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Development of Twist Structure during Dry Spinning of Carbon Nanotubes

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1. Introduction

For the practical application of carbon nanotubes (CNTs), it is required to organize CNTs into the assembled structure that provides effective stress transfer between CNTs. This study has focused on a twisted CNT yarn and the development of yarn structure during dry spinning of the yarn has been studied with small-angle X-ray scattering (SAXS).

2. Experiment

A mat of single-walled CNTs with a diameter of 1.7 nm was cut into a rectangle 3 mm wide and 17 mm long and twisted into a yarn at a constant length by applying a slight tension for removing sagging. The inclination angles, α, of the CNTs at the surface of the yarn calculated based on $\tan \alpha = \pi DT$ from the yarn diameter, D, and the twist number, T, were 31.6° and 48.6° at T = 588 and 941 turns m^{-1}, respectively. During the twisting of the yarn, SAXS measurements were carried out until the yarn broke.

3. Results and Discussion

When the CNT yarn is twisted, CNTs tend to incline from the yarn axis and a tensile stress arises under the condition of constant yarn length. Simultaneously, the yarn diameter decreases so that the length of the helix along which CNTs lie is kept constant. As shown in Fig. 1, the yarn diameter decreases with twisting up to the twist number of about 600 turns m^{-1}, while it is almost unchanged with higher twisting. It is considered that slippage between CNTs or bundles of CNTs takes place with higher twisting. Under the condition of constant yarn length, the decrease in the yarn diameter represents the densification of the yarn which contributes to enhancing stress transfer between CNTs.

Fig. 2 shows azimuthal SAXS intensity distributions of the CNT yarn at various twist numbers. The increase in the scattering intensity with twisting except for near break is caused by the densification of the yarn. Fig. 3 shows the Hermans orientation function, f, determined from the intensity distributions shown in Fig. 2. The Hermans orientation function is defined as $f = (3\langle\cos^2\varphi\rangle - 1)/2$ where φ is the angle between the CNT axes and the yarn axis and < > stands for taking the average. It is found that the orientation function takes a maximum at the twist number of about 600 turns m^{-1}. It is considered that although the decrease in the orientation function is caused by the inclination of CNTs with twisting, the tensile stress straighten undulating CNTs at the early stages of twisting.

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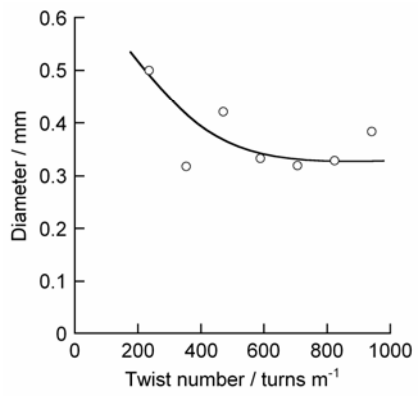

Fig. 1 Diameter of CNT yarn versus twist number.

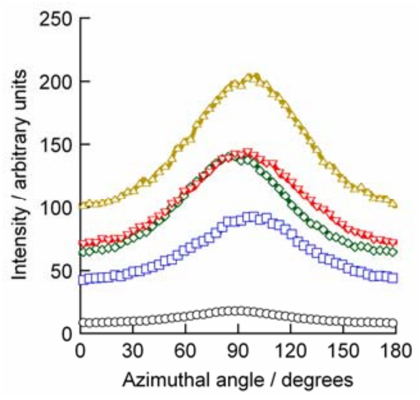

Fig. 2 Azimuthal SAXS intensity distributions of CNT yarn at twist numbers (○) 0, (□) 235, (◇) 471, (△) 706 and (▽) 941 turns m^{-1}.

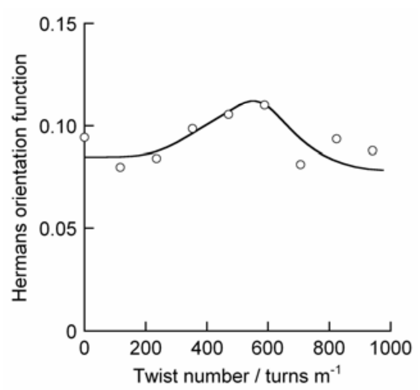

Fig. 3 Hermans orientation function of CNT yarn versus twist number.