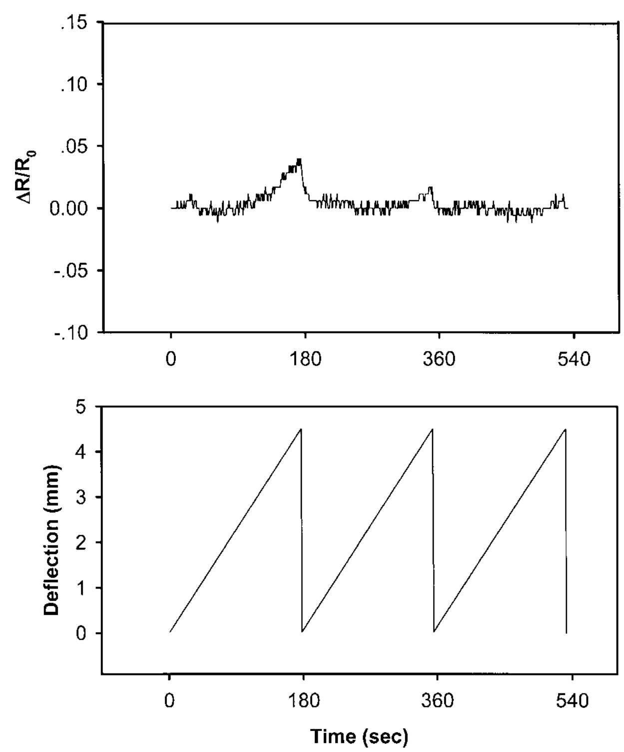

Figure 8 The changes in the fractional electrical resistance of a 50/50 CF/GF composite versus the time during cyclic bending and recovery (4.5-mm deflection).

samples increased with increasing CF weight percentage. The hybrid composites with a CF content of more than 40 wt % had a strain sensitivity higher than 1.54.

The changes of the fractional electrical resistance under bending were not so dominant compared to the results under tension. This was attributed to the action of the two cancelling effects of increasing and decreasing resistance that are due to tension and compression, respectively. During recovery from an applied deflection, the electrical resistance decreased slowly, and it was regarded as resulting from the increase in the fiber contacts that were due to the reorganization of ruptured CFs during the recovery.

Consequently, the composites incorporating CF might be applicable as a smart composite according to the existence of irreversible electrical resistance after tension and bending. However, the strain sensitivity under tension was larger than that under bending, which was ascribed to the difference in their mechanical behaviors.

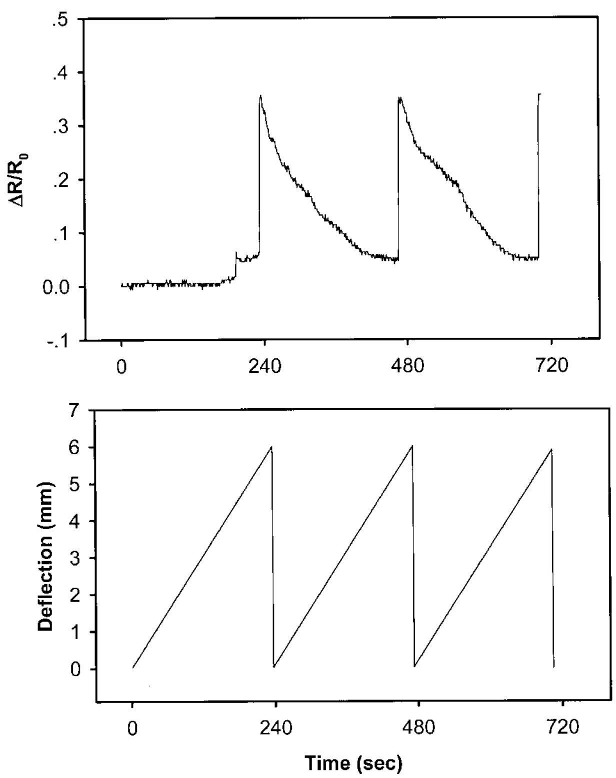

Figure 9 The changes in the fractional electrical resistance of a 50/50 CF/GF composite versus the time during cyclic bending and recovery (6-mm deflection).

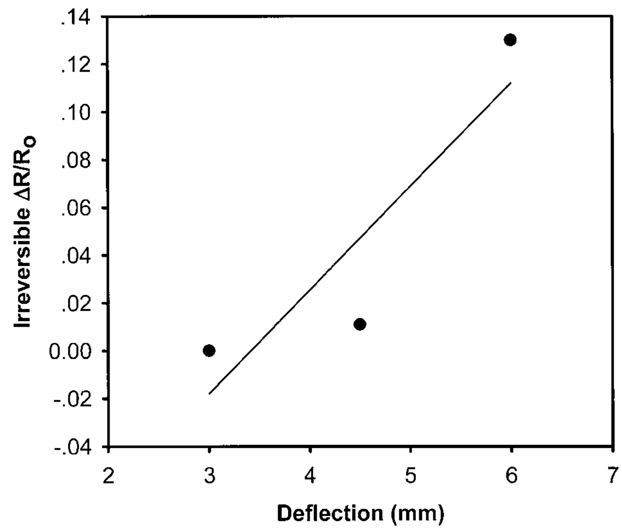

Figure 10 The irreversible electrical resistance of a 50/50 CF/GF composite versus the deflection during bending.

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