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Japanese Journal of Applied Physics
Vol. 46, No. 4A, 2007, pp. 1815–1817

Brief Communication

Determination of Carbon Nanocoil Orientation by Dielectrophoresis

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(Received October 19, 2006; accepted December 25, 2006; published online April 5, 2007)

The alignment of carbon nanocoils (CNCs) has been demonstrated by electrophoresis and dielectrophoresis. In the case of DC electric field, while most of all CNCs moved toward a cathode and formed a chain structure in a suspension, no CNC alignment was observed after the evaporation of the suspension. In contrast, in the case of AC electric field with a frequency higher than 1 kHz, the CNCs were aligned along the electric field and connected to each other even after the evaporation of the suspension. This difference is discussed in terms of the fluidic perturbation of the suspension.
[DOI: 10.1143/JJAP.46.1815]

KEYWORDS: carbon nanocoil, dielectrophoresis, electrophoresis, alignment, dipole moment, carbon nanotube

Carbon nanocoils (CNCs) have attracted considerable attention for various applications, such as composite materials and nanomechanical and electromagnetic device components, because of their unique coiled structure,[1–4] mechanical characteristics as springs, and conductive nature.[5,6] To fabricate high-performance devices using CNCs, the alignment and positioning of CNCs are very crucial. The accurate control of the positioning and alignment of carbon nanotubes has been realized by a nanomanipulation technique using electron microscopes.[7,8] This technique is also applicable to the measurement of the mechanical and electrical properties of individual CNCs.[5,6] Furthermore, we have demonstrated the alignments of carbon nanotubes by electrophoresis[9] and dielectrophoresis[10] without nanomanipulation. This enables us to align a large amount of nano-materials without nanomanipulation, whereas the accuracy of positioning is lower than that obtained with nanomanipulation. These electrophoresis-based techniques are currently widely used for the alignment, positioning, purification, and separation of metallic and semiconductive nanotubes. However, the alignment and positioning of CNCs by these electrophoresis-based techniques are still open subjects. In this study, we demonstrated the electric field orientation of CNCs by dielectrophoresis.

The carbon nanocoils used in this study, 10 to 100 μm in length and 100 to 700 nm in coil diameter, were prepared by a chemical vapor deposition method.[11] The line diameter and coil pitch ranged from 100 to 200 nm and from 100 to 700 nm, respectively. The nanocoils with 0.03 wt % were ultrasonically dispersed in isopropyl alcohol (IPA) for 5 min. The suspension was dropped onto a gap of coplanar Cu electrodes formed on glass substrates, where the gap of the electrodes was changed from 0.2 to 1.1 mm in order to change the electric field. Subsequently, a DC or AC electric field was applied to the electrodes until the suspension had evaporated completely at room temperature. The applied voltage was fixed at 60 V_{rms}. The frequency was changed from 0 to 1 MHz. The motion of the CNCs during dielectrophoresis was observed using an optical microscope and recorded on a video. Samples with nanocoils on substrates after the evaporation of IPA were observed using a scanning electron microscope (SEM).

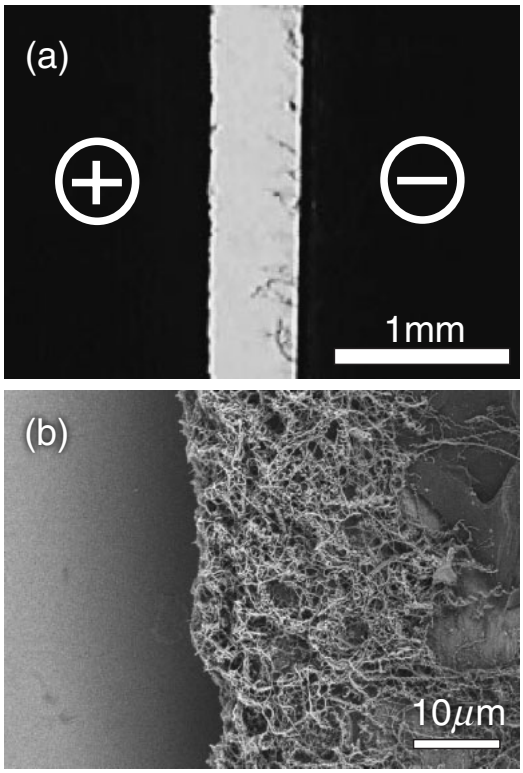

Fig. 1. (a) Optical microscopy image obtained during DC electrophoresis of CNCs and (b) SEM image obtained around cathode edge after evaporation of suspension.

Figure 1(a) shows the optical microscopy image obtained during electrophoresis at a DC electric field of 1.2×10^3 V cm^{-1}. Most particles in the suspension move toward a cathode and form a chain structure in the suspension. This treelike chain structure is formed by the modification of the electric field line due to the carbon materials in contact with the cathode. When a conductive carbon structure is in contact with a cathode, the free end of this structure has the

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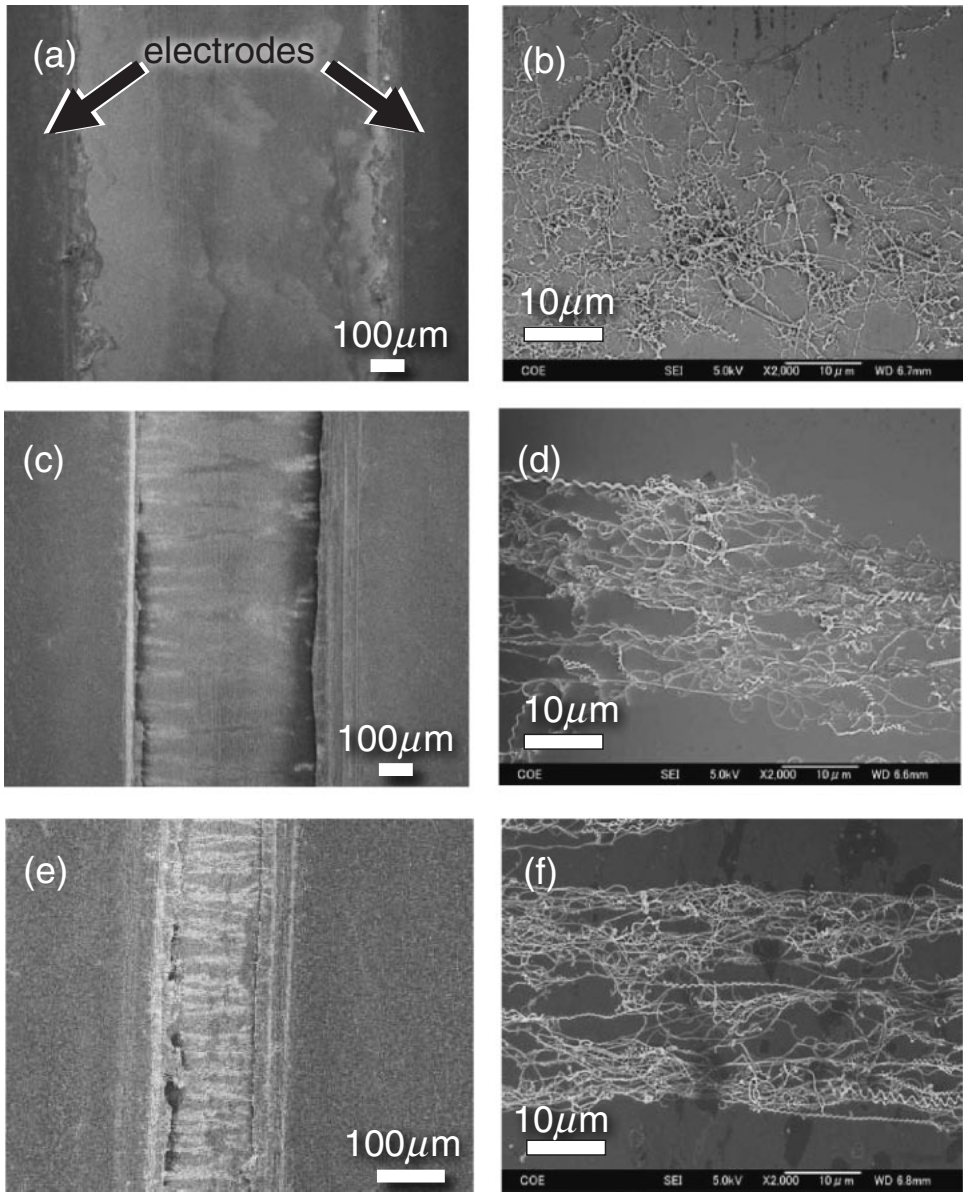

Fig. 2. Series of SEM images for electric field dependence of dielectrophoresis with frequency of 100 kHz after evaporation of suspension. The electric fields for (a) and (b), (c) and (d), and (e) and (f) are 0.5, 1.2, and 3.0 $kV_{rms}\,cm^{-1}$, respectively; (a), (c), and (d) are low-magnification images and (b), (d), and (e) are high-magnification image obtained around center of electrode gap.

same potential as the cathode, at which an electric field is concentrated because of an antenna effect and a local electric field becomes stronger. Therefore, CNCs with a high aspect ratio near this structure are affected by Coulomb interaction and move toward the free end of this structure and stick to it. The repetition of this process at the free ends of several CNCs results in a treelike structure. This process occurs at a large extent when the density of carbon materials in the suspension is high.

From these results, it was revealed that the CNCs are positively charged in IPA and covered with negative ions, such as carboxyl ions, forming an electric-double-layer, which is very similar to the case for arc-discharged carbon nanotubes.[9] The thickness of the electric-double-layer named the Debye length $1/\kappa$ around colloidal CNCs was estimated to be $\sim$500 nm from the ion density in IPA measured from the conductivity of the suspension and the drift mobility of ions was assumed to be $2 \times 10^{-4}\,cm^2\,V^{-1}\,s^{-1}$.[9] The estimated Debye length of 500 nm is comparable to the coil diameters and much larger than the coil line diameters. In this case, the coil structure is screened by the electric-double-layer around the CNCs, so that the CNCs act as rods.

Figure 1(b) shows a SEM image of the CNCs near the cathode after the evaporation of IPA. The CNCs aggregate at the edge of the cathode electrode and do not align. The alignment of the CNCs in the suspension is distorted by surface tension and/or the convection of IPA during evaporation. With the DC and low frequency conditions under which the ions can move in response to the electric field, the CNCs function as rods in the suspension. In this case, the driving force for the alignment of the CNCs along the electric field is the anisotropy of the electrophoretic motion parallel or perpendicular to the movement direction in the fluid, as described in the nanotube case.[9] Therefore, fluidic perturbations, such as the movement of a meniscus on

a substrate and the convection of IPA, easily distort the alignment of CNCs.

Figure 2 shows a series of SEM images for the AC electric field dependence of the alignment of the CNCs at a frequency of 100 kHz. At a low electric field of 0.5 kV_{rms} cm^{-1}, no CNC alignment is observed after the evaporation of IPA, as shown in Figs. 2(a) and 2(b). In contrast, the alignment of the CNCs after the evaporation of IPA is clearly observed at a high electric field of 1.2 kV_{rms} cm^{-1}, as shown in Figs. 2(c) and 2(d). On the other hand, at the same electric field of 1.2 kV_{rms} cm^{-1}, the alignment of the CNCs is distorted after the evaporation of IPA in the case of DC electrophoresis shown in Fig. 1. The orientation degree of the CNCs along the electric field is improved at a high electric field of 3 kV_{rms} cm^{-1}, as shown in Figs. 2(e) and 2(f), even after the evaporation of IPA.

At a frequency higher than 1 kHz corresponding to that of dielectrophoresis, the CNCs form chains between the electrodes, resulting in a treelike structure along the electric field lines during dielectrophoresis, as previously described. At this frequency, the ion layer surrounding the CNCs cannot follow the alternation of electric field polarities and no screening effect is induced from the surrounding ion layers. Thus, an electrical dipole is induced on each CNC. The driving force for the alignment along the electric field is the dipole moment induced by the external AC electric field. This alignment mechanism based on the electrostatic attraction is different from the DC electrophoresis mechanism. This implies that the torque for the orientation of the CNCs induced by the dipole moment is stronger than the perturbation from the fluidic motion of the suspension. Thus, dielectrophoresis is more effective for the alignment of the CNCs than DC electrophoresis.

The movement of the CNCs at the AC electric field is induced by the nonuniform electric field in the suspension, as described in ref. 10. The electric field around the edge of the electrodes is higher than that around the electrode gap. As a result, the Coulomb force attracting the dipole is stronger for this higher electric field, whereby the dipole moves towards the site of this higher electric field. This induces the formation of the chain of CNCs.

In conclusion, the alignment of CNCs has been investigated by electrophoresis and dielectrophoresis. In the case of a DC electric field, most of the CNCs moved toward a cathode and formed a chain structure in a suspension. However, the alignment of the CNCs was observed to be distorted by the evaporation of the suspension. In contrast, in the case of an AC electric field with a frequency higher than 1 kHz, the CNCs were aligned along the electric field and connected to each other, and the alignment degree was improved at a high electric field. This implies that the potential energy of the induced dipole moment, which is the driving force of the alignment of the CNCs at the AC electric field, is larger than those of fluidic perturbations.

Acknowledgements

This work was supported by Osaka Prefecture Collaboration of Regional Entities for the Advancement of Technological Excellence, JST, and was partially supported by a Grant-in-Aid for Research from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

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