ASIATRIB 2002International Conference
JEJU ISLAND, KOREA

Friction and Pull-off Forces on Submicron-Size Asperity Measured in High Vacuum

Y. Ando [1]

[1] *Institute of Mechanical Systems Engineering,*
National Institute of Advanced Industrial Science and Technology (AIST)
1-2 Namiki, Tsukuba, Ibaraki, 305-8564, JAPAN

Asperity arrays and Independent asperities were fabricated on a silicon plate. Then pull-off and friction forces were measured on each asperity pattern by using AFM (atomic force microscope) in humid air and high vacuum of 2×10^{-5} Pa. The probe of AFM cantilever has a flat square of about 1 μm^2 on its tip. The results showed that the pull-off force was proportional to the curvature radius of asperity peak in each ambient condition. The friction force was proportional to the pull-off force and was slightly higher in the humid air than in the high vacuum.

Keywords : Atomic Force Microscope, Capillary, Adhesion, Radius, Focused Ion Beam

1. INTRODUCTION

When the adhesion force is predominant for the friction force, the friction force can be controlled by adhesion force that can be changed by applying a suitable roughness to the surface. The author examined the relation between contacting geometry and the pull-off and friction forces by using hemispherical asperity and showed that the forces were proportional to the curvature radius of asperity peak and that the magnitude of pull-off force correspond to an attraction force caused by Laplace pressure in condensed water [1]. In these conditions, the pull-off and friction forces were affected by a relative humidity [2].

It is helpful to control the amount of condensed water for determining the effects of condensed water on the adhesion and friction forces. Because the amount of condensed water would be negligibly small in high vacuum, it may be possible to measure the pull-off and friction forces unaffected by condensed water. Furthermore, more quantitative analyses are expected to be possible by using a shape-controlled surface. In this report, we have measured the pull-off and friction forces on periodic asperity arrays and independent asperities in humid air and in vacuum of 10^{-5} Pa, and examined the effects of condensed water on adhesion and friction.

2. MEASUREMENT

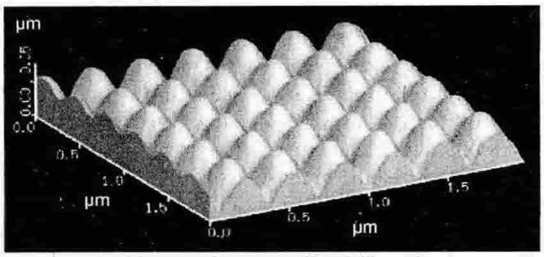
2.1 Preparing periodic asperity arrays

An FIB (focused ion beam) system was used to fabricate periodic asperity arrays on a single-crystal silicon plate. The FIB milled grooves on the specimen through a sputtering process. When multiple grooves of uniform spacing are milled in two perpendicular directions, "un-milled" parts remain, thereby forming a periodic asperity array. By changing the milling conditions, we fabricated some patterns. Each pattern had the different radius of curvature around the asperity peak (the peak curvature radius). An independent asperity was also made on the same plate. Figure 1 shows AFM images of the asperity array and independent asperity. The peak curvature radii R were calculated from the AFM measurement using a curve-fitting program and are shown in Table 1.

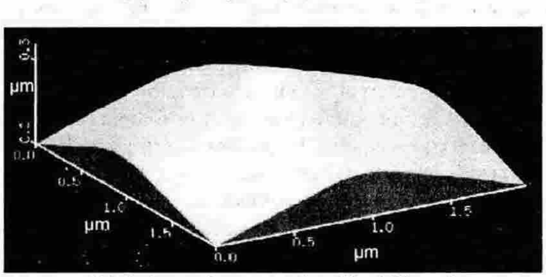
2.2 Measurement procedures

A commercially available AFM (atomic force microscope) was used to measure the pull-off and friction forces. In the AFM system, the sample, PZT scanner and cantilever were installed in a vacuum chamber. A turbo molecular pump and a rotary scroll pump were used to evacuate the chamber. The minimum pressure achieved in the chamber was 2×10^{-5} Pa.

When measuring the friction force, a raster scanning was made, and the friction force was calculated from the difference in torsion of cantilever in back and forth motion. A force curve mode was used to measure the pull-off force. The pull-off force was calculated by multiplying the spring constant of the cantilever by the displacement of the cantilever when the probe jumped off from the surface.



(a) Asperity array (R =140 nm)



(b) Independent asperity (R =130 nm)

Fig. 1 AFM images of asperity fabricated by FIB

Table 1 Peak curvature radii on asperity

Asperity array						
Radius, R	140	180	220	250	400	630
Standard deviation	6	10	20	20	50	80
Independent asperity						
Radius , R	130	220	230	430		

Unit: nm

Table 2 Measurement conditions

	Asperity array	Independent asperity
Si_3N_4 Cantilever	Spring constant: 0.75 N/m	
Sliding speed (μm/s)	4	2
Scanning area (μm^2)	2 x 2	0.5 x 0.5
External applied load (nN)	< 10	
Ambient condition	2-6 x 10^{-5}Pa, 29-32%RH	

The probe of AFM cantilever has a flat square of about 1 μm^2 on its tip. We used the flat probe to measure the pull-off and friction forces on each asperity pattern. The relation between the forces and the peak curvature radius of the asperity was examined for humid air and high vacuum. The conditions for measuring the forces are summarized in Table 2

3. RESULTS AND DISCUSSIONS

The pull-off forces measured on asperity array and independent asperity are plotted against the peak curvature radii, which is shown in Fig. 2. Each pull-off force shows the average of 10- to 20-times measurements and the error bars show the maximum and minimum pull-off forces. The average pull-off force increased with lager peak curvature radius of asperity array in Fig 2a. The gradient of the pull-off force decreased with lager radius because the peak of asperity array was mainly in contact with a corner of the flat probe square that has a radius. In Fig. 2b, the pull-off force was almost proportional to the peak curvature radius.

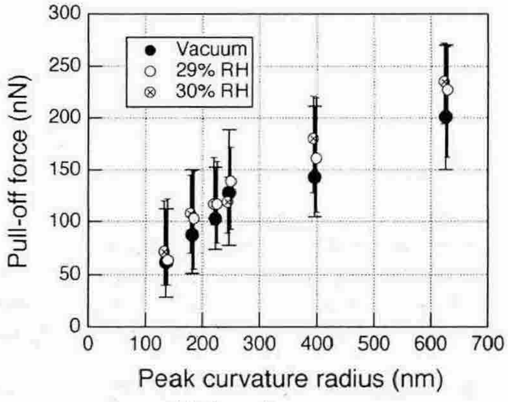
The size of a water capillary between two contacting surfaces decreases with lower relative humidity. In high vacuum, the capillary becomes negligibly small. If the Laplace pressure causes the adhesion force, the pull-off force is proportional to the radius of curvature around the contact area and would not be affected by the size of capillary. Therefore, the pull-off force is sensitive to the micro roughness or irregularity on the spherical surface in high vacuum. In Fig 2, the pull-off force measured in the high vacuum was lower than in the humid air, which is clearer on asperities having a larger peak curvature radius, because a small bump could affect the contact area more for the larger radius.

Figure 3 shows the relation between the friction force and the pull-off force measured on asperity array. The friction force was almost proportional to the pull-off force. The gradient of friction force against the pull-off force was slightly higher in the humid air than in the high vacuum.

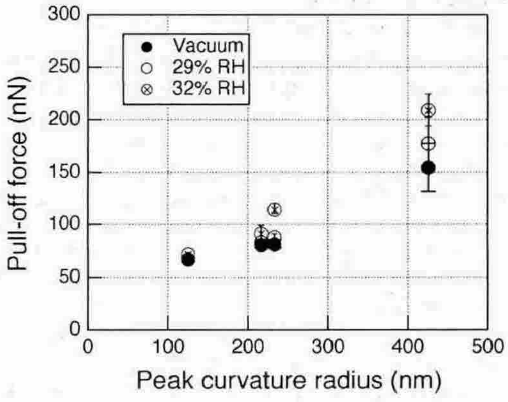
When the external load is negligibly lower than the adhesion force, the gradient of friction force against the pull-off force is equivalent to the friction coefficient. The "friction coefficient" was almost constant in Fig. 3, probably because sheering force in the real contact area was dominant in the friction force. There also likely existed a viscous resistance in a condensed capillary, which worked as a part of friction force. Therefore, the friction coefficient in the humid air was higher than the high vacuum and was still proportional to the peak curvature radius, because size of the capillary is also proportional to the radius.

5. CONCLUSION

The pull-off and friction forces were measured between a flat probe and hemispherical peaks of asperity array and independent asperity in the humid air and the high vacuum by using an AFM. The results showed that the pull-off force was almost proportional to the peak curvature radius of the asperity in each humid air and high vacuum and was slightly higher in the humid air than in the high vacuum. The friction force was proportional to the pull-off force. The gradient of the friction force that was equivalent to the friction coefficient was higher in the humid air than in the high vacuum.



(a) Asperity array



(b) Independent array

Fig. 2 Relation between pull-off force and the peak curvature radius measured on two kinds of asperity

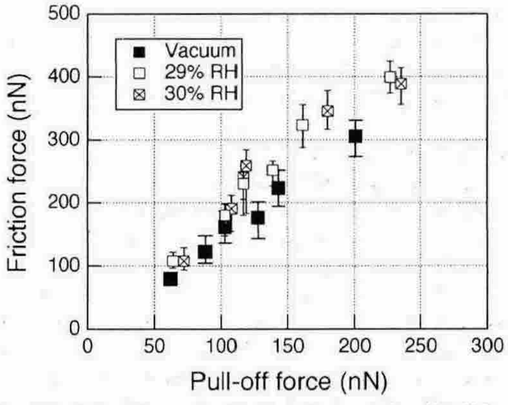


Fig. 3 Relation between friction force and pull-off force measured on asperity array

6. REFERENCES

[1] Ando, Y. and Ino J., "Friction and Pull-off Forces on Submicron-size Asperities Wear, Vol. 216, pp. 115-122, 1998.

[2] Ando, Y., "The Effect of Relative Humidity on Friction and Pull-off Forces Measured on Submicron-Size Asperity Arrays, Wear, Vol. 238 pp.12-19, 2000.