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High friction of a vertically aligned carbon-nanotube film in microtribology

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The frictional behavior of a vertically aligned carbon-nanotube (VACNT) film against gold tips was studied in air. In these experiments, the film was 6 μm thick, the tip radii 4.5–30 μm, the applied forces smaller than 5 μN, and speeds were 0.15–24 μm/s. In spite of the null adhesion force to the gold tip, extremely high friction coefficients of 1.0–2.2 were found for the VACNT film. No dependence of friction on speed or tip radius was observed. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1804254]

We have investigated the microtribological properties of forestlike vertically aligned carbon-nanotube (VACNT) films with a thickness of 6 μm. Gold tips were used as a counter surface. The relationship between applied and friction forces of the VACNT film in air was investigated. A model of the friction of VACNT film is discussed on the basis of *in situ* tribological experiments inside a scanning electron microscope (SEM).

A microtribometer was equipped with a cantilevered probe and an optical lever system to measure adhesion and friction forces. Probe tips were glued on aluminum cantilevers. A VACNT film was prepared by microwave plasma-enhanced chemical vapor deposition (CVD) on Si(100), whose surface was thermally oxidized. Details on the deposition method and film characterization have been described elsewhere.[1] SEM observations revealed that the thickness of the VACNT film was approximately 6 μm. Multiwalled carbon nanotubes grew on the silicon, with diameters determined to be approximately 20 nm by transmission electron microscopy (TEM). Gold tips with apex radii of 4.5, 20, 28, and 30 μm were prepared by electrochemical etching, and then cleaned in ethanol for 5 min. Measurements of friction forces and force-displacement curves of the VACNT film were carried out in air at a relative humidity of less than 30% with applied forces of less than 5 μN. Friction experiments were carried out in reciprocating sliding configurations at speeds from 0.15 to 24 μm/s. In addition to carrying out experiments in air, *in situ* tribological experiments inside a SEM were performed to observe contact regions between the gold tips and the VACNT film during frictions.

Figure 1 shows a typical force-displacement curve of the VACNT film. No force-displacement curve obtained indicated any negative force, i.e., no adhesion force. Figure 2(a) shows the friction forces measured at three different applied forces with a sliding speed of 8 μm/s using the 28 μm radius tip. Smooth flat friction forces during forward and backward scans reveal that stick-slip motion did not take place. The average friction force versus applied force is shown in Fig. 2(b), obtained under the same sliding conditions as in Fig. 2(a). The friction force was found to be proportional to the applied force; a high friction coefficient of 1.7 was calculated from this linear relationship. Figure 2(c) shows the friction force at scan speeds of 0.15–24 μm/s at an applied force of 1.9 μN; it can be seen that the friction force did not depend on the scan speed. Measurements of friction coefficients of the VACNT film, calculated by the linear relationship between applied and friction forces, were conducted using four gold tips with different radii. The results are shown in Fig. 2(d). The friction coefficients ranged from 1.0 to 2.2; the scatter of the friction coefficient is so high that little dependence of friction on the tip radius can be recognized.

As shown above, the friction properties of the VACNT film satisfies the Amontons-Coulomb friction law, except for extremely high friction. It is well understood that extremely high friction coefficients result from friction between two clean metal surfaces in a vacuum environment due primarily to the high adhesion force. The VACNT film showed no notable adhesion. Carbon nanotubes are formed by graphene sheets (*sp*^{2} networked carbon atoms layer). While graphite also consists of graphene sheets, in air it shows low friction.[2] It has been reported that in spite of the high stiffness of carbon nanotubes (having a Young's modulus of more than 1 TPa), they can be elastically deformed under large lateral displacement.[3–5] As determined by *in situ* SEM (not shown), no wear tracks were formed on the contact region of the VACNT film after friction experiments. These facts imply that the elastic deformation was concentrated at the contact regions during the frictional process. In other words, the carbon nanotubes of the VACNT film should deform elastically to maintain sliding.

Ni and Sinnott have studied the tribological properties of carbon nanotube bundles using classical molecular dynamic

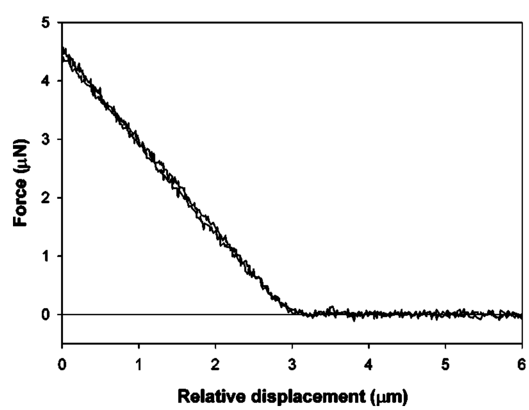

FIG. 1. Typical force-displacement curve of a CNT film. Note that the adhesion force is zero.

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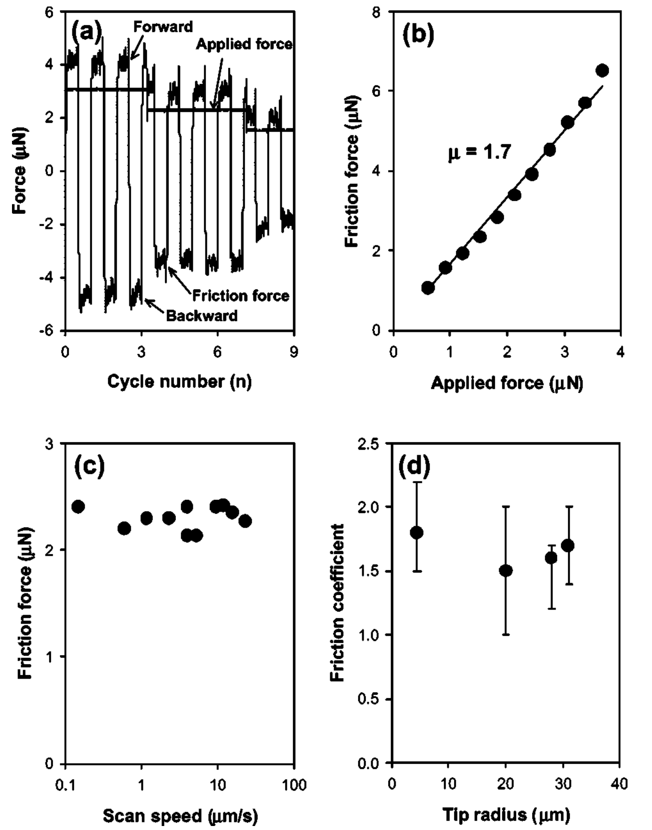

FIG. 2. Friction data of a VACNT film. (a) Friction force at three different applied forces. (b) Typical friction force as a function of applied force. (c) Friction force as a function of scan speed. (d) Friction coefficients as a function of tip radius.

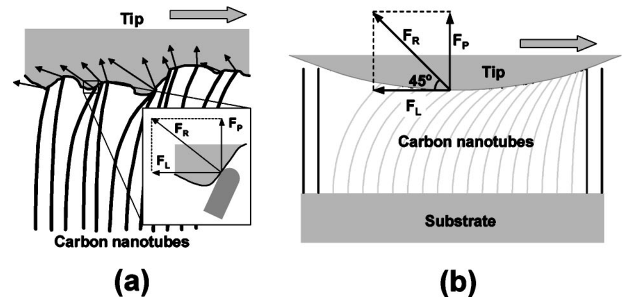

FIG. 3. Model showing the mechanics of friction observed on a VACNT film. (a) Possible configuration of contacts between each carbon nanotube and the tip surface, and (b) a simplified model for calculating friction force.

simulations.[6] In one of their simulations, the carbon nanotube bundle consists of six vertically aligned single-walled nanotubes with a length of 2.5 nm, which are covalently attached to a hydrogen-terminated diamond surface. The other ends of the nanotubes have caps, on which another hydrogen-terminated diamond surface slides. The model of this simulation seems to be similar to our experiments. However, the length and number of carbon nanotubes in the simulation are entirely different from those in our experiments. Wong *et al.* experimentally showed that the bending force of individual carbon nanotubes almost follows beam theory.[4] Qui *et al.* reported that the penetration resistance of VACNT films in indentation measurements is due to the continuous bending of carbon nanotubes; their model considering beam theory and VACNT's geometry obeys the force-penetration depth curves.[5] We propose a model of VACNT film friction, in which carbon nanotubes are assumed as the cantilever beam, and that bending of the carbon nanotubes follows beam theory. Figure 3 depicts the model as a tip moves on the surface of a VACNT film. To let the tip move horizontally while keeping an applied force, the tip must continuously push carbon nanotubes. At this moment, the tip receives high repulsive forces F_R due to the bending of the carbon nanotubes. Each repulsive force can be resolved into a lateral force F_L and a perpendicular force F_P, with respect to the horizontal line. Figure 3(a) shows contacts between the sharp-pointed ends of the carbon nanotubes and a tip surface, which is rough on a microscopic scale. Some high carbon nanotubes experience large bends, with smaller bends exhibited by lower carbon nanotubes. As shown in Fig. 3(a), the directions of the repulsive forces depend on the locations where the ends of the carbon nanotubes contact the tip surface. The sum of these repulsive forces determines the direction of the complete repulsive forces of the carbon nanotubes. To explain the extremely high friction coefficient, the direction of the sum of the repulsive forces should be less than 45° with respect to the horizontal line. It is likely that the ends of the carbon nanotubes stick easily at steep regions on the tip surface, leading to repulsive forces in low-angle directions. The friction force of a VACNT film is computed by the sum of the repulsive forces under conditions of a carbon nanotube radius of 10 nm, length of 6 μm, area density of 300 nanotubes/μm^2, Young's modulus of 1.2 TPa,[3–5] repulsive force directions of 45° with respect to the horizontal line, tip radius of 20 μm, and an applied force of 2.1 μN. A schematic of the computed result is shown in Fig. 3(b), where the carbon nanotube lengths and the tip radius are shown at the same magnification, and the density of the carbon nanotubes is thinned to make individual carbon nanotubes visible. The computed result gives a friction force of 2.1 μN and an indentation depth of 1.0 μm. The tip does not make contact with the substrate, since the high flexibility and stiffness of the carbon nanotubes and their high density can sustain the tip at this applied force. This simple model of friction can also explain the linear relationship between the applied and friction forces and the observation that the friction coefficient has little dependence of the tip radii.

In summary, we have found high friction coefficients for VACNT films, which did not depend on the scan speeds and the tip apex radii, in spite of there being a null adhesion force. These friction behaviors obey the Amontons-Coulomb friction law. A simple model of friction processes between the VACNT film and the tip showed that low-angle directions of repulsive forces due to the bending of carbon nanotubes are necessary to explain the extremely high friction coefficients.

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