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나노스케일과 마이크로스케일 사이에서 Mica의 접착 및 마찰 거동

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Adhesive and frictional behaviors of Mica between nanoscale and microscale

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ABSTRACT

The size effects for adhesive and frictional characteristics were studied. The specimen was Mica and the AFM tips were SiO2. The radii of SiO2 tip were 280, 380, 930, and 2230 nm on which tribological tests had never been performed. It was found that the adhesive forces and the frictional coefficients increased non-linearly with tip radius. Compared with previous studies at nanoscale and microscale, the results showed behaviors bridging each previous result. It could be said that these results were clues to explain the material behaviors between nanoscale and microscale both in adhesion and friction.

Key Words : Adhesion(점착력), friction(마찰력), Atomic Force Microscopy(원자현미경), Contact Area(접촉면적)

1. Introduction

The study of adhesion, friction, and wear between interacting surfaces in relative motion, described today as the field of tribology, has been a ripe area of study for centuries. Particularly, the relationships that friction force is proportional to the normal force and independent of the contact area at macroscale, first postulated by Bowden & Tabor (1950) [1], are the cornerstone of most current friction theories [2-4]. Recent technological advances in experimental instrumentation, in particular the development of the atomic force microscope (AFM) [5-8] and the surface force apparatus (SFA) [9-12], have made it possible to measure, for the first time, adhesive and frictional properties of interacting surfaces at the atomic and molecular levels. Many researchers including Kim [13], Bhushan [14], Carpick [15-16], and Yoon [17] found that the contact area affects tribological properties at nanoscale and microscale [18-20].

On the other hand, adhesive and frictional behaviors have hardly been examined experimentally between nanoscale and microscale. From previous studies, it could be seen that those behaviors show very different characteristics at each scale. As nanosystems or microsystems assembled with elements of various sizes are considered, it is necessary to examine experimentally for adhesive and frictional behaviors between nanoscale and microscale to predict or evaluate the stability, durability, and reliability of these systems. Accordingly, in this article, the size effects on adhesion and friction were investigated by using SiO2 tips with radii ranging from 280 to 2230 nm between nanoscale and microscale. The results were compared with previous sources [13-14, 17].

2. Theoretical Background

There have been a number of continuum models of contact mechanics developed to describe the elastic contact between two bodies, the pioneering work being done by Hertz. Among these models, the Hertzian model [21] did not take into account attractive forces between the contacting surfaces, and Johnson-Kendall-Roberts (JKR) model [22] which took surface forces into account had the weak point to ignore the forces acting just outside the edge of the contact circle. To account for the shortcomings of the Hertz and JKR models, Derjaguin and cowokers [23] developed an alternative theory, known as the DMT theory. According to the DMT theory, the attractive force between the surfaces has a finite range and acts outside the contact zone, where the surface shape is assumed to be Hertzian and not deformed by the effect of the interfacial forces. In this case, the contact radius, a and the adhesive force, Ps are given by following:

$$a^3 = \frac{(P+P_s)R}{K} \qquad (1)$$

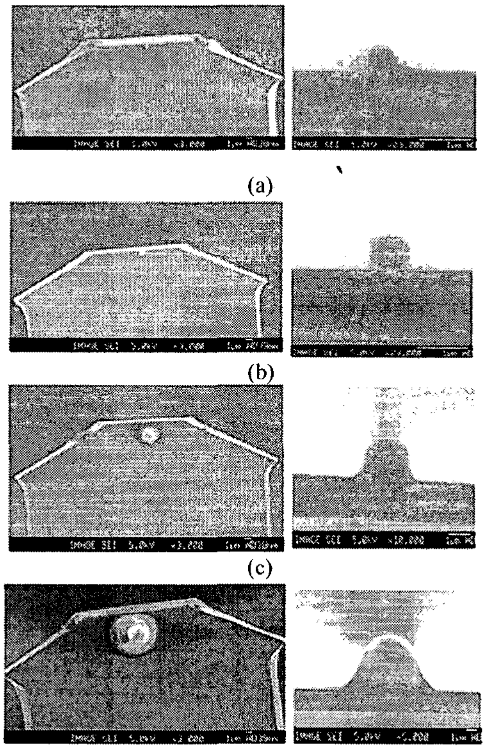
$$P_s = -2\pi R\gamma \qquad (2)$$

where P is the applied normal load. R is the reduced radius, K is the reduced stiffness, and γ is the surface energy. When radii of two spheres are R1 and R2, Young뭘moduli are E1 and E2, and Poisson뭘 ratios are ν1 and ν2, the reduced radius and the reduced stiffness are defined by

$$\frac{1}{K} = \frac{3}{4}\left[\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right] \qquad (3)$$

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \qquad (4)$$

It is generally agreed that for a hard solid of low surface energy and small radius of curvature the DMT theory would be appropriate, while the JKR theory would be more accurate for soft materials with relatively high surface energy and large radius of curvature. In this study, because specimen is hard solid and the tip size is small, the contact radius will be calculated by DMT theory.



(a)

(b)

(c)

(d)

Fig. 1 SEM images of four kinds of nanospheres mounted at the end of rectangular cantilever beams. The radii of the sphere are (a) 280, (b) 380, (c) 930, and (d) 2230 nm.

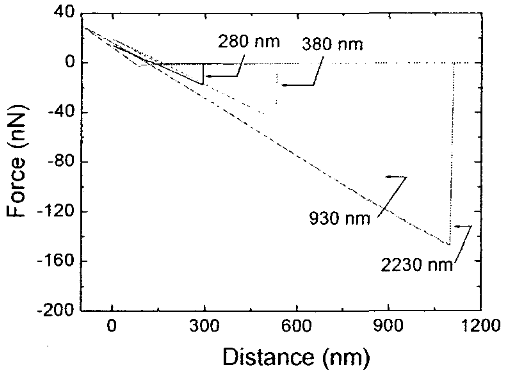


Fig. 2 Force distance curves for each tip radius

3. Materials and Experiments

Adhesion and friction tests were conducted with a commercial AFM (Seiko, SPA 400). The specimen was Mica and the AFM tip was SiO_2 fabricated by Novascan company. Fig. 1 shows scanning electron microscopic (SEM) images of four kinds of the nanosphere mounted at the end of a rectangular cantilever beam with bending stiffness of 0.65 N/m which was provided from a manufacturer. The radii of the sphere were 280, 380, 930, and 2230 nm as measured by SEM images. Temperature and humidity were controlled to 23 ± 2 °C and 40 ± 3 % relative humidity.

Adhesive force measurements were conducted in the 뱋orce curve canvas mode? The horizontal distance in the curve, z_{max} is used for calculating the adhesive force by Eq. (5).

$$P_s = k_z z_{\max} \qquad (5)$$

where k_z is the bending stiffness of the cantilever.

Frictional coefficients were obtained from the slope of frictional forces measured as a function of normal force ranging from 1 to 110 nN. In AFM, the specimens were moved orthogonal to the cantilever axis to obtain frictional forces. The frictional distance was then 5 μm and the test speed was 1 Hz (10 μm/s).

4. Results and Analysis

Fig. 2 shows the force distance curves for each tip radius. The horizontal distance, z_{max} which is used to calculate the adhesive force increased with the tip radius. In Fig.3, it was seen that the adhesive forces increased non-linearly with tip radius. Each data point is an average of thirty different measurements. The results could be said to show the behaviors bridging Yoon뭘[17] and Bhushan뭘

[14] results because Yoon뮐 results at nanoscale showed the adhesive forces increased linearly with tip radius, and Bhushan뮐 at microscale showed the forces were constant with tip radius. Therefore, as the tip radius changes from nanoscale to microsacle, it can be said that the adhesive force increase continuously, but the increasing tendency changes from linear to non-linear, and after all the force becomes constant with the tip size.

Fig. 4 is a plot of frictional force vs. normal force. It could be seen that the frictional force increased linearly with the normal force. The frictional forces for each tip radius were different when the normal force was zero because the adhesive forces were different according to each tip radius. Frictional coefficients could be obtained from these plots. Fig. 5 shows the variation in frictional coefficients as a function of tip radius. Each data point is an average of nine measurements on different spots on the sample. It could be seen that the coefficients were not varied for small two tip sizes in agreement with reported AFM frictional experiments, but increased for larger tip sizes. Though the friction force increases with tip radius at nanoscale, the frictional coefficients were not varied. The behavior for larger tips could be explained by the transition of frictional mechanisms according to the contact size. Fig. 6 shows the contact radius as a function of the tip size calculated by DMT theory. The contact radius were about 5 ~ 15 nm for small two tip sizes, and these were about 20 ~ 35 nm for large two tip sizes. Therefore, the contact area varies four times to ten times according to the tip sizes. The normal stresses on small tips are much larger than those on large tips under the same normal forces. Fig. 7 shows the normal stresses with normal forces at each contact size. The stresses for small two tips reached to 210 ~ 350 MPa enough for wear to happen, but the stresses for larger tips were small for wear to happen because the fracture strength of Mica is generally over 150 MPa. Of course, if the wear happens, the contact radius can not be calculated by DMT theory because the contact is no longer elastic contact. However, it is reasonable that the normal stress on the small tip sizes is enough for wear to happen. Unfortunately, the wear markers could not be seen after tests by the AFM tips with SiO_2 beads because the tip is too large to be used for analysis of the surface. Moreover, even if the tip is changed for analysis of the surface, or the surface is analyzed by SEM, wear markers could not be found because the worn positions could not be again found by AFM or SEM. However, the wear marks were seen easily if general AFM tips with a radius of about 10 nm were used because the surface could be analyzed well by the tips. The wear debris happened by small tips may make the interfacial surfaces between specimens and tips smooth such as a lubricant, and the frictional coefficients become then lower than those at large tips. Therefore, it can be said that the size effect for a frictional behavior comes from the transition of frictional mechanism by the contact size.

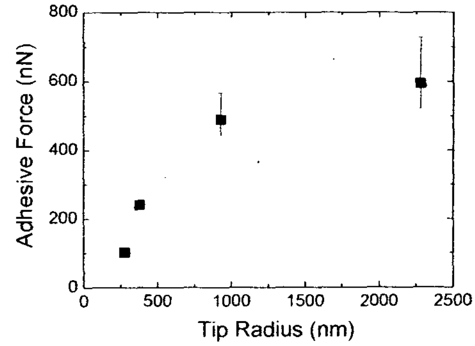


Fig. 3 Adhesive forces calculated by Eq. (8)

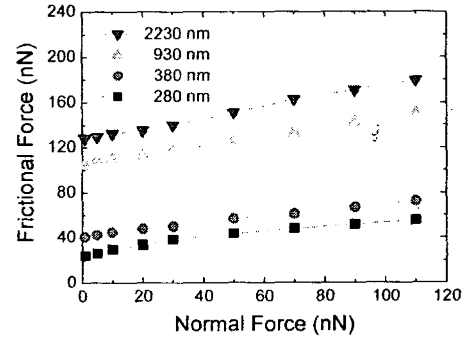


Fig. 4 Plot for calibrated frictional force vs. normal force.

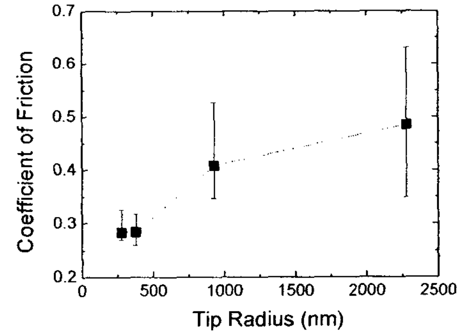


Fig. 5 Plot of coefficient of friction vs. tip radius.

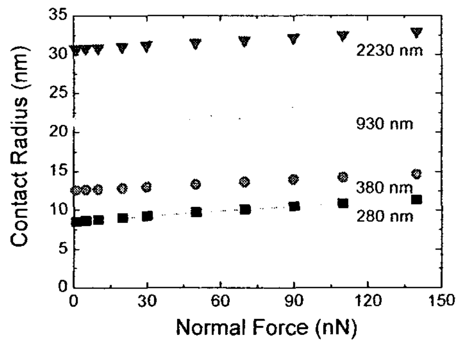


Fig. 6 Plot of the contact radii as a function of normal force as calculated by DMT theory

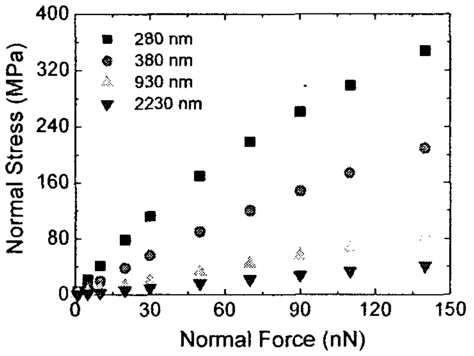


Fig. 7 Plot of normal stress vs. normal force

5. Conclusion

In this article, adhesive and frictional behaviors between nanoscale and microscale were uncovered on Mica. Adhesive results showed the bridging behavior, and frictional results could be explained by the transition of fictional mechanism according to the contact area. Therefore, it could be said that those results were clues to explain the material behaviors between nanoscale and microscale both in adhesion and friction.

Acknowledgement

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