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Changes in Structure of Carbon Nanotube Yarn during Twisting

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1. Introduction

For the effective use of superior mechanical properties of carbon nanotubes (CNTs), they need to be assembled into a structure that provides effective stress transfer between CNTs. A candidate of such structure is the CNT yarn. In order to obtain the fundamental knowledge needed to develop optimum yarn structure, the changes in the structure of a CNT yarn during twisting have been investigated using small-angle X-ray scattering (SAXS). In this fiscal year, twist number has been extended to a wider range by decreasing the width of the starting CNT mat and a model analysis has also been made.

2. Experiment

A mat of single-walled CNTs with a diameter of 1.7 nm, cut into the size of 17 mm long by 1 mm wide was twisted at a constant length. SAXS measurements were carried out during twisting the CNT mat into a yarn until it broke. The twist angle of the CNT mat on the surface of the yarn and the yarn diameter were measured with an optical microscope.

3. Results and Discussion

A model analysis of the orientation distribution of CNTs was made based on the following assumptions: The CNTs were randomly oriented in the plane of the starting CNT mat before twisting. The CNT mat followed a helical pass after twisting. By twisting, the CNT mat was inclined from the yarn axis and simultaneously increased in length by the amount calculated from the measured yarn diameter and the twist number. The CNTs were inclined towards the longitudinal direction of the CNT mat without changing their length by the amount corresponding to the longitudinal deformation of the CNT mat.

The yarn diameter and the twist angle of the CNT mat on the yarn surface measured with an optical microscope and the Hermans orientation function determined by the SAXS measurements are shown in Fig.1(a) to (c). The twist angle of the CNT mat calculated from the yarn diameter and the twist number and the Hermans orientation function predicted by the model analysis are shown in Fig.1(b) and (c). The Hermans orientation function is defined as $(3\langle\cos^2\varphi\rangle - 1)/2$ where φ is the angle between the CNT axis and the yarn axis and $\langle\ \rangle$ stands for taking the average. The Hermans orientation function is 0 for the random orientation, 1 for the perfect orientation in parallel to the yarn axis and -1/2 for the perfect orientation perpendicular to the yarn axis.

At the beginning of twisting, the measured twist angle was close to the predicted value. At the twist angles exceeding about 30°, however, the measured twist angle was smaller than the predicted value. The difference between the measured and calculated values relates to the yarn structure. The scanning electron microscope (SEM) images shown in Fig.2 indicate that the twisted yarn forms a twist structure in which the twisted CNT mat follows a helical path. This structure allows for the smaller twist angle as compared with the value predicted

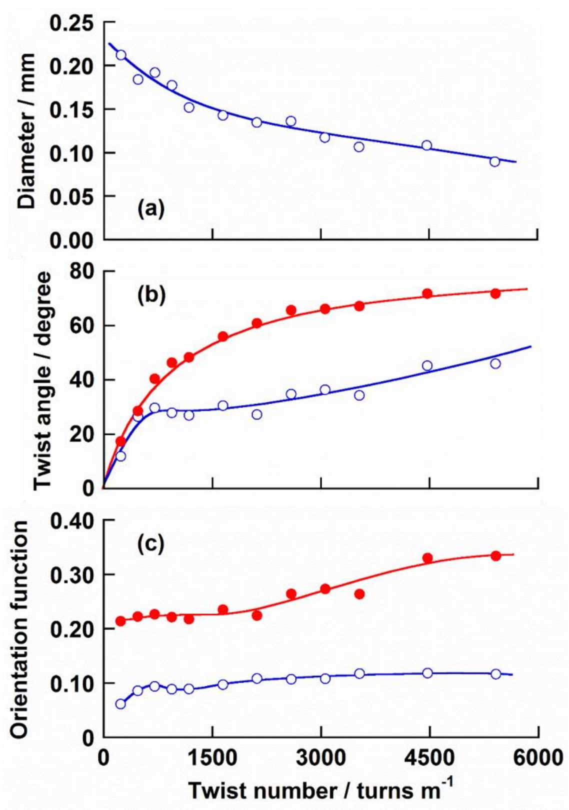

Fig.1 (○) Measured and (●) predicted values of (a) yarn diameter, (b) twist angle of CNT mat on yarn surface and (c) Hermans orientation function of CNTs versus twist number.

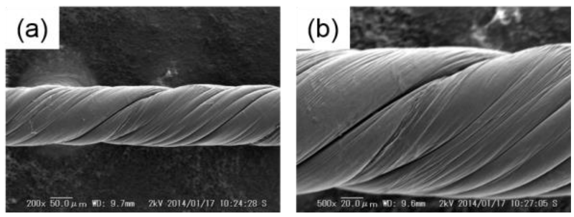

Fig.2 SEM images of twisted CNT yarn at twist number of 3059 turns m^{-1} observed at magnifications of (a) 200× and (b) 500×.

by a simple helical structure.

In Fig.1(c), the measured value of the Hermans orientation function was smaller than the predicted value. It is suggested that CNTs were not completely in parallel to the plane of the starting CNT mat before twisting.

In conclusion, the twisted yarn assumed a twist structure in which the twisted CNT mat followed a helical path at the twist angles exceeding about 30°. The measured value of the orientation function was smaller than the value predicted by assuming that the CNTs were in parallel to the plane of the starting CNT mat before twisting.

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