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Estimation of Surface Forces in Micro Rough Surface Contacts

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In a micro-scale contact, surface forces such as capillary force and van der Waals interaction significantly influence the contact between asperities of rough surfaces. Little is, however, known about the variation of these surface forces as a function of chemical property of the surface (hydrophilicity), relative humidity and deformation of asperities in the real area of contact. A better understanding of these surface forces is of great necessity in order to find an optimal solution for reducing friction and adhesion of micro surfaces. We proposed an effective method to analyze capillary and van der Waals forces in nano-scale contact. In this method, Winklerian foundation model was employed to analyze the contact of rough surfaces that were obtained from atomic force microscopy (AFM) height images. Self-mated contact of diamond-like-carbon (DLC) coatings was analyzed, as an example, by the proposed model. It was shown that the capillary force was significantly influenced by relative humidity and wet angle of the DLC surface. The deformation of asperities to a critical magnitude by external loading led to a considerable increase of both capillary and van der Waals forces.

Keywords: Surface Force, Rough Surface, Micro Contact, Van Der Waals Force, Capillary Force, Relative Humidity

1. INTRODUCTION

Adhesion, friction and wear of sliding components in micro-electromechanical systems are known as main failure modes result in the malfunction and limit the lifetime of the system [1, 2]. As system size is reduced to micro scale, a ratio of surface to volume increase inversely proportional to the size reduction rate. Consequently, surface forces such as capillary force and van der Waals interaction cause the stiction or make contact condition severer in the micro and nano contacts [3, 4]. Therefore, a better understanding of these surface forces is of great necessity in order to reduce adhesion, friction and wear of moving micro elements.

In this publication, we proposed the simplified numerical method using Winklerian foundation model [5, 6] to analyze the surface force in micro asperity contact of rough surfaces. Moreover, it was examined that effects of relative humidity, hydrophilicity and deformation of surface on the surface forces using the proposed numerical model.

2. EXPERIMENTS

Atomic force microscopy (AFM) topography image was used as the surface height data in this study. Each topography data point was modeled as a spring with rectangular cross section. In this numerical model, we analyzed van der Waals interaction by the Lennard-Johnse potentials and capillary force by the capillary condensation due to the relative humidity. The analyzed surface was divided into three different areas: repulsive, meniscus formation and van der Waals interaction area. In the repulsive area (real contact area), compressive force as a function of deformations of asperities can be written as follow:

$$F_r = \frac{E^*}{kh}\delta_i \tag{1}$$

where E^* is effective elastic modulus, k is compliance, h is the foundation depth, δ_i is the deformation [5,6].

In the meniscus formation area, menisci are formed by the capillary condensation at small clearance around the contact area. The meniscus height, s is specified as a function of relative humidity by the Kelvin equation and the Laplace pressure is acting across the meniscus [7]. The adhesive force by the meniscus formation can be written as follow:

$$F_c = \frac{\gamma_l}{s}\left(\cos\theta_1 + \cos\theta_2\right) \tag{2}$$

where γ_l is the surface tension of water, $\theta_{1,2}$ are the contact angle of two surfaces.

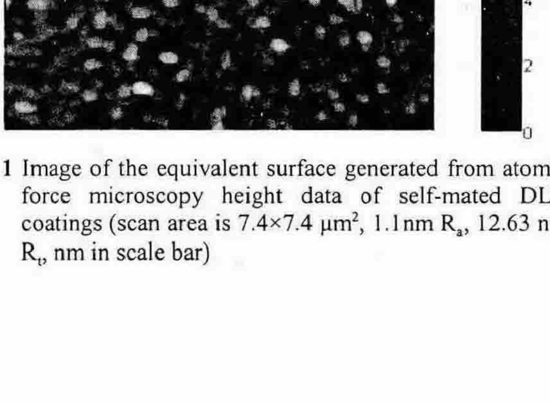

Fig. 1 Image of the equivalent surface generated from atomic force microscopy height data of self-mated DLC coatings (scan area is 7.4×7.4 μm^2, 1.1nm R$_a$, 12.63 nm R$_t$, nm in scale bar)

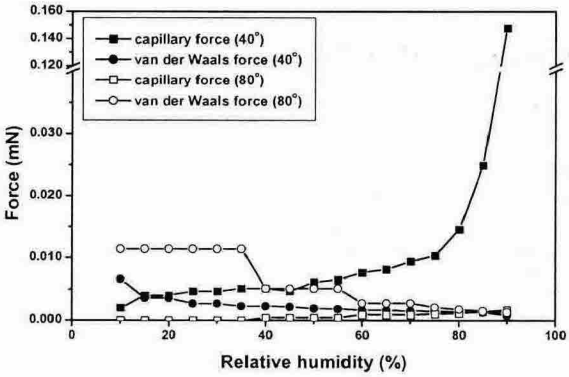

Fig. 2 Variation of surface forces as a function of relative humidity at zero deformation of asperities

In the van der Waals interaction area, the specific force can be presented as bellow as a function of the clearance separating the surfaces in accordance with the Lenard-Johnse potential:

$$F_v = \frac{8}{3}\frac{\gamma_{12}}{\varepsilon}\left(\frac{\varepsilon}{l_i}\right)^3 - \left(\frac{\varepsilon}{l_i}\right)^9 \qquad (3)$$

where γ_{12} is the interfacial energy of two surfaces, ε is interatomic length. The simplified numerical model has been reported elsewhere in detail [8].

To investigate the influence of parameters such as relative humidity, hydrophilicity and deformation of surface on the surface forces, we analyzed the contact of diamond-like-carbon (DLC) coating. We generated an equivalent surface from AFM data of DLC coating assuming that two identical DLC coated surfaces were in contact. The topography image of equivalent surface is shown in Fig. 1, revealing the grain-like structure of the coating and rough nature of the microasperities.

3. RESULTS AND DISCUSSIONS

The simulation was conducted using the proposed model under zero deformation condition to examine the influence of relative humidity on the surface forces in the surfaces with different hydrophilicity. Fig. 2 shows the variation of the surface forces as a function of relative humidity for the surfaces with contact angle 40° and 80°. In the surface with small contact angle, capillary force is dominant and rapidly increased above 80 % relative humidity. This result is in good agreement with the work done by Rabinovich et al. and others [9]. By contrast, for the surface with high contact angle (less hydrophilic), van der Waals interaction was a dominant force and it decreased inversely proportional to the relative humidity. It is conceivable that the small clearance, free from the meniscus formation due to lower hydrophilicity of the surface, resulted in higher van der Waals interaction.

Surface parameters such as roughness and bearing ratio are very important, as the surface forces are highly dependent on the distance between two surfaces. Fig. 3 shows the surface force variation as a function of asperities deformation at 50 % relative humidity. The critical deformation of asperities led to a considerable increase of both capillary and van der Waals forces. As the asperities deformation increased, the clearance reduced and the areas effective for surface forces increased at the same time. At specific deformation, this effective area became maximum and resulted in high surface forces. Further increase of the deformation caused the reduction of surface forces due to the removal of clearance between two surfaces. We note that the surface forces can be increased by not only the surface hydrophilicity, humidity and topography of surface but also the deformation caused by external loading.

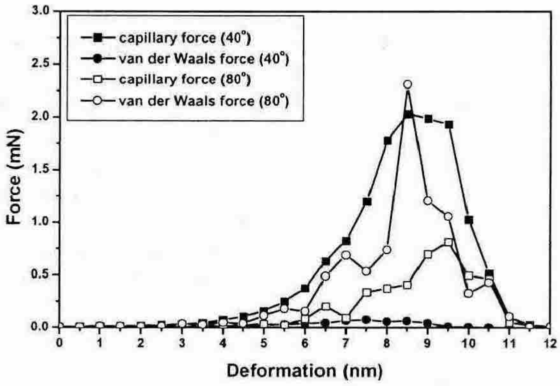

Fig. 3 Variation of surface forces as a function of surface deformation at 50 % relative humidity

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