Expanding and Contracting Motions of Carbon Micro-Coils Induced by Alternating Current

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We studied the movement of carbon micro-coils (CMCs), 4–5μm in coiling diameter and 1 mm long, which are a new material with a three-dimensional helical/spiral structure, under applied voltage. By applying an alternating voltage of several different frequencies to the CMC, a series of expanding and contracting motions is observed as the electric current passes through. For a clockwise CMC, the expanding motion occurs when the negative amplitude reaches maximum. The contracting motion, i.e., the motion of the CMCs contracting to its original length, occurs at the positive amplitude of the electric current. The counterclockwise CMC acts as the reverse of the motion of the clockwise CMC. The number of expanding and contracting motions for both CMCs increases linearly with the frequency under a constant applied voltage. The amplitude of the CMCs decreases with a higher frequency, and the number of CMC motions increases in proportion to a higher frequency. The electromagnetic power owing to the spiral conformation of the CMC may explain these motions.

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KEYWORDS: carbon microcoils, chemical vapor deposition, magnetic properties, alternating current, expanding and contracting motions

1. Introduction

There is ongoing development of micro observation tools for micro and nano substrates in conjunction with the increasing need of greater miniaturization. The component elements of these tools are also undergoing further miniaturization.

Carbon micro-coils (CMCs) are a new material with a three-dimensional helical/spiral structure. Motojima et al.1,2 prepared microcoiled vapor-grown carbon fibers (abbreviated as “carbon microcoils” or “CMC” hereafter) having a coil radius of 1 to 10μm and a coil length of 0.1 to 5 mm using Ni metal-activated pyrolysis of acetylene in the presence of a small amount of sulfur or thiophene as an impurity.

Since CMCs have a three-dimensional helical/spiral structure, they have unique characteristics, such as the ability to absorb electromagnetic waves,3 and the stereo-specific nature of magnetoresistance, measured using a superconducting magnet,4 and the electrical resistivity measured by a probe unit installed in a scanning electron microscopy (SEM).5 A CMC can be used as a micro magnetic sensor,6 and it can also behave as a mechanical spring.7

Akagi et al. have recently reported a conductive polyacetylene with a helical structure. Its electrical properties under applied electromagnetic or optical fields have been discussed.8 The contributions of helical structures to electron distribution and mechanical behavior have been discussed recently to some extent with nano-tube, nano film,9 and nano coil materials.10

In the present study, we found that a CMC expands and contracts when an AC is applied to it. This motion is generated according to the frequency of the AC. Dynamic movements have been observed using a microscope charge-coupled device (CCD) camera with high magnification. This phenomenon is discussed in conjunction with CMC's structural conformation of clockwise and counterclockwise, coil diameter and fiber diameter.

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2. Experimental

The CMCs with clockwise and counterclockwise coils, shown in Fig. 1, were obtained by catalytic pyrolysis of acetylene at a high temperature.11 CMCs used in this experiment were arranged by cutting the original coils. All CMC samples are listed in Table I with coil diameter and fiber diameter. Samples No. 1 to No. 3 were clockwise CMCs, and samples No. 4 to No. 6 were counterclockwise CMCs.

![Fig. 1. SEM image of Carbon micro-coils.](image)

<table>
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<th>Table I. Characteristic of CMC samples.</th>
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<td>CMC No.</td>
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<tr>
<td>Clockwise CMC</td>
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<tr>
<td>1</td>
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<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>Counter-clockwise CMC</td>
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<td>4</td>
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<td>5</td>
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was recorded on videotape. Then, the behaviors of CMCs and the moving distances were examined with scenes obtained from the slow-motion videotape.

Using another circuit with a solid joint, we also observed the CMC expanding and contracting motions. Two CMCs were set up parallel to each other. Carbon fiber (CF) was set up perpendicular to two parallel CMCs, and connected to CMCs with silver paste, as shown in Fig. 4. We applied an alternating voltage to this unit, and observed the movement of the coil parts with a high-magnification microscope with CCD camera using a 3,000 times zoom lens. The picture obtained with the microscope was recorded. The moving behavior of the CMC was analyzed using a personal computer. The brightness of the CMC surface area was measured using picture-analyzing software (Ulead PhotoImpact 7 SE, Ulead Systems, Tokyo). The brightness was estimated with the average number of the brightness of red, green, and blue per pixel in a selected area. We observed CMC brightness changed with its motion, depending on the alternating current.

3. Results and Discussion

3.1 Dependence of CMC expanding and contracting motions on type of coiling and frequency of electric current

By using experimental set up shown in Fig. 2, CMC motion was examined under applied voltage. The relationships between the electric current frequency and the periodic motions of expansion and contraction for clockwise and counterclockwise CMCs are shown in Fig. 5. The numbers of expanding and contracting motions for both types of CMC

Fig. 5. Relationship of the frequency of applied AC vs number of motion vibrations.
increase linearly with the frequency under the constant applied voltage.

When the DC, namely 0 Hz frequency, and AC were applied to the CMC unit, CMC expanding and contracting motions were observed only at the latter case. In the clockwise CMC, the expanding motion occurred when the negative amplitude reached maximum. The contracting motion, i.e., when the CMC returns to its original length, occurred at the positive amplitude of the electric current. The patterns of a continuous series of CMC expanding and contracting motions during AC applied voltages are shown in Fig. 6.

It is supposed that expanding and contracting motions of a CMC may be generated by its electromagnetic power and spring-like characteristics.

### 3.2 Distances of CMC expansion and contraction

The movement of CMC, listed at Table I, were observed using microscope system, shown at Fig. 3. Photos of expanding and contracting CMC motions are shown in Fig. 7. The ratio of the CMC length at maximum expansion ($L_1$) and at extreme contraction ($L_2$) is 1.2, in Fig. 7. The relationship between the distances ($L_1 - L_2$) and the frequency of the electric current is shown in Fig. 8. From Figs. 7 and 8, the distances obtained in both clockwise and counterclockwise CMCs decrease with a higher frequency.

The different distance of $L_1 - L_2$ may depend on its own electric resistance and its amorphous structure. Therefore, the difference in the distances for each CMC, in Fig. 8, is assumed to be derived from these differences in physical characteristics.

These results are explained below. Since the frequency per unit time of CMC motion increases according to the frequency of the electric current, the CMC expanding and contracting motions could not physically continue at the higher electric current frequency since a carbon structure is a relatively hard structure for a spring.

### 3.3 Variation in pixel brightness according to CMC motions

We applied an alternating voltage to unit arranged with...
parallel CMCs connected by a CF set perpendicularly shown in Fig. 4. We observed a part of the CMC under an applied voltage of 20 V, 1 Hz. The part is expressed as a square in Fig. 9(a).

We also investigated the change in brightness in the square part of the photo, in relationship to the applied frequency estimated with picture-analyzing software. The varieties of brightness is shown in Fig. 9(b). We found that the changes in brightness were corresponding to CMC motion. The brightness of the CMC surface had a higher value of a contracted rather than expanded CMC. When the CMC was expanded, a coil-to-coil gap developed, and the brightness of this gap area decreased. It is also clear that the CMC expanding and contracting motion occurred according to the alternating voltage.

4. Conclusions

The spiral property of CMC would be one of the structural characteristics of CMCs. By applying an AC voltage at several different frequencies, a series of CMC expanding and contracting motions are first observed using a microscope-video-CCD camera system.

The distance of the CMC expanding and contracting motions tended to decrease with an increase in the frequency. Thus, the cycle of CMC motion can be controlled by electric current frequency. In summary, from observation of CMC motion, it is clear that this is a type of conversion of electrical energy into the energy of mechanical motion. These micro motions could be applied to micro machining and micro-actuators in the future.

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