Correlation of Change in Electrical Resistance with Strain of Carbon Fiber-Reinforced Plastic in Tension

MEI XUAN XU,[1,*] WEN GUANG LIU,[1] ZHEN XIANG GAO,[1] LU PENG FANG,[2] and KANG DE YAO[3]

[1]Department of Applied Chemistry, [2]Department of Materials, Mechanics, and Measurement, and [3]Department of Materials Science and Engineering, Tianjin University, Tianjin 300072, P. R. China

SYNOPSIS

A study was carried out on the variation in the electrical resistance of carbon fiber-reinforced unsaturated polyester/polyurethane (UP/PU) IPN composites during static tension, cyclical loading, and unloading in tension. The resistance was found to vary nonlinearly with strain and increase abruptly when the composite approached the fracture. Under a certain constant tension, the change in electrical resistance showed time dependence, and it is suggested that the creep of the IPN network imposed an impact on the variation of resistance. The resistance probing revealed that carbon fiber-reinforced plastic can function as a sensor that is capable of self-diagnosing the fatal fracture in composites. © 1996 John Wiley & Sons, Inc.

INTRODUCTION

The nondestructive evaluation (NDE) of carbon fiber-reinforced composites has become more important and demanding as composites are increasingly used in safety-critical fields such as the aircraft industry and in nuclear power plants. Conventional NDE applied in composites by ultrasonic testing,[1] eddy current testing,[2] and transient thermography[3] can detect surface-breaking flaws or microdefect. However, these methods fail to monitor the fatal damage of composites, especially the fractures of the aircraft *in situ*. Recently, Yanagida[4] investigated the change in electrical resistance of carbon fiberglass fiber-reinforced plastic (CFGFRP) composites by selecting the type of the carbon fibers during loading and unloading. It is anticipated that the CFGFRP promised to be a smart material that can foresee the fracture by self-diagnosis.

In the present work, Yanagida's work was extended by examining the alteration in electrical resistance of carbon fiber-reinforced unsaturated polyester/polyurethane interpenetrating polymer network (UP/PU IPN) under static tension and cyclical loading and unloading in tension. An attempt was made to describe the correlation of the strain and the number of the broken carbon fibers with the change in electrical resistance. Furthermore, time-dependence of electrical resistance during step-by-step loading was preliminarily investigated.

EXPERIMENTAL

Materials

The carbon fibers (PAN-based carbon fibers) were obtained from Ji Lin Chemical Engineering Co. Each bundle of fibers comprise 6000 filaments. Unsaturated polyester/polyurethane IPN prepared in our lab was used as matrix. Its preparation is omitted here, but the detailed synthesis method was described in our previous communication.[5]

Preparation of Tested Samples

The samples for tensile testing were in the form of rods (with a sectional area of 82 mm^2 and a testing length of 150 mm) by embedding the carbon fibers unidirectionally in the UP/PU IPN matrices in a glass tube model.

Change in Electrical Resistance Versus Strain

A conductive adhesive was used to bind copper leads with carbon fiber ends that were buried in the sam-

---

[*] To whom correspondence should be addressed.

Journal of Applied Polymer Science, Vol. 60, 1595–1599 (1996)

CCC 0021-8995/96/101595-05

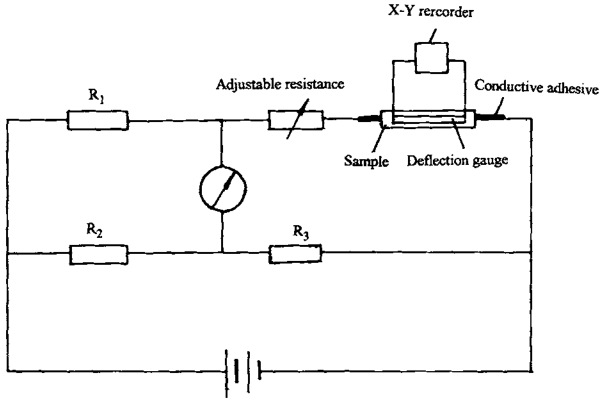

Figure 1 Schematic illustration of the circuit used to monitor the loading, deflection, and change in electrical resistance of the sample.

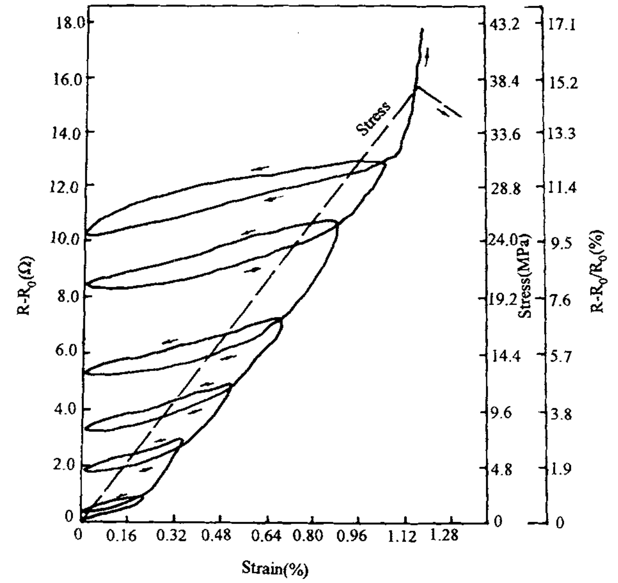

Figure 3 Variations in electrical resistance and stress during loading and unloading as a function of strain for the composite containing three bundles of carbon fibers.

ples to avoid breaking the fibers. Specimens were loaded or unloaded in tension at a rate of 1.0 mm/min on a Shimadzu Tester. To detect the deflection, a deflection gauge was attached onto the specimens. Electrical resistance was measured via a Wheatstone Bridge, schematically shown in Figure 1. An X-Y recorder kept record of loading and deflections of the samples.

RESULTS AND DISCUSSION

Variation of Electrical Resistance Under Tension

The changes in electrical resistance of samples containing one, three, and six bundles of carbon fibers during and after loading are displayed in Figures 2, 3, and 4, respectively. It can be seen that the resistance increases approximately linearly and diminishes after the tension is removed at the low-strain region. The change in electrical resistance returns above the initial line, forming a hysterisis loop, as indicated by arrows. For each cycle, a residual resistance remains. With the further increase of strain, the resistance varies unlinearly. It is found that the resistance goes up abruptly near the fracture point. In the figures, the linear variation of stress in proportion to the strain is demonstrated until the damage of the samples occurs.

For the sample containing one bundle of carbon fibers under one cycle of tension up to the time of

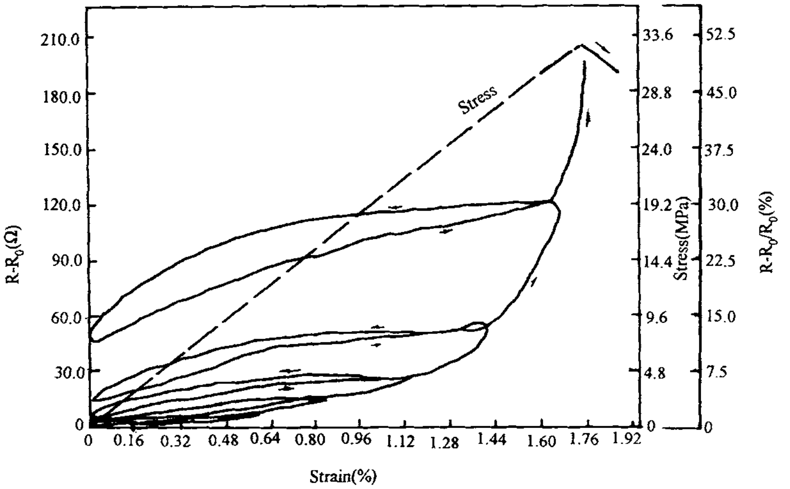

Figure 2 Variations in electrical resistance and stress during loading and unloading as a function of strain for the composite containing one bundle of carbon fibers.

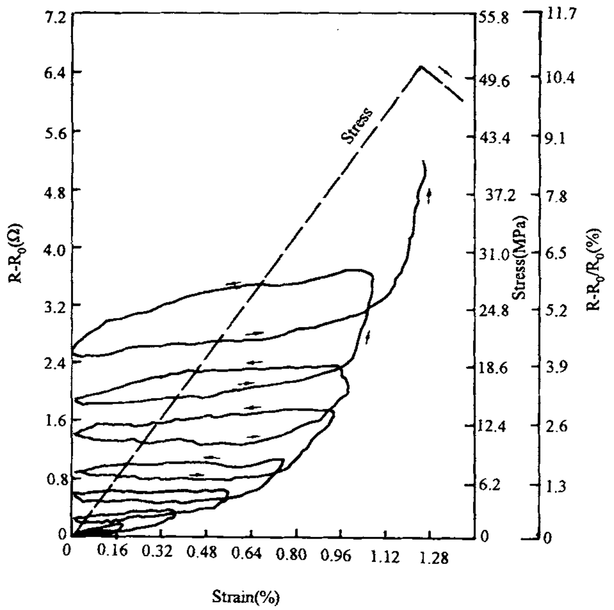

Figure 4 Variations in electrical resistance and stress during loading and unloading as a function of strain for the composite containing six bundles of carbon fibers.

fracture (termed static tension), the tremendous variation in electrical resistance indicates clearly the damage of the sample (Fig. 5).

The electrical resistance of carbon fiber changes when the fiber is strained (this is common with conductive materials).[6] Assuming that the resistance R_f of each single carbon fiber in the sample is equal, and each fiber is arranged in parallel, the total initial resistance R_0 between the two ends is[7]

$$R_0 = R_f/n \tag{1}$$

where n is the total number of carbon fibers. Because

$$R_f = \rho L_0/A \tag{2}$$

in eq. (2), ρ, L_0, and A refer to specific electrical resistivity, the initial length, and the sectional area of a single carbon fiber, respectively. Substituting eq. (2) into eq. (1) leads to

$$R_0 = \rho L_0/An. \tag{3}$$

After the fibers are loaded, the length becomes L; in the same direction, ρ is regarded as constant; and for the brittle material like carbon fiber, A remains unchanged. Thus, when the fibers are subjected to loading, the resistance can be given by the following equation:

$$R = \rho L/A(n - n_f) \tag{4}$$

where n_f is the number of broken fibers. From eqs. (3) and (4), one can deduce the variation in resistance ΔR of carbon fibers:

$$\begin{aligned} \Delta R &= R - R_0 \\ &= \rho(L - L_0)/A(n - n_f) + \rho L_0 n_f/A(n - n_f)n \end{aligned} \tag{5}$$

When eq. (5) is divided by eq. (3), the relative change in resistance, $\Delta R/R_0$ can be obtained.

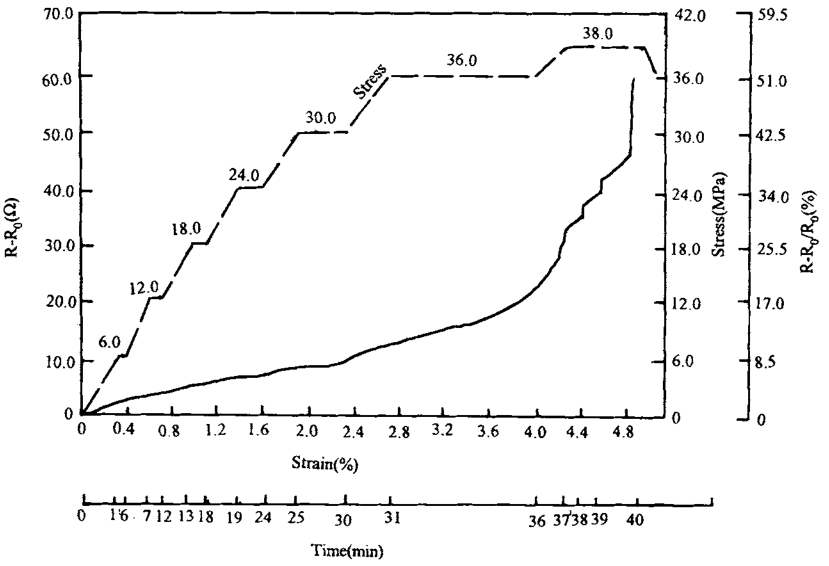

Figure 5 Changes in electrical resistance and stress under static loading as a function of strain for the composite containing one bundle of carbon fibers.

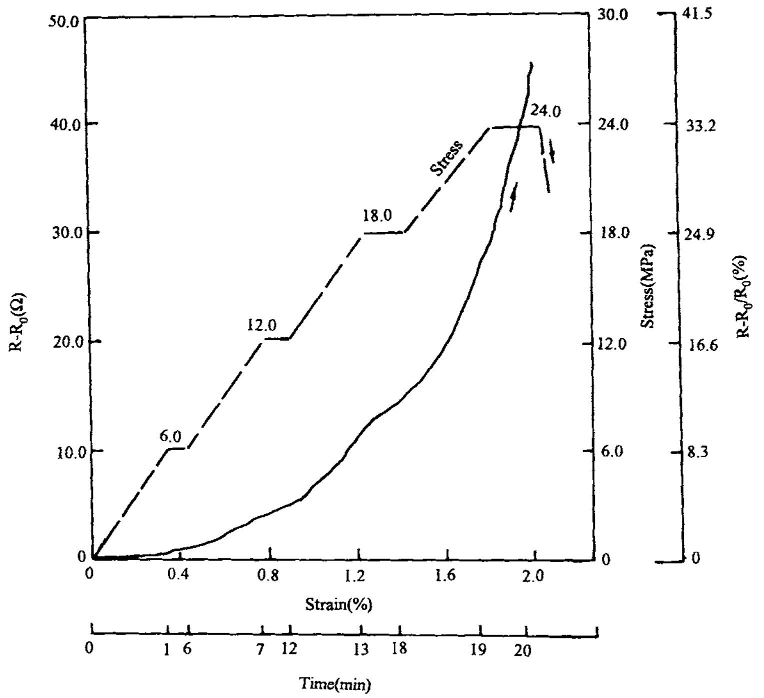

Figure 6 Time-dependence of resistance under constant tension for the composite made from a bundle of carbon fibers and UP/PU(95/5) IPN.

$$\Delta R/R_0 = n\varepsilon/(n - n_f) + n_f/(n - n_f) \qquad (6)$$

in which ε is strain. In the condition that other disturbance factors are neglected, it is apparent that the change in resistance results from the variation of ε and n_f. At low stress, no fibers fracture ($n_f = 0$), the electrical resistance varies linearly with strain. In this case, the change in resistance is less obvious due to the low strain of the carbon fibers. When the tension is raised, the fracture of fibers occurs. In eq. (6), two variables exist, i.e., ε and n_f. This causes $\Delta R/R_0$ to change unlinearly with ε. The tremendous alteration in resistance is attributed mainly to the number of the broken fibers. Moreover, the greater n_f is, the larger $\Delta R/R_0$ becomes. Equations (5) and (6) also clearly indicate that after the stress is removed, although the strain can return to its initial value, the broken fibers cannot be recovered. This is the main reason for the formation of residual resistance. It may be reasonable to think that after the tension is removed, the partial recontacting of fibers makes n_f lower than its past value, which may lead to the decrease of the electrical resistance after loading. Equation (5) shows that with the augment of the number of carbon fibers, ΔR diminishes, as can be reflected by comparing Figure 2 with Figures 3 and 4. All these results coincide well with the work done by Yanagida.[8]

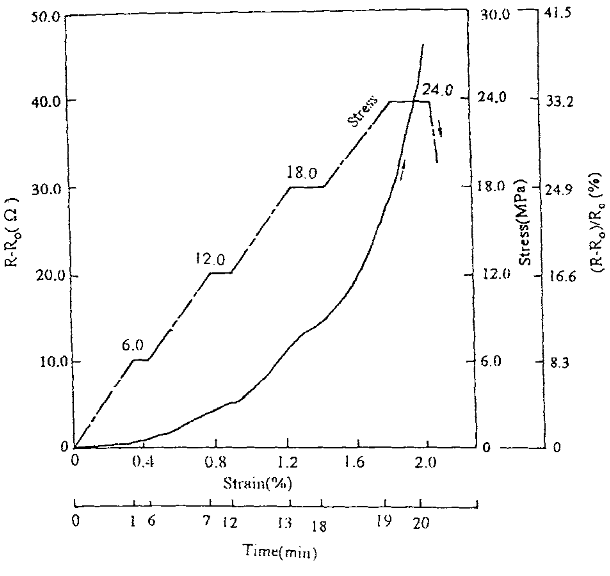

Figure 7

Time-Dependence of the Electrical Resistance

The electrical characteristics of most carbon fibers are time-independent.[9] However, the time dependence of electrical resistance is observed (Figs. 6 and 7). To check the influence of matrices, we selected the ratios of 95/5 and 85/15 of UP/PU IPNs, in which a bundle of carbon fibers are embedded, respectively. Table I lists the properties of matrices

Table I The Properties of Matrices and Composites

Material	Break Elongation (%)	Tensile Strength (MPa)	Initial Electrical Resistance (Ω)
UP/PU(95/5) IPN	4	35	
UP/PU(85/15) IPN	12.5	22	
Composite made from a bundle of carbon fiber and UP/PU(95/5) IPN	4.8	38	200
Composite made from a bundle of carbon fiber and UP/PU(85/15) IPN	1.85	24	220

and composites. During the experimentation, the stress is applied from low to high values, and each stress is held 5 min to monitor the variation of resistance. The time interval of enhancing a lower stress to a higher one is 1 min. As shown in Figure 6, although the stress is kept constant, the strain increases gradually with elapsing time. This results from the creep of the IPN network. Moreover, the creep grows more evident as the stress is enhanced. Interestingly, the resistance increases as time is extended. The behaviors of linear and unlinear variation in resistance corresponding to lower and higher stress respectively are observed. In initial stage, the change in resistance with time may come from the variation of the strain that is contributed from the creep of the IPN network. It is conceivable that the unlinear alteration of the electrical resistance with strain is attributed to the creep of IPN network and the broken fibers. As the higher stress is transferred to the fibers, the break of the fibers happens. In this situation, the number of broken fibers plays a dominant role in the change of resistance.

It is worthy to note that in Figure 6, after the stress is raised to 38 MPa, little overshots of resistance are seen at the moments of 38 and 39 min. This implies that most of fibers have broken. The maximum stress is held merely 3 min, and the sample collapses accompanying a rapid increase of electrical resistance.

A similar phenomenon is observed for the sample made from the matrix of UP/PU(85/15) IPN (Fig. 7). Nevertheless, with the increase of flexible PU content in IPN, the strength of matrix diminishes, and its break elongation grow larger (Table I). The matrix with a greater strain cannot match the brittle carbon fiber very well. All these tend to result in the earlier fracture of the sample; thus, the observation lasts merely 20 min. From the results obtained, we can imagine that the varied creep from different polymer matrices may bring about the discrepancy of the change in the electrical resistance. The investigation of the time-dependence of electrical resistance with different matrices and with varied volume fraction of carbon fiber is in progress.

CONCLUSION

The electrical resistance in carbon fiber-reinforced plastic (CFRP) has been found to increase under static tension and cyclical loading and unloading in tension. Near fatal damage, the resistance goes up abruptly. Time-dependence of resistance is observed for CFRP made from UP/PU(95/5) and UP/PU(85/15) IPNs matrices. So carbon fiber-reinforced plastic can function as a sensor that is capable of self-diagnosing the fatal damage by monitoring the variation in the electrical resistance of carbon fibers.

REFERENCES

1. H. Kaczmarek and S. Maison, *Comp. Sci. Technol.*, **51,** 11–26 (1994).
2. P. Cawley, *Composites,* **25**(5), 351–357 (1994).
3. M. P. D. Goeje and K. E. D. Wapenaar, *Composites,* **23**(3), 147–157 (1994).
4. N. Muto and H. Yanagida, *J. Am. Cer. Soc.,* **76**(4), 857–861 (1993).
5. M. X. Xu, J. S. Xiao, W. H. Zhang, and K. D. Yao, *J. Appl. Polym. Sci.,* **54,** 1659–1663 (1994).
6. A. S. Kaddour, T. A. R. Al-Satehi, and S. T. S. Al-Hassani, *Comp. Sci. Technol.,* **51,** 377–385 (1994).
7. K. Schuite and Ch. Baron, *Comp. Sci. Technol.,* **36,** 53–76 (1989).
8. N. Mato and H. Yanagida, *J. Cer. Soc. Jpn.,* **100**(12), 1429–1439 (1992).
9. C. N. Owston, *J. Phys. D: Appl. Phys.,* **3,** 1615–1626 (1970).

Received June 15, 1995
Accepted October 7, 1995