Bending Stress Dependent Electrical Resistivity of Carbon Fiber in Polymer for Health Monitoring System

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Influences of compressive and tensile stresses on an electrical resistivity of carbon fiber in polyvinyl acetate polymer on bending test are studied as a basic research to develop high sensitive stress sensors. It is confirmed that a compressive stress of less than 0.3 GPa on bending test reversibly decreases the electrical resistivity of carbon fiber due to enhancement of the density of state of π bonding electron. A tensile stress of less than 0.3 GPa on bending test also decreases the electrical resistivity of carbon fiber, reversibly, because of decreasing the density of electron scattering sites.[doi:10.2320/matertrans.MRA2007105]

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1. Introduction

Carbon fibers, with their advantages of lightweight and high strength, are increasingly being applied as structural materials in the fields of aerospace and rapid transport engineering.1,2) Recently, the drastic temperature change of electrical resistivity of carbon fiber has been also applied for security thermo sensor for static motion.3)

On the other hand, many works have been investigated for influences of tensile test under high stress on electrical resistivity of carbon fiber.4,5) The tensile test under high stress has irreversibly increased the electrical resistivity, although remarkable decreasing in electrical resistivity by tiny tensile stress has not been found. Thus, influences of tiny tensile stress on electrical resistivity of carbon fiber have been precisely studied.6) A negative linear relationship between tensile stress and the electrical resistivity has been obtained.5) If it is possible to apply for a stress sensor in carbon fiber reinforced polymer (CFRP), dependence of compressive stress on electrical resistivity is required.

The carbon fibers are also applied for CFRP as a structural material in the wing of a huge aircraft B-777 recently developed. When the B-777 with long main wing of 32 m length takes off and lands, the maximum practical value of wing deflection is 2.5 m. If the deflection is below the linear relationship between electrical resistivity and strain of carbon fiber in polymer, it can be applied for the health-monitoring sensor, as well as structural materials of CFRP in aircraft wing. Therefore, influences of bending stress on an electrical resistivity of carbon fiber in polymer have been studied as a basic research to develop stress sensors in CFRP.

2. Experimental Procedure

2.1 Sample preparation

Figure 1 shows schematic drawing of sample and bending test. The sample is constructed with carbon fiber (TORAY-CA-T800HB by Toray Ltd. in Tokyo) and soft polyvinyl acetate polymer (JAN-code: 4901490101221, Konishi Ltd, Osaka). The sample setting carbon fiber on compressive inside performs the compressive test, whereas the sample setting carbon fiber on tensile outside performs the tensile test.

2.2 Bending test

Figure 1(b) shows schematic diagram of bending test. The stress is loaded from three point bending tests. Total length L (mm), width W (mm), thickness h (mm) and gage length L (mm) are 50.0 mm, 10.0 mm, 0.45 mm and 20.0 mm, respectively. Stress and strain are calculated from curvature radius R (mm). The R is distance from the compressive carbon fiber to neutral point and is expressed by a following equation.

\[ R = b - n \] (1)

Here, length from centerline in the composite sample to carbon fiber at compressive side n (mm) is 0.075 mm.

The curvature diameter from center to neutral point b (mm) is expressed by a following equation.

\[ b = (L^2 + y^2)/2y \] (2)

Here, y (mm) is bending displacement.

The bending strain ε is estimated by a following equation.

\[ \varepsilon = n/R \] (3)

On the other hand, when length from centerline in the composite sample to carbon fiber n (mm) is at tensile side, R (mm) is expressed by a following equation.

\[ R = b + n \] (4)

Bending stress σ (GPa) is expressed by a following equation.

\[ \sigma = E \cdot r/2R \] (5)

Here, Young’s modulus E (GPa) and diameter r (μm) of carbon fiber are 294 GPa and 0.006 mm, respectively.

2.3 Electrical resistivity measurement

The electrical resistivity was measured by using the standard DC four-probe method with silver paste electrical contacts (D-550, FUJIKURA Ltd, Tokyo) on single fiber.7) The outer two contacts, which inter-distance was 40 mm, were for measuring a current; the inner two contacts, which inter-distance was 20 mm, were for voltage measurement.

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The fiber with four-probe is set on the polymer sheet, which thickness was 0.15 mm, before dipping carbon fiber into polymer sheet of 0.30 mm thickness.

As shown in Fig. 1(b), the sample with four probes is set on bending test. The electrical resistivity $\rho (\mu \Omega \cdot \text{m})$ is expressed by a following equation as a function of electrical current $I (\text{A})$.

$$\rho = \frac{V S}{I l} \quad (6)$$

Here, electrical potential $V (\text{V})$, cross section area $S (\text{mm}^2)$ and the distance of inner two contacts $l (\text{mm})$ for voltage measurement are $5 \text{V}$, $3.0 \times 10^{-5} \text{mm}^2$ and $20 \text{mm}$, respectively.

### 3. Results

Figure 2 shows elastic stress-strain curves on bending of compressive and tensile stressed carbon fibers in polymer. The tensile stress shows higher elasticity than that of compressive stress.

![Figure 1](image1.png)  
**Fig. 1** Schematic diagrams of sample and bending test. (a) Sample, (b) Bending test and (c) Loading sample.

The electrical resistivity of carbon fiber has been measured under different bending stresses. Figure 3 shows changes in electrical resistivity of carbon fiber at compressive $\bigcirc$ and tensile $\bigtriangledown$ points in polyvinyl acetate polymer against bending stress. It is confirmed that the compressive stress gradually decreases the electrical resistivity of carbon fiber.

On the other hand, the low tensile stress on bending test reversibly decreases the electrical resistivity of carbon fiber in polymer, whereas the excess stress increases the electrical resistivity in the high tensile stress zone. The minimum value of electrical resistivity is found at 0.3 GPa of tensile stress. Whenever the sample bends, micro-hole by pulling out fiber at compressive part and micro-cylinder of terminating fiber at tensile part in the polymer matrix have never been observed. Namely, it is clear that the pullout phenomenon doesn’t occur.

To confirm the linearity of stress dependent electrical resistivity in Fig. 3, the electrical resistivity is precisely measured. Figure 4 shows linear relationships of electrical resistivity of carbon fiber at compressive $\square$ and tensile $\bigtriangleup$ points in polyvinyl acetate polymer against tiny bending stress of less than 0.2 MPa. It is confirmed that the tensile bending stress $\sigma_t (\text{GPa})$ in the low stress zone reversibly decreases the electrical resistivity $\rho_t (\mu \Omega \cdot \text{m})$ of the carbon fiber.
carbon fiber in polymer. On the other hand, increasing compressive bending stress \( \sigma_c \) (GPa) gradually decreases the electrical resistivity \( \rho_c \) (\( \mu \Omega \cdot \text{m} \)) of carbon fiber. When correlation coefficients of equations (7) and (8) are 0.9669 and 0.9895, respectively, linear relationships are reversibly expressed by following equations.

\[
\rho_c = -2.073\sigma_c + 21.32 \quad (0 < \sigma_c < 0.2 \text{ GPa}) \quad (7)
\]

\[
\rho_t = -3.127\sigma_t + 21.20 \quad (0 < \sigma_t < 0.2 \text{ GPa}) \quad (8)
\]

When the compressive stress is zero, the electrical resistivity is 21.32 \( \mu \Omega \cdot \text{m} \). When the tensile stress is zero, the electrical resistivity is 21.20 \( \mu \Omega \cdot \text{m} \). The negative slope of the tensile stress dependence of electrical resistivity is 51\% higher than that of the positive compressive slope value.

4. Discussion

4.1 Reduced electrical resistivity applied for health monitoring

Dominant factors of electrical resistivity are generally phonon, nano-structure and point defects, which are controlled by temperature, pressure and composition. Since vacant sites in hexagonal graphite structure probably affect the electrical resistivity at constant temperature, individual values of electrical resistivity are slightly different of each carbon fiber sample at constant temperature. In addition, the inter-distance value of inner two contacts cannot be perfectly reproduced for voltage measurement. In order to evaluate the precise stress dependence, a reduced electrical resistivity \( \rho/\rho_0 \) is one of useful tool to neglect the experimental error of inter-distance value and defects dependence induced by sample difference. Here, \( \rho_0 \) is \( \rho \) of carbon fiber sample unloaded.

Figure 5 shows change in reduced electrical resistivity of carbon fiber against bending stress. The right (negative) and left (positive) sides of horizontal axis are for tensile and compressive stress, respectively. Increasing in the both compressive and tensile stresses under the low stress zones decreases the electrical resistivity of carbon fiber. The stress dependent electrical resistivity in tensile zone on bending test is 1.51 times higher than that on compressive zone. It shows that the sensitivity of electrical resistivity of carbon fiber on the tensile zone is higher than that on the compressive zone. Furthermore, the linear relationships between the stress and electrical resistivity of carbon fiber can be also applied for stress sensor as well as thermo-sensor.

The linear relationships are obtained from 0 to 0.25 GPa of stress, which corresponds to the deformed strain from 0 to 0.1\%. Thus, maximum deformed strain for the linear relationship is 0.1\%.

When the aircraft B-777 takes off and lands, the maximum estimated value of wing deflection, which have linear relationship between electrical resistivity and stress, is 4.4 m. It is larger than the maximum practical wing deflection (\( \pm 1.25 \) m) from the top to bottom of main wing with 32 m in length. The skin thickness of airplane is generally less than 10 mm. Based on the eqs. (1), (2), (3) and (4), the practical deformed strain is less than 0.0025\% on taking off and landing of B-777 airplane. Since the maximum deformed strain (0.1\%) for the linear relationship is apparently higher than the practical deformed strain (0.0025\%), it is easy to apply for a health-monitoring sensor in main wing of aircraft. The carbon fiber in CFRP can be probably applied for precise strain gage sensors, as well as strong structural materials in airplane wings.

4.2 Compressive stress dependent electrical resistivity

Figure 6 shows schematic drawing of atomic hexagonal graphite structure of carbon fiber under each bending stress. Figures 6(a) and 6(b) are under compressive stress and before loading, respectively. Although an inter-atomic \( \sigma \) bonding maintains hexagonal graphite structure, a \( \pi \) bonding electron, which contributes an electrical conductivity, is usually distributed below and above hexagonal graphite structural planes.

It is thought that layer distance of graphite structure becomes small on compressive stress. As shown in Fig. 6(a), the compressive stress decreases the layer distance of graphite structure. Since the layer distance becomes small, the density of state of \( \pi \) bonding electron becomes high. Therefore, the compressive stress decreases the electrical resistivity (see Fig. 5).
4.3 Tiny tensile stress dependent electrical resistivity

An influence of simple tensile stress on electrical resistivity has been investigated. Based on the results, the present tiny tensile stress dependence is discussed for carbon fiber buried in polymer during bending test, as shown in Fig. 5. Although the tensile loading during the bending test is not simple, the present results are important to be applied for the practical use. Dangling bonds, which density affects mobility, electron scattering and density of state, exist in most of carbon fibers, resulting in increasing electrical resistivity. The carbon fiber has graphene structure with dangling bonds. The coulomb repulsive force of the dangling bond pairs should generate the micro residual stress and strongly contributes the increasing in electric resistance. Since the coulomb repulsive force at the dangling bond distorts unloaded graphite structure (see Fig. 6(c)), it increases the electrical resistivity of carbon fiber.

Figure 6(c) shows a one-directional extended hexagonal structure with translation symmetry under tiny tensile loading. When the carbon fiber is loaded by low tensile stress, the hexagonal structure shows a preferred oriented direction. Since the structure is ordered by loading low tensile stress, the distortion probably becomes small. Thus, the electrical resistivity decreases, as shown in Fig. 5. Since the periodic distribution of the density of state of π bonding electron probably decreases the electron scattering, the tiny tensile loading decreases the electrical resistivity (Fig. 5).

4.4 High resistivity induced by high tensile stress

A high tensile stress of more than 0.3 GPa enhances the electrical resistivity (see Fig. 3). Figure 6(d) shows a one-directional extended hexagonal structure with translation symmetry under high tensile stress with excess dangling bonds. Two reasons of increasing in the inter-electronic distance at dangling bonds and excess formation of dangling bonds have been suggested.

Since the high tensile stress of more than 0.3 GPa elongates the inter-electronic distance at dangling bond pairs (see Fig. 6(d)) and probably decreases the electron transport between pairs, it increases the electrical resistivity (see Fig. 3), reversibly.

When dangling bonds are generated by a further excess tensile stress, the electrical resistivity should increase irreversibly. The further addition of the excess loading enhances the density of dangling bonds, which disorder the hexagonal structure and then irreversibly increase the electrical resistivity.

On the other hand, if a huge compressive stress exists in the carbon fiber, it probably enhances the dangling bonds density and probably increases the electrical resistivity. Although the high resistivity has not been measured under the compressive stress of more than 1.8 GPa, the stress dependent resistivity in Fig. 3 becomes small from 0.3 to 1.8 GPa of high compressive stress.

5. Conclusion

Influences of bending stress on an electrical resistivity of carbon fiber in polyvinyl acetate polymer are studied as a basic research to develop high sensitive stress sensors.

(1) It is confirmed that an initial compressive stress of less than 0.3 GPa on bending test reversibly decreases the electrical resistivity of carbon fiber due to enhancement of the density of state of π bonding electron.

(2) An initial tensile stress of less than 0.3 GPa on bending test also decreases the electrical resistivity of carbon fiber, reversibly, because of decreasing the density of electron scattering sites.

(3) The stress dependent electrical resistivity on tensile test is 1.51 times higher than that on compressive test. It shows that the sensitivity of the electrical resistivity of carbon fiber on the tensile test is higher than that on the compressive test.

(4) The linear relationships between the initial stress and electrical resistivity of carbon fiber can be also applied for stress sensor as well as thermo-sensor. The carbon fiber in CFRP can be probably applied for precise strain gage sensors, as well as strong structural materials in airplane wings.

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