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Study of liquid-mediated adhesion between 3D rough surfaces: A spectral approach

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ABSTRACT

In this work, a three-dimensional model for liquid-mediated adhesion between two rough surfaces is presented. The approach is based on a spectral (multi-scale) representation of compressive rough surface deformation along with the capillary equations governing the tensile deformation. An iterative numerical algorithm is designed to solve the equations of elasticity and capillarity simultaneously. It is shown that, under certain conditions, a contact instability occurs leading to unbounded rates of change of tensile force, average gap and wetted radius. The effects of liquid volume, liquid surface tension, surface topography, nominal contact area, and external load on the stability of contact interface are studied. Key dimensionless ratios are identified that govern the equilibrium state and onset of instability.

1. Introduction

Significant attention has been given to liquid-mediated adhesion between solid surfaces in recent years due to its influence in micro/nano-scale devices [2–7]. Small spacing between solid surfaces and high surface area to volume ratio make the surface-driven forces such as adhesion important in small-scale devices such as micro/nano-electro-mechanical systems (MEMS/NEMS), head-disk interface (HDI), and the tip of atomic force microscope (AFM). The presence of a wetting liquid between solid surfaces causes adhesion which negatively affects the performance of these devices. The wetting liquid present in the interface due to condensation, contamination, or lubrication produces large concave meniscus curvatures at the liquid–vapor interface which induces large negative pressures. In fact Yang et al. [8], based on experiments with an AFM tip, concluded that the pressure can be negative down to -160 MPa.

Several authors have developed models to describe the behavior of solid–solid contact in the presence of a liquid film [9–20]. These works can be divided into two categories: (1) liquid-mediated adhesion between smooth surfaces [9–12], and (2) liquid-mediated adhesion between rough surfaces [13–20]. Matthewson and Mamin [9] modeled the liquid film adhesion between two ultra-flat solid surfaces where different regimes were identified according to the varying amounts of liquid between the surfaces. Matthewson [13] also modeled the liquid-mediated adhesion between two rough spheres concentrating on the viscous component of adhesion. Poon and Bhushan [14], and Tian and Bhushan [15] presented a numerical contact model for the contact between three-dimensional rough surfaces in the presence of a liquid film. In their model, liquid-mediated adhesion arises from many isolated capillary bridges in the contact interface. The stiction phenomenon is investigated and results are obtained for the meniscus force versus the topographical properties of the rough surfaces. Their work is relevant for films of liquid thinner than considered in the current work. Persson [17] studied the effect of relative humidity on the work of adhesion and the contact area between two elastic solids with randomly rough surfaces. Streator and Jackson [18] and Streator [19] used spectral and deterministic approaches, respectively, to model the contact between 2D elastic rough surfaces in the presence of a liquid film. The tensile force between the surfaces due to liquid-mediated adhesion is calculated and a “surface collapse” phenomenon is observed in their work which corresponds to a sudden jump in the tensile force between the surfaces.

In the current work, a model for the liquid-mediated adhesion between three-dimensional (3D) rough surfaces is presented using a multi-scale contact model developed by Jackson and Streator [21] (from here on referred to as the JS model). The JS model is based on representing contact between surfaces in multiple scales of roughness based on Fourier series coefficients. The present investigation represents an extension of previous work on the liquid-mediated adhesion between 2D rough surfaces [18], as well as a continuation of preliminary work done by the authors on liquid-mediated adhesion between 3D rough surfaces [22].

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Nomenclature

A	contact area of a sinusoidal asperity
$(A_{JGH})_1$	contact area at early contact of sinusoidal asperity per JGH model [1]
$(A_{JGH})_2$	contact area at near complete contact of sinusoidal asperity per JGH model [1]
A_n	nominal contact area between two rough surfaces
A_r	real contact area between two rough surfaces
A_w	area of wetted region
B	aspect ratio (ratio of sinusoidal asperity amplitude to its wavelength)
β	equivalent 1D Fourier coefficient
Δ	amplitude of sinusoidal asperity
Δg_k	reduction in the average surface separation at frequency scale k
Δp	capillary pressure drop
ΔV_c	volume loss due to compressive stresses
ΔV_t	volume loss due to tensile stresses
ΔV_{tot}	total volume loss
E	elastic modulus
E'	reduced or effective elastic modulus
$E(k)$	elliptical integral of the second kind
η	areal density of asperities
f	spatial frequency (reciprocal of wavelength)
F	total force between two rough surfaces
F_c	compressive force between rough surfaces
F_t	tensile force between rough surfaces
F_t^*	non-dimensional tensile force
$F(k_x, k_y)$	2D FFT coefficients
g	local surface separation for a single asperity
$\overline{g}$	average surface separation for a single asperity
γ	surface tension of liquid
Γ	non-dimensional adhesion parameter
h_{fs}	surface separation at the free surface of the liquid
$\overline{h}$	average surface separation
$k_{x,y}$	indices correspond to spatial frequencies in x and y directions
$\overline{\kappa}$	mean curvature at the free surface of liquid
$\kappa_{I,II}$	principal curvatures at the free surface of the liquid
l_c	correlation length
$L_{x,y}$	scan lengths in x and y directions
λ	wavelength of sinusoidal asperity
$n_{x,y}$	indices correspond to spatial coordinate in x and y directions
$N_{x,y}$	number of nodal points in x and y directions
υ	Poisson's ratio
$\overline{p}$	average contact pressure of a sinusoidal asperity
p^*	average contact pressure for complete contact of a sinusoidal asperity
P	external load applied to rough surfaces
P^*	non-dimensional external load
r	radial coordinate
r_w	radius of wetted region
$R_{I,II}$	principal radii of curvature at the free surface of the liquid
σ	root mean square of rough surface heights
$\theta_{A,B}$	contact angles between the liquid and rough surfaces
$u_t(r)$	surface deformation due to tensile force
V_0	liquid volume
V_0^*	non-dimensional liquid volume
$z(x,y)$	rough surface heights
z_{max}	maximum value of the surface heights

2. Contact model

Fig. 1 shows schematically the interface of interest. It consists of a rough surface having side length L in both x and y directions and with surface heights in the z direction. A rigid flat surface (shown as transparent in Fig. 1), with the same dimensions, deforms the rough surface in the presence of a liquid film bridging between the two surfaces. The nominal contact area, A_n, is just L^2. It should be noted that the combination of a rigid flat and a rough surface used in this work is a model of two hypothetical elastic rough surfaces, whereby the rough surface of the model is given the combined roughness and flexibility of the hypothetical surface pair. It is well-known that if the liquid wets the two surfaces, a sub-ambient pressure will be developed within the liquid bridge which induces tensile (adhesive) stresses between the two surfaces [23]. This pressure drop depends on the curvature at the free surface of the liquid film and the curvature, in turn, is inversely proportional to the local spacing at the free surface of the liquid film. As the surfaces are pulled together, and the gap between them decreases, the more the liquid tends to pull them together. As the surfaces are brought into closer proximity, the compressive stresses begin to rise at the points of contact. There are two potential scenarios [18,19]: (1) the tensile and compressive forces come into balance with an average gap in the order of composite surface roughness, or (2) the tensile force dominates the compressive force, and the interface collapses such that the average gap is a very small fraction of composite surface roughness. In the current work, the goal is to

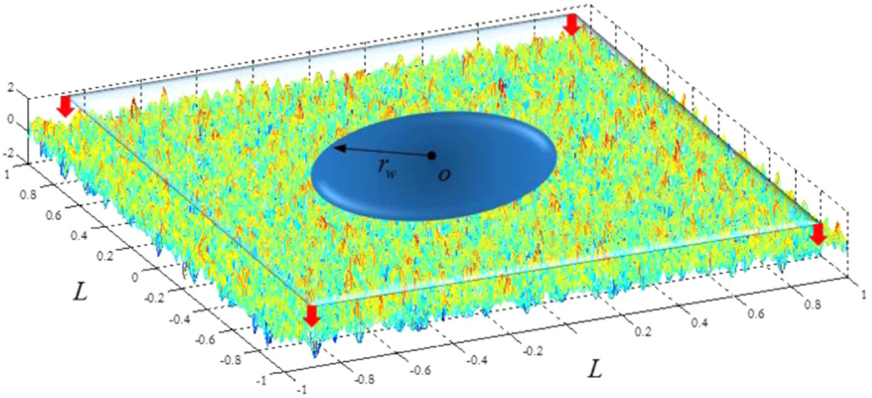

Fig. 1. Schematic depiction of the contact interface: contact of a rigid flat surface and a simulated 3D elastic rough surface in presence of a liquid film.