

Influence of Elastic Tensile Stress on Electrical Resistivity of Carbon Fiber

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An influence of elastic tensile stress on electrical resistivity of carbon fiber has been investigated as a basic research to develop a strain sensor. The initial elastic stress reversibly decreases the electrical resistivity, although the large stress causing irreversible deformation increases the resistivity. In addition, a linear relationship between initial stress and reduced electrical resistivity is obtained in the initial elastic stress zone. As the initial elastic stress probably enhances the periodicity of graphite structure, decreasing in the electrical resistivity with tensile elastic stress is explained. [doi:10.2320/matertrans.MRA2007003]

(Received April 25, 2007; Accepted August 27, 2007; Published October 11, 2007)

Keywords: stress dependence, carbon fiber, electrical resistivity, initial stress, tensile test

1. Introduction

Since a carbon fiber exhibits the high strength with lightweight, it has been applied for rapid transports as structural materials.^{1,2)} Furthermore, it has been also realized a high sensitive thermo sensor of static motion for security.³⁾ On the other hand, high strength joining has been obtained by using percussion welding, which has been applied to the junction of carbon fiber to pure metals.⁴⁾ Although the heating above 200°C tremendously decreased the fracture stress values in adhesive materials and soldering alloy, the fracture stress value above 1 GPa is observed for the carbon fiber junction to titanium bulk below 400°C.⁵⁾ As a basic research to develop strain sensors bedded in high strength composite materials, the influence of elastic stress on electrical resistivity of the carbon fiber at room temperature has been investigated.

2. Experimental Procedure

2.1 Sample preparation

Figure 1 shows schematic drawing of sample for tensile test. Carbon fiber (6 μm in diameter, TORAYCA-T800H, Toray Ltd, Tokyo, Japan) is cut into pieces 50 mm in length. As shown in Fig. 1, both grips of fiber sides are fixed by papers chuck with a punched rectangular hole by an adhesion bond.

The effective length of naked carbon fiber is 1 mm to obtain the stress-strain curves. To measure the electrical resistivity by using four probe technique, the carbon fiber is contacted with copper wire by electrical conductive joining by silver paste (D-550, Fujikura, Ltd. Tokyo). After drying the joining part, surplus parts of carbon fiber are cut off.

2.2 Tensile tester with measurement of electrical resistivity

The fracture stress for fine carbon fiber is measured by using an Instron type tensile machine with twisting relaxation apparatus (see Fig. 2),⁶⁾ although the relaxation system is fixed to stabilize the four-probe measurement of resistivity measurements. The tensile test is performed at constant strain

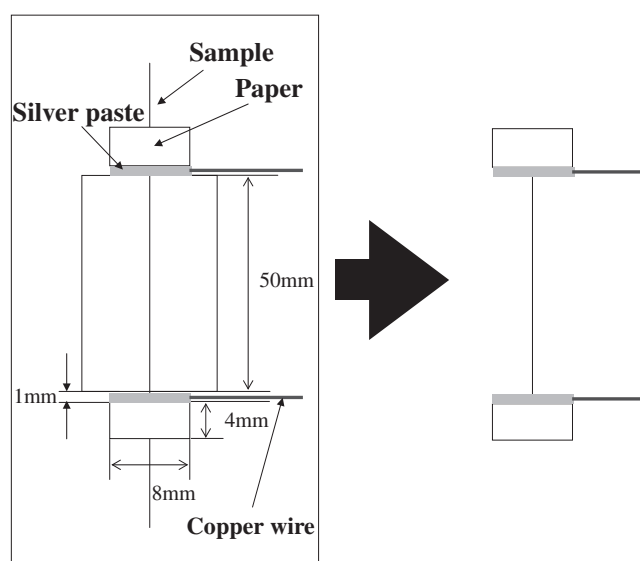


Fig. 1 Schematic drawing of sample for tensile test.

rate from 10^{-6} to 10^2 s^{-1} . To decrease the residual shear stress, the fiber sample is mounted by a hooklet system.

To measure the load, a micro load cell (LSV-50GA, Kyohwa-Dengyo, Tokyo) is used. A displacement measurement system of light spot (LK-030, Keyence, Osaka) with a laser amplifier (LK-2000, Keyence, Osaka) is applied to measure the strain. It is important to measure a length displacement (ΔL) of laser spot on the screen to evaluate a strain, precisely. A relationship between the ΔL value and the electrical potential (ΔE) of the light ray sensor is expressed by a following equation.

$$\Delta L \text{ (mm)} = 0.9837 \times \Delta E \text{ (V)} + 0.0344 \quad (1)$$

The strain (ε) is expressed by a following equation.

$$\varepsilon(\%) = \{(\Delta L + y_0)/y_0\} \times 100 \quad (2)$$

Here, y_0 is the length of the carbon fiber (50 mm).

The electrical resistivity at room temperature of carbon fiber under each tensile stress has been measured by four-probe technique.⁷⁾ The elevated temperature is proportional to the square value of the electrical current density. When the

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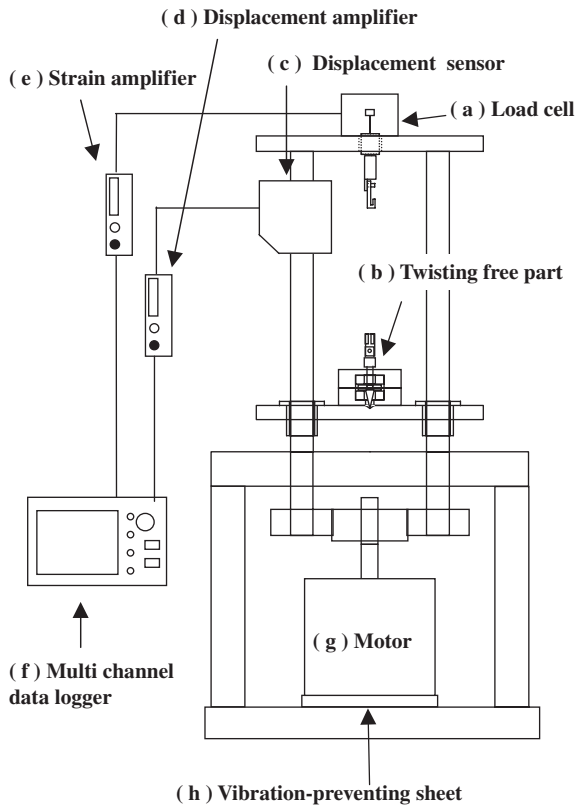


Fig. 2 Schematic diagram of twisting free tensile tester.

electrical current in the carbon fiber sample becomes 0.5 mA, the temperature increase is 5 deg. Since the electrical current is 0.15 mA to measure the potential, it doesn't significantly raise the temperature less than 1.5 deg. Such an experimental error is considered as negligible small.

3. Results

3.1 Stress-strain curves of carbon fiber

Figure 3 shows stress-strain curves of torsion free carbon fibers. The slope values of samples A, B, and C are approximately the same. The Young's modulus estimated by the slope is about 130 GPa. Furthermore, the fracture stress values of the carbon fiber samples A, B and C is from 2.6 to 2.9 GPa, while fracture stress of the carbon fiber has been generally obtained from 1.7 to 4.0 GPa.⁸⁾ Therefore, it is possible that the reproducible experimental values can be obtained for the samples A, B, and C.

3.2 Stress dependent electrical resistivity of carbon fiber

The electrical resistivity of carbon fiber under each tensile stress has been obtained with low electrical current density at room temperature. Figure 4 shows changes in electrical resistivity of each carbon fiber against tensile stress. Since the samples A, B and C are cut from same carbon fiber, their slopes of stress dependences are as same as each others (see Fig. 4). On the other hand, the electrical resistivity values of the samples A, B and C are different from each other. The differences are probably caused by residual stress and density of dangling bonds, as well as experimental errors in the length of each specimen.

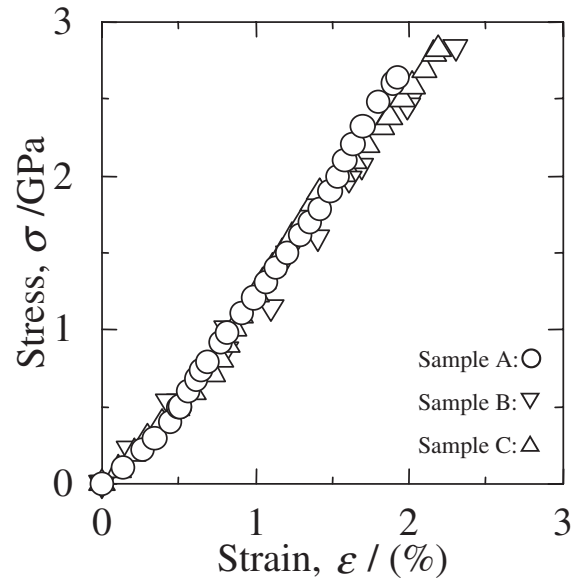


Fig. 3 Stress-strain curves of carbon fibers.

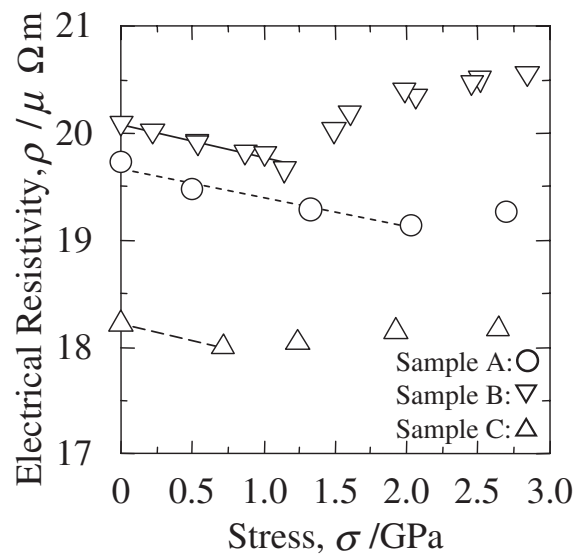


Fig. 4 Changes in electrical resistivity of carbon fibers against elastic tensile stress.

The initial elastic stress decreases the electrical resistivity, whereas the large stress irreversibly increases the electrical resistivity of each carbon fiber. All measured specimens show the minimum values in electrical resistivity versus stress, which is slightly different from each carbon fiber sample.

The linear relationship between elastic tensile stress and electrical resistivity in the initial stress zone is obtained for each specimen. The slope is constant.

On the other hand, the large stress beyond the turning point causes irreversible deformation and increases the electrical resistivity for each carbon fiber (see Fig. 4). The slope of stress dependence is not reproducible.

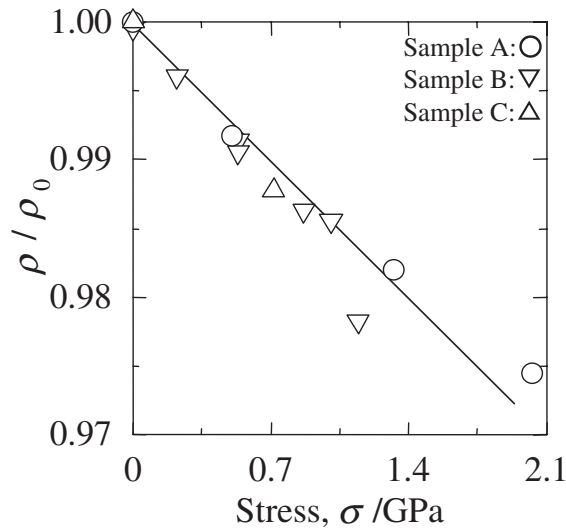


Fig. 5 Linear relationship between reduced electrical resistivity of carbon fiber and elastic tensile stress.

4. Discussion

4.1 Reduced electrical resistivity

Dominant factors of electrical resistivity are generally phonon, structure, composition, elastic stress and point defects. Since vacant sites in hexagonal graphite structure probably affect the electrical resistivity at constant temperature, individual values of electrical resistivity are slightly different each other 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 (ρ/ρ_0) is one of the useful tools to neglect the experimental error of specimen length, contact problems and defects density for each sample. Here, the ρ_0 value is the resistivity value of each unloaded carbon fiber.

Figure 5 shows changes in reduced electrical resistivity (ρ/ρ_0) of carbon fibers against tensile stress in the elastic region. Although the stress dependent ρ/ρ_0 values are different from each other in the high stress region, the stress dependent ρ/ρ_0 value of samples A, B and C in the initial stress region corresponds to each other. When the correlation coefficient is 0.9771, a linear relationship is expressed by a following equation fitted.

$$\rho/\rho_0 = -0.0166\sigma + 1.00 \quad (3)$$

Although the stress dependence exhibits the high linearity, the electrical resistivity of carbon fiber sample unloaded often deviates from the linear relationship, as shown in Fig. 4. The experimental error is generated by fiber slack remaining from the fiber processing. If the initial stress is effective to take up the slack, it can be explained. Therefore, the electrical resistivity of unloaded sample is estimated to be an ideal value extrapolated by data in linear relationship, as shown in Figs. 4 and 5.

4.2 Discussion of electrical resistivity

Figure 6 shows schematic atomic hexagonal graphite

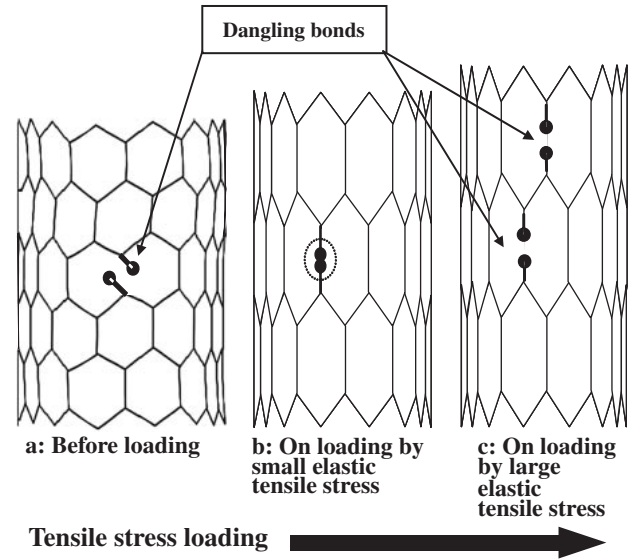


Fig. 6 Schematic hexagonal structure of carbon fibers before and after loading under small and large tensile stress values.

structure of carbon fiber at each tensile loading. The inter-atomic σ -bonding electrons maintain the hexagonal graphite structure, whereas π -electrons are generally distributed below and above hexagonal graphite structural planes. Since the hexagonal plate of rod-like carbon fiber is not perfectly flat, as shown in Fig. 6(a), the electrical resistivity is higher than that of ideal ordered graphite structure. In addition, dangling bonds, which density probably affects the electrical conductivity, exist in most of carbon fibers.⁹⁾ Thus, the density enhancement increases the electrical resistivity.

Furthermore, electrons of dangling bonds generally sandwiched in π -electrons distributed on the graphite hexagonal structure. Thus, they are probably distributed inside of the hexagonal structure. Since the repulsive force of electrons of dangling bonds disorders the hexagonal structure (see Fig. 6(a)), the electron scattering occurs, resulting in high electrical resistivity.

When the carbon fiber is loaded by a low tensile stress, the hexagonal structure with dangling bonds shows the periodic structure, as shown in Fig. 6(b). As the forming of periodical distribution of π -electron probably decreases the electron scattering, the low stress decreases the electrical resistivity. Namely, initial stress probably decreases the electrical resistivity, as shown in Fig. 4. This phenomenon is often observed.^{10,11)} However the detailed discussion has not been reported, yet. The initial elastic stress reversibly decreases the electrical resistivity in the present work, although the large stress irreversibly increases the resistivity. As the initial elastic stress annihilates the electron scattering, decreasing in the electrical resistivity is probably explained on tensile elastic stress.

On the other hand, it is a serious problem to apply the carbon fiber as a new strain sensor, because its electrical resistivity is sensitive to strain, temperature and dangling bond. Namely, the complex dependence of stress and temperature on electrical resistivity has been often observed in different carbon fibers.

A large stress above the deviated point increases the

electrical resistivity, as shown in Fig. 4. This phenomenon has been reported previously.^{10,11)} The resistivity enhancement generated by large loading above deviated point has been discussed as following sentences. The large stress elongates the inter-electronic distance at dangling bond pairs (see Fig. 6(c)) reversibly increases the electrical resistivity, because it enhances the density of dangling bonds, which disorder the hexagonal structure.

On the other hand, the electrical resistivity values of samples are different from each other, as shown in Fig. 4. If the electrical resistivity probably depends on the density of dangling bonds,¹²⁾ the carbon fiber with low density of dangling bonds shows the high periodical distribution of π -electrons. Therefore, we conclude that the experimental error of electrical resistivity of each carbon fiber depends on the density of dangling bonds.

5. Conclusion

The linear relationship between elastic stress and electrical resistivity obtained in the initial stress zone below deviated point were useful as a basic research to develop strain sensor. Although the large stress increased the resistivity, it was confirmed that the initial stress in the elastic region decreased the electrical resistivity. The linear relationship ($\rho/\rho_0 = -0.0166\sigma + 1.00$) between stress (σ) and reduced electrical resistivity (ρ/ρ_0) was obtained. The decreased electrical resistivity can be explained by the electron scattering when the initial elastic stress is applied.

Acknowledgement

Authors would like to thank Mr. Hiroyuki Kobayashi and Prof. Wilfried Wunderlich for their useful help.

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