Reducing the High Frictions on Carbon Nanotube Films by Applying an Oscillating Motion under Micronewton Loads

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Under micronewton loads, the high frictions on carbon nanotube (CNT) films (with a friction coefficient of 1.7) were decreased to less than the noise level (which was roughly a friction coefficient of 0.05) by applying an oscillating motion to a cantilever on which a sliding ball was glued. This large decrease of the friction coefficient has been never observed in previous studies. The applied oscillating motion caused the twisting and bending oscillations of the cantilever, which applied the lateral and normal oscillating forces to the sliding ball. The friction force decreased with increasing the oscillating amplitudes of the twisting and bending forces, and the frequency dependences of the friction force reduction was observed.

Keywords: microtribology, carbon nanotube films, oscillating motion, reducing friction

1. Introduction

MEMS (micro-electromechanical systems) devices experience significant problems with high adhesion forces. The presences of capillary forces (due to the adsorption of water between two contacting surfaces) and van der Waals forces lead to high adhesion forces, and the high surface-to-volume ratios of MEMS devices means that these high adhesion forces can have a significant negative influence [1]. In MEMS devices, the high adhesion forces cause sticktions and high friction forces. Although highly hydrophobic coatings such as fluorine coatings have been introduced in attempts to reduce the high adhesion forces produced by water adsorption, these coatings do not work against van der Waals forces [2]. Reducing the friction levels in MEMS devices is also difficult, because conventional friction-reduction methods such as lubricants increase the viscosity and the adhesion forces between contacting surfaces. Therefore, MEMS bearing and gear devices—in which surfaces contact with each other—do not function well. Another method for the reduction of friction forces applies oscillations of motions or normal loads between two sliding surfaces, which has been widely applied with various normal load ranges, from nanonewtons to newtons [3-6]. Although this method is not used in conventional sized machines (in non-micro-scale machines), it could be appropriate for use in MEMS devices with moving parts (described

here as moving MEMS devices). In fact, friction reducing effects produced by vibration normal load have been observed in a MEMS device [3].

Although low friction forces are desirable in moving MEMS devices, high friction forces are also necessary, to allow the motion in these devices to be stopped. We previously reported that under micronewton loads, carbon nanotube (CNT) films showed steady high friction (with a friction coefficient μ of more than 1) with no obvious stick-slip motion, even in high humidity [7]. In addition to the presence of high friction forces, no adhesion force on CNT films is observed using tips with curved surfaces; although the adhesion force of individual CNT is not low [8], no adhesion force arises from similar to the point-by-point peel-off detachments [9] from the edges of the contact point when used the curved tips. The high friction and low adhesion force are good for the high-friction MEMS materials used in brakes, and on the surfaces of manipulator grips. If the high frictions on CNT films could be reduced to be very low frictions using oscillating motions, this would mean that CNT films would be a material in which the level of friction could be controlled from very high to very low, in the presence of very low adhesion forces; this would be beneficial for contact surface materials in moving MEMS devices.

In this study, reducing the high frictions on a CNT film by applying an oscillating motion to a cantilever with a sliding ball was measured under micronewton

loads. The oscillation amplitude and frequency dependences of the decrease of the friction force were investigated.

2. Experiments

The formation of a CNT film on a silicon oxide film substrate was achieved using thermal chemical vapor deposition (CVD). A Fe layer with a thickness of 4 nm was deposited on the substrate, and Fe nanoparticles were formed using an annealing treatment (performed at 750°C in a 30 Pa H₂ flow, for 40 min). The CVD process for the formation of the CNT film was carried out with a gas mixture of C₂H₂ and H₂, at a substrate temperature of 750°C, for 20 min, and at a pressure of 300 Pa. A CNT film consisting of multi-walled CNTs, which were vertically aligned on the substrate, was produced, and it had a thickness of approximately 80 µm.

A schematic illustration of the microtribometer used in this study is shown Figure 1. The microtribometer was equipped with a cantilever and an optical lever system, with a laser diode and a quadrant photodetector to measure lateral and normal forces; this was similar to the setup for conventional atomic force microscopy (AFM). The twisting and bending of the cantilever (produced by lateral forces and normal force) caused the laser focus point displacements in the horizontal and vertical directions on the quadrant photodetector. The signals of the quadrant photodetector went to an I-V conversion amplifier (cut-off frequency: 15 kHz), and then to both a A/D converter in a personal computer (PC)(sampling frequency: 2.5 kHz) and a digital oscilloscope (sampling frequency: 100 MHz). Although the sampling frequencies of the two methods were quite different, the signals of the two methods were almost identical. The signals obtained by the A/D converter were used to control normal load, and obtained with synchronizing a reciprocating motion and applied oscillation signals in order to make analysis easily. The data shown in this article were used by stored signals in the PC with the A/D converter. The cantilever (2 mm width, 15 mm long, and 0.05 mm thick) was larger than conventional AFM cantilevers; this allowed micronewton forces to be

measured. Calibrations of the measured lateral force and the measured normal force were carried out using aluminum wire weights with a diameter of 0.05 mm, and lengths of 10-80 mm. An SUJ2 ball with a radius of 1 mm was glued on one side of the cantilever, and slid on the CNT film surface. The CNT film sample was moved in reciprocating and vertical motions to create friction, and to keep normal loads constant, respectively by an XYZ piezoelectric stage. The other side of the cantilever was attached to a piezoelectric actuator, which provided a vertical oscillating motion. The sliding speed was 90 µm/s, with a reciprocating length of 90 µm. A normal load was 40 µN. The applied oscillating motion to the cantilever had an amplitude of ~0.8 µm and a frequency range of 0~2100 Hz. The sliding ball was cleaned in acetone for 5 min, ethanol for 5 min, and water for 5 min, and finally dried. Frictional experiments were carried out under ambient laboratory conditions at a relative humidity of less than 30%, and a temperature of 23°C.

The friction force was high under initial sliding; after more than a hundred cycles, it decreased and reached a steady state value. The wear track produced by the sliding was clearly observed using scanning electron microscopy (SEM) [10,11]. Only the topmost surface of the CNT film was plastically deformed and compressed to flat planes, and the inside of the CNT film seems not to be damaged. The initial high friction forces arose from the plastic deformation of CNTs in the CNT film. The frictional data in this study were collected after the steady-state friction was reached.

3. Results and discussion

Figure 2 shows typical lateral and normal forces collected by varying the applied oscillation amplitude to the cantilever at a frequency of 1140 Hz. The raw normal force (dark gray) is plotted in the upper graph. The raw lateral force (black) and its average (light gray) are shown in the middle graph. The average lateral forces were calculated by averaging the raw lateral forces during the previous and next 0.05 s. The lower graph shows the applied oscillation amplitude to the cantilever, which increased gradually, increasing by 0.08 µm, until the amplitude of 0.8 µm was reached. Because of the reciprocating motion for friction, friction forces were estimated from $((\text{backward lateral force}, F_b) - (\text{forward lateral force}, F_f))/2$. Namely when a difference between F_b and F_f was large, a friction force was high; in contrast, a friction force was low as the difference was small. A high level of a friction force ($\mu = 1.7$) was observed in the absence of the applied oscillating motion. This high friction force dropped dramatically in magnitude when the applied oscillating motion was switched on, and decreased to lower than the noise level (roughly $\mu = 0.05$) at the applied oscillation amplitude of 0.8 µm. The increase in the applied oscillation amplitude to the cantilever led to a decrease of the friction force. After the oscillation was switched off, the friction force

Fig. 1 Schematic illustration of the tribometer used in this study.

Fig. 2 Typical lateral and normal force data with the variation of the applied oscillation amplitude to the cantilever at a frequency of 1140 Hz. The upper graph shows the raw normal force, the middle graph does the raw lateral load and its average, and the lower graph does the applied oscillation amplitude.

Fig. 3 Illustration diagrams in various cases as measuring the lateral and normal (oscillating) forces. (a) Only the normal load was applied, (b) the normal oscillating force was applied with keeping the normal load, (c) CNT film slid to the left without the oscillation, and (d) the lateral oscillating force was applied with sliding the CNT film.

returned to its previous high level. The very low and very high friction states were fully reversible, and occurred as the oscillating motion was switched on and off.

Under the applied oscillating motion, the measured raw lateral and normal forces were oscillated, which came from twisting and bending oscillations of the cantilever. Since the cantilever was very soft, the vertical applied oscillating motion to the cantilever led to both the bending oscillation and the twisting oscillation. The oscillations of the twisting and bending of the cantilever applied the lateral and normal oscillating forces to the sliding ball. When the amplitude of the applied oscillating motion was 0.8 μm in Fig. 2, the amplitude in the lateral oscillating force was 35 μN (the half of the oscillation width), and the amplitude in the normal oscillating force was 6.5 μN (the half of the oscillation width).

Figure 3 shows the illustration diagrams in cases when the lateral and normal forces, and oscillating forces, were measured. Fig. 3(a) shows the case as applying the normal load without any applied oscillation, in which the cantilever was bended by which the XYZ piezoelectric stage pushed the CNT film. The focal point of the laser light was shifted down according to the normal load. Fig. 3(b) shows the case as applying the normal oscillating force with keeping the normal load, in which the focal point was oscillated around the point according to the normal load. In the vertical direction the sliding ball was applied both the normal load and the bending oscillation force. In Fig. 2, the measured raw normal force had no minus values with the applied oscillation, indicating that the sliding ball consistently contacted with the CNT film surface. Fig. 3(c) shows the case when CNT film slid to the left by the XYZ piezoelectric stage without any twisting oscillation. In the case a friction force increased the twisting angle of the cantilever, and the laser light was shifted to the right according to the friction force. Fig. 3(d) shows the case as CNT film slid to left with the applied twisting oscillation, in which the focal point was oscillated around the point according to the friction force. In the horizontal direction the sliding ball was applied the friction force and the twisting oscillating force. When the friction force was almost zero shown in Fig. 2 (at the applied oscillation amplitude of 0.8 μm), the focal point was oscillated around the neutral position. Without applying the oscillating motion, the friction force was mainly affected by the normal load. Under the applied oscillating motion, in addition to the normal load, the normal oscillating force and lateral oscillating force would influence the friction force.

The friction force (the upper graph) and the oscillation amplitudes in the lateral and normal forces (the lower graph) are shown in Figure 4, as a function of the applied oscillating frequency, with the applied oscillation amplitude to the cantilever of 0.16 μm. The friction force decreased around particular oscillation frequencies (including 630, 900, 1150, 1530, and 1900 Hz); when this occurred, the amplitudes of the oscillating

Fig. 4 The friction force (the upper graph), and the amplitudes of the lateral and normal oscillating forces (the lower graph), as a function of the frequency of the applied oscillating motion, with the applied oscillation amplitude of 0.16 μm .

forces became large. Especially around 1530 kHz, the amplitude of the lateral oscillating force became huge (the maximum value was 192 μN). Thus the scale of the horizontal axis in the lower graph is ranged from 0 to 30 μN . These particular oscillation frequencies were the mechanical resonance frequencies of the cantilever, thus the twisting and bending oscillations of the cantilever were significantly increased. It is very likely that the decrease in the friction force arose from the increases in the oscillation amplitudes of the lateral and normal oscillating forces.

Figure 5 illustrates the relationships between the amplitudes of the lateral and normal oscillating forces and the friction force (replotted from Figure 4). Black circles indicate the lateral oscillating forces and white circles show the normal oscillating forces. The friction force decreased with increasing the oscillating force amplitudes. The decreasing rate of the friction force in the normal oscillating force was much larger than that in the lateral oscillating force. In this study, since the oscillation amplitudes of the twisting and bending of the cantilever were not separated, it is unknown which oscillations were most important for the decrease of the friction forces. Lines in the figures indicate each

Fig. 5 The relationships between the amplitudes of the lateral and normal oscillating forces and the friction force. Black circles show the lateral oscillating force, and white circles show the normal oscillating force. This graph is replotted from Figure 4. Lines indicate each frequency range and arrows show the increasing direction of the frequency.

frequency range and the arrows show the increasing direction of the frequency. As shown in Fig. 5, there was a frequency dependence of the decreasing friction force in the lateral oscillating force, i.e., in the same lateral oscillating force the friction forces obtained at different frequencies were not identified. In magnified view the frequency dependence of the normal oscillating force was also observed. The tendencies of the frequency dependences were not ordered and complicated.

The samples used in the previous studies about friction reducing by oscillations [3-6] were conventional solid materials. CNT film has fibrous structure. Although their structures are very different, friction reduction effects by oscillation were observed in the materials. In CNT film, there would be particular mechanism of friction reduction by oscillation. We previously proposed a model for the high frictions on CNT films [12]. In the model, during friction, since the sharp-pointed ends of the CNTs stick on the rough surface of a sliding tip, the CNTs are bent until these sticktions are broken. The sliding tip therefore experiences highly repulsive forces, because of the high bending force of CNTs—i.e., a high friction is experienced. Specifically, the sticktions and the high bending forces of CNTs may result in high levels of friction. It has been reported for nanometer-sized contacts that the atomic stick-slip motions (that lead to friction) disappear under the perpendicular oscillating motion [4]. In this study, it is likely that the oscillating forces made the removal of the sticking CNTs easier, which led to the observed reductions in the friction force.

4. Summary

In this study, the high friction sliding ($\mu = 1.7$) dropped to lower than the noise level (roughly $\mu = 0.05$) by the applied oscillating motion. Such large friction dropping has not been observed among other experiments using other materials and other applied load ranges. The increase in the applied oscillation amplitude to the cantilever and the mechanical resonance frequencies increased the oscillation amplitude of the lateral and normal oscillating forces applying to the sliding ball, which led to the friction force reductions. The frequency dependence of the friction force reductions was also measured.

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