Relationship between Electrical Resistance and Strain of Carbon Fibers upon Loading

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ABSTRACT: The changes in electrical resistance of carbon fibers during a tensile elongation were investigated to understand the electromechanical mechanism in carbon fibers. The fractional electrical resistance of carbon fibers initially increased slightly with increasing elongation, however, increased abruptly beyond a certain strain where the rupture of fibers began to increase. Contribution to this change in electrical resistance was analyzed in terms of dimensional change of fibers, number of ruptured fibers, and degree of fiber contacts. The effect of the number of ruptured fibers was the most dominant, whereas the effect of the dimensional change of carbon fibers due to elongation was relatively small. The degree of contacts between fibers affected the change in electrical resistance dominantly at the large elongation. The residual electrical resistance appeared upon removal of the applied strain and increased with increasing elongation, regardless of the static and dynamic loading. Consequently, the smart characteristics of carbon fibers due to the existence of the residual electrical resistance are primarily ascribed to the number of ruptured fibers and contacts between fibers. © 2000 John Wiley & Sons, Inc. J Appl Polym Sci 77: 2082–2087, 2000

Key words: carbon fiber; electrical resistance; elongation

INTRODUCTION

Advances in carbon fiber-reinforced technology have led to widespread use of composites in aerospace, automotive, and other industries owing to their high specific modulus and strength. However, because the composite structures are susceptible to repeated loading or straining in service, the damage-sensing techniques are required to prevent the fatal damage in composite structures during and after loading. As a method of sensing the strain, there have been 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 simple and durable because of using the structure material as itself a sensor, whereas installation of sensors inside the materials tends to degrade the mechanical properties of the composite, and an acoustic emission method is very expensive. Therefore, the electrical resistance technique is a useful candidate for assessing the damage in composites and monitoring a degree of composite structures damage in real time during or after various loading. On the other hand, it is also applicable to the quality control in the composite fabrication process by monitoring the residual stress and temperature of carbon fiber epoxy–matrix composites.[7]

Studies regarding changes of electrical resistance in carbon fiber-reinforced composites have been recently reported. Schulte et al.[8] showed that the variation of the electrical resistivity of carbon fiber-reinforced composites during tensile and fatigue loading could be taken as a damage analogue. According to Wang et al.,[9] the unidirec-

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tional carbon fiber-reinforced epoxy composite could sense its own strain in the fiber direction, due to its longitudinal electrical resistance decrease and transverse resistance increase upon longitudinal tension. Muto et al.[4] suggested that the carbon fiber/glass fiber hybrid composite was more effective in the application of the electrical resistance technique because it did not experience brittle failure, and therefore, prevented fatal fractures. We have also reported the changes in electrical resistance of conducting aramid fibers via the vapor-phase polymerization of pyrrole.[10]

The conducting property of carbon fibers seems to play an important role in sensing the variation of the electrical conductivity as an indicator of the rupture of fibers in carbon fiber-reinforced composites. Therefore, the increase of electrical resistance in a composite upon loading is regarded to arise primarily from the reduction in the number of carbon fibers. Despite this, the influences of other factors such as fiber property, fiber type, fiber volume fraction, fiber alignment, and laminate stacking sequences are also included. The degree of fiber alignment neatness has been suggested to be related to the irreversible electrical resistance in carbon fiber composites upon longitudinal cyclic tension.[9] It was reported that the relation between the electrical resistance and strain for a single carbon fiber was reasonably straight, owing to dimensional change rather than resistivity change, although a small percentage of the fibers behaved in an anomalous manner.[11] However, more precise information for the contribution of factors affecting the variation of electrical resistance in carbon fibers is not currently available for assemblies of carbon fibers other than carbon fiber-reinforced composites.

In this article, the electromechanical behavior of carbon fiber bundles alone, not in fiber-reinforced composite form, is investigated by focusing the contribution of factors associated with the change in electrical resistance. The reversibility of fractional electrical resistance is also analyzed by applying the static and dynamic loading and unloading.

EXPERIMENTAL

The fibers used were polyacrylonitrile-based and unsized carbon fibers (Besfight G30-500, Toho Co.) of 3,000 filaments, diameter 7 μm, density 1.76 g/cm^3, and electrical resistivity $1.5 \times 10^{-3}\ \Omega \cdot$ cm. The tensile strength of carbon fibers was 2.1 GPa, tensile modulus 140 GPa, and ultimate elongation 2.5%, as measured by tensile test at an elongation rate of 5 mm/min, with a gauge length of 50 mm. The change in electrical resistance of carbon fibers was measured during loading along the fiber axis via a two-terminal DC method,[4] using a multidisplay digital multimeter (Metex M-4640A) with a personal computer interference. The distance between electrical contacts was 120 mm, and silver paint was used for all electrical contacts. The variation of electrical resistance during loading was continuously monitored in real time on the computer as a function of time. The fractional electrical resistance ($\Delta R/R_o$) was defined as a fraction of the change in electrical resistance (ΔR) to the electrical rsistance of unloaded sample (R_o).

The elongation of samples was accomplished with an Instron tensile tester by applying both static and dynamic tensile loading.[10] The static loading was made with a constant elongation rate ranging from 0.5 mm/min to 200 mm/min up to the breaking of sample, but most measurements were performed at the rate of 0.5 mm/min and with a gauge length of 50 mm. For the dynamic testing, two sets of experiments were carried out. In the first set, the samples were loaded at a rate of 0.5 mm/min, and then instantaneously unloaded, which was done cyclically with a progressive increase in strain. During loading and its recovery, the variation of electrical resistance was also recorded as a function of time. The second set of experiments was performed in the same way as the first set, except the loading up to the constant strain for all cycles.

The number of fibers ruptured during the loading cycles was measured visually by counting after the sample was elongated up to a fixed strain. A comb sorter was used for separating the ruptured fibers from the fiber bundles. For each measurement, 10 samples were employed, and their average value was used to calculate the fractional electrical resistance of carbon fibers.

RESULTS AND DISCUSSION

Figure 1 shows a plot of the fractional electrical resistance vs. the applied strain of carbon fibers when the sample is elongated to fracture. The percent strain at break of the carbon fiber bundles used does not usually exceed a maximum of 2.5%. The fractional electrical resistance of the sample initially increases very slightly with increasing strain, but it starts to increase faster at more than 1.5% strain. Upon further elongation up to

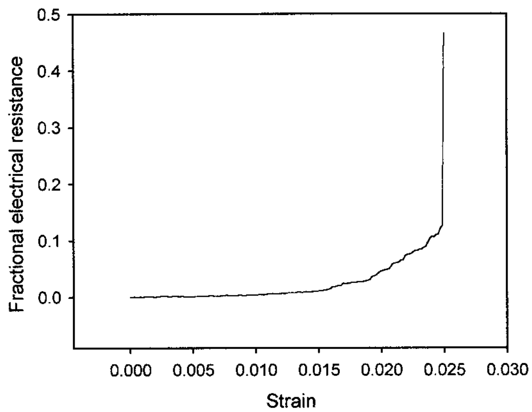

Figure 1 Fractional electrical resistance of carbon fibers vs. strain during tensile loading.

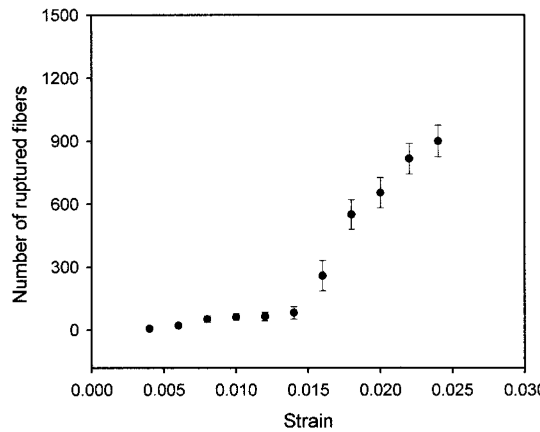

Figure 2 Number of ruptured fibers vs. strain during tensile loading.

near the breaking point, the fractional electrical resistance increases dramatically. This indicates that the fractional electrical resistance of carbon fibers is dependent on the magnitude of applied strain. The strain sensitivity,[11] which is defined as the fractional electrical resistance per unit strain, is 1.43 at low strain, whereas it is 14.70 at high strain (1.5–2.0%), which indicates it is very high near the rupture of the sample.

To analyze the origin of electrical resistance variation in the carbon fibers,[12–14] the change of electrical resistance upon loading was theoretically considered. By assuming no change in electrical properties of carbon fiber, an equal electrical resistance of each carbon monofilament, no interaction between fibers and no molecular reorientation effect on straining, the change in electrical resistance can be expressed in terms of the contributions from the dimensional change of carbon fibers and number of the fracture of carbon fibers,[4] respectively. Therefore, it is possible that the calculated fractional resistance, $\Delta R_c/R_o$, can be written as a following equation

$$\Delta R_c /R_o = n_f /(n - n_f) + (1 + 2\nu)\epsilon \qquad (1)$$

where n is the total number of carbon fibers ($n = 3{,}000$), n_f is the number of fractured fibers, ν is Poisson's ratio of carbon fiber, and ϵ is the applied strain. The measured values of n_f are shown in Figure 2. As the strain increases, the number of fractured fibers increases slowly at low strain, but increases abruptly beyond a strain of about 1.5%, which seems to be associated with the large increase of the electrical resistance in Figure 1. Therefore, it is considered that the fractional electrical resistance is strongly affected by the number of ruptured fibers. By substituting the data in Figure 2 into eq. (1), and using $\nu = 0.27$,[15] we can calculate the value of $\Delta R_c/R_o$ as a function of the applied strain. Thus, contributions from the dimensional change and the number of ruptured fibers to the $\Delta R_c/R_o$ can be evaluated, respectively, which is shown in Figure 3. The contribution from the dimensional change of the sample is proportional to the applied strain over the strain ranges, although its effect is not as strong. The strain sensitivity due to the dimensional change only can be calculated as 1.54, and it is very close to the experimental value of 1.43 at the low strain. The contribution from the number of rup-

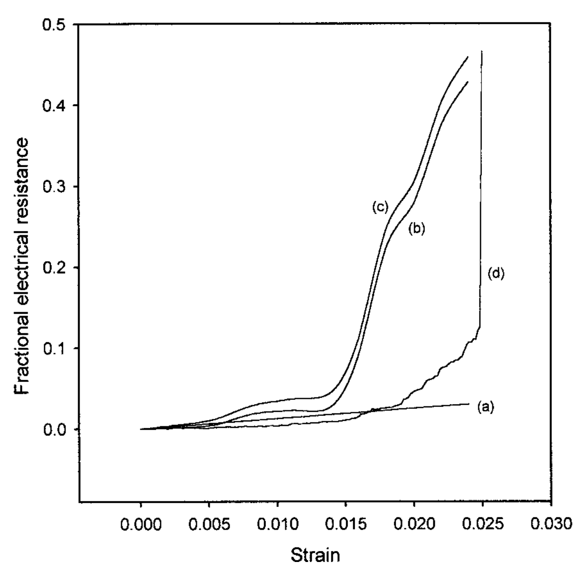

Figure 3 Fractional electrical resistances of carbon fibers vs. strain obtained theoretically and experimentally: (a) dimensional change, (b) fiber rupture, (c) calculated, (d) experimental.

tured fibers is about two times higher than that from dimensional change at the low strain range, and is especially dominant beyond a strain of about 1.5% where the fiber rupture begins to increase abruptly. Therefore, beyond a strain of 1.5%, that of dimensional change is negligible compared with the effect of the fiber rupture. These are in good agreement with other researcher's results for a single carbon fiber and a short carbon fiber epoxy–matrix composite.[9,11]

On the other hand, the experimental value of fractional electrical resistance is lower than the calculated value, as shown in Figure 3, and this trend is more evident beyond a strain of about 1.5%. Figure 3(c) and (d) represent the fractional electrical resistances obtained by calculation and experiment, respectively, and Figure 3(a) and (b) show the calculated values contributed from dimensional change and fiber rupture, respectively. In the theoretical derivation, no interaction between fibers was considered because the fibers were assumed to be independent of each other. However, in the real experiments, the fibers have many contacts because they are in a form of bundles, and the position and number of contact points vary with the elongation of fiber bundles. As the load is applied, the wavy fibers becomes tensioned and straight, and this leads to the decrease in contacts between adjacent fibers. Thus, the electrical resistance along the fiber axis decreases, whereas that perpendicular to the fiber axis increases. Such a phenomenon was reported for the carbon fiber-reinforced composites.[12] In our experiment, such a negative change in fractional resistance along the fiber axis with strain did not appear, which is ascribed to the relatively straight alignment of fibers. However, upon loading at large strains where the fiber rupture occurs, the number of fiber contact points increases dominantly, because the number of fiber contact points increases largely due to the absence of tension in the ruptured fibers. This results in lowering the fractional resistance in the fiber axis direction compared with the calculated case. That is, the experimental fractional resistance is lower than the calculated one. Therefore, we can persist that the difference between the experimental and calculated resistances of fiber bundles at the large strain is ascribed to the result of variation in contact points due to the increase of ruptured fibers. Consequently, the changes in electrical resistance of carbon fibers result from the number of ruptured fiber bundles, the dimensional change, and the contacts between fibers. Particularly, the contributions from the degree of contacts as well as the number of ruptured fibers are important to the change in electrical resistance as the number of ruptured fibers increases.

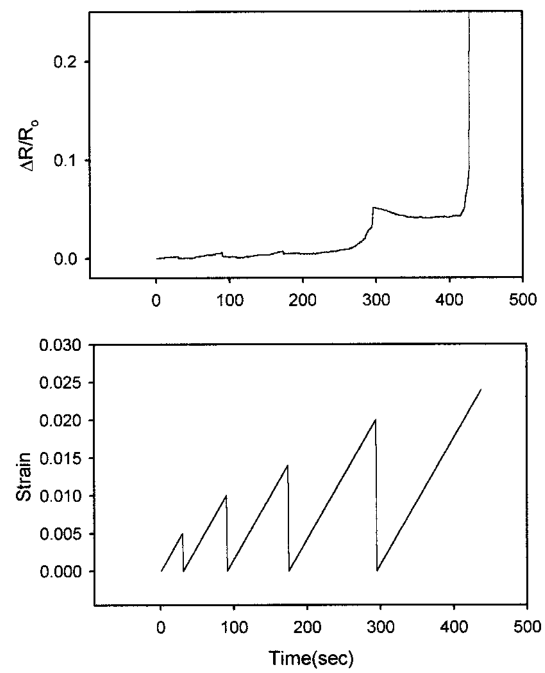

Figure 4 Changes in the fractional electrical resistance vs. time during the cyclic tensile loading with a progressive increase in strain for carbon fibers.

Figure 4 shows the $\Delta R/R_o$ as a function of time for carbon fibers on loading and unloading cyclically under a progressive increase in strain. The fractional electrical resistance increases upon loading, and recovers upon subsequent unloading at every cycle, depending on the magnitude of strain. At low cycles, the fractional resistance changes nearly reversibly, but as the number of cycle increases, the irreversible part increases gradually. Owing to the existence of the irreversible electrical resistance, the residual fractional resistance is left after the unloading of each cycle, and it strongly depends on the magnitude of applied strain. Therefore, the larger the the repeating number of the progressive loading cycle, the larger the residual resistance. Such a result can be observed in Figure 5, which is replotted from Figure 4 as a function of strain. The residual electrical resistance increases with increasing elongation, and it may be useful for assessing the degree of damage in the carbon fibers. It implies that the residual electrical resistance is affected by the magnitude of the strain previously applied, and in particular, by the applied strain rather than the loading. It is more evident by the change in electrical resistance in the stress relaxation

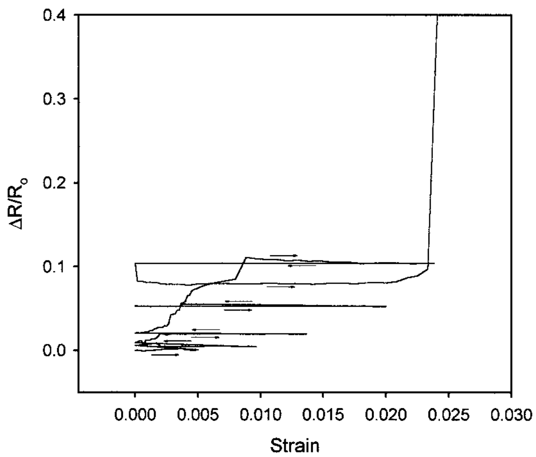

Figure 5 Changes in the fractional electrical resistance of carbon fibers vs. strain.

experiment, as shown in Figure 6. Under a constraint of constant strain, the stress continues to decrease monotonously, but the fractional resistance retains a constant value with time. Generally, the fibers show the stress relaxation because of their viscoelastic properties.[16] In our experiments, a single carbon fiber also showed a similar stress relaxation response as the carbon fiber bundles. This implies that the stress relaxation behavior of carbon fiber bundles arises from the viscoelastic nature of the carbon fiber itself, although the carbon fiber exhibits a good linearity in tensile stress–strain relationship. Despite this, the resistance change of the carbon fiber under constant elongation does not vary with time. This means that the resistance change is dependent on the strain, not on the stress.

Figure 7 shows the changes in fractional electrical resistance during the cyclic repetition of loading and unloading for various strains as a function of time. In the case of loading at a low strain such as 0.5 and 1.0%, the fractional electrical resistance changes similarly as in a strain, although there appears an overall level-off of a peak fractional resistance with time due to fiber realignment. However, in the case of the strain of 2.0% where the rupture of the fibers increases significantly, the large residual resistance remains even after the first loading cycle, and afterward nearly the same residual resistance appears. This is ascribed to the fact that the rupture of most fibers occurs at the first cycle, and after the second cycle the behavior is determined by the dimensional change and fiber contacts. At the strain of 2.4%, which is around the breaking strain, the magnitude of residual fractional resistance is quite large, and it increases gradually with increasing the number of the loading cycle. This reflects that the successive rupture of fibers occurs continuously with the number of cycles during the excessive loading such as strain of 2.4%. However, it is interesting that on the recovery of the applied strain of 2.4%, the electrical resistance does not decrease quickly but shows some relaxation, as shown in the mechanical relaxation of viscoelastic fibers or polymers. Such a phenomenon is ascribed to the redistribution of contacts for many ruptured fibers, which are subjected to the abrupt unloading. Therefore, the number of ruptured fibers and their contacts play an important role in determining the final residual electrical resistance.

CONCLUSION

The relation between the resistance change and strain for carbon fibers was investigated, and the following conclusions were obtained.

The fractional electrical resistance of carbon fibers was dependent on the magnitude of elongation, and showed a sharp increase near the breaking point of the sample. The electromechanical effect was interpreted in terms of the number of

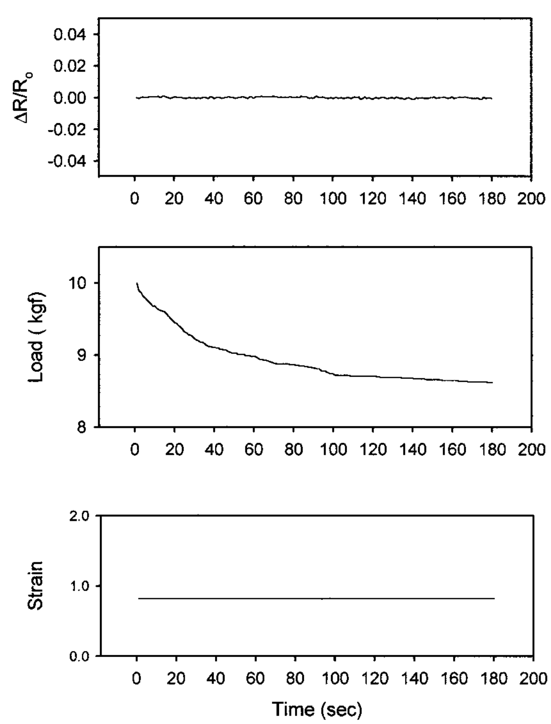

Figure 6 Changes in the fractional electrical resistance and load under a constraint of constant strain.

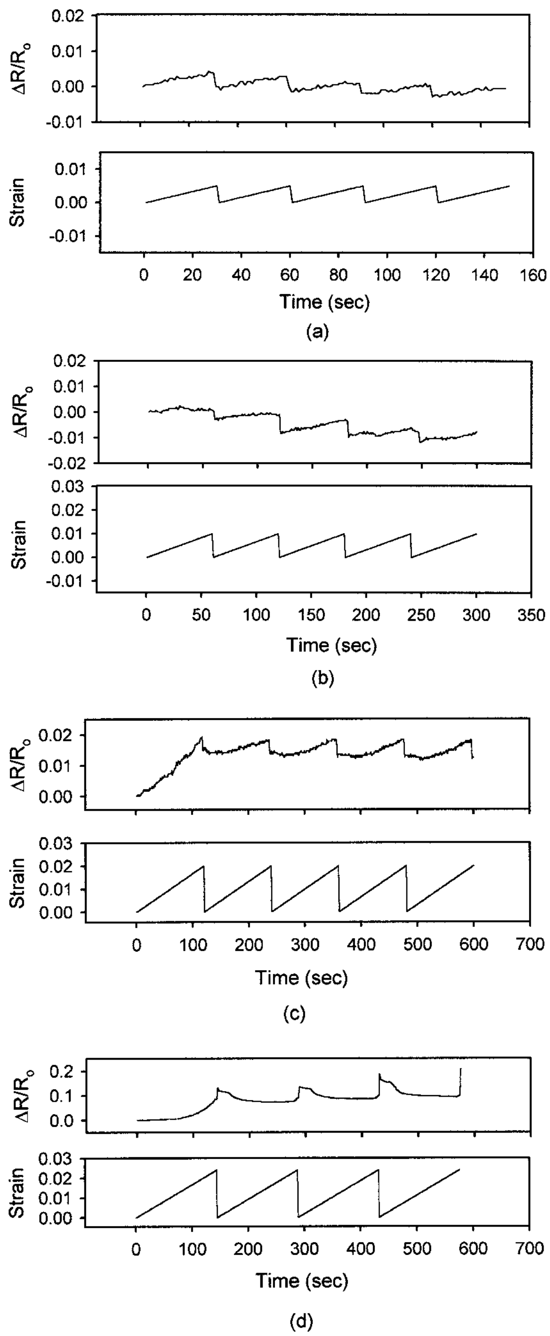

Figure 7 Changes in the fractional electrical resistance of carbon fibers vs. time during cyclic loading and unloading: (a) 0.5% strain, (b) 1.0% strain, (c) 2.0% strain, (d) 2.4% strain.

ruptured fibers, dimensional change, and the fiber contacts. It was found that the quantitative evaluation of fiber contacts effect was possible by using the theoretical and experimental results, and its effect was very strong in the case of a large elongation. The contribution of dimensional change to resistance change was small compared with the number of ruptured fibers and the degree of fiber contacts, and could be neglected in a high elongation region.

The residual electrical resistance appeared upon the removal of the applied strain, and was dependent on the magnitude of strain. On the dynamic loading, the residual electrical resistance increased with increasing elongation, and did not nearly change owing to the number of cycles in the case of low elongation. However, in the case of high elongation, it increased with increasing elongation. The existence of residual electrical resistance for static and dynamic loading could lead to the assessment for damage in the carbon fibers through its monitoring.

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