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EFFECT OF SURFACE ROUGHNESS ON ADHESION AND FRICTION OF MICROFIBERS IN SIDE CONTACT

Mircea Teodorescu
School of Engineering
Cranfield University
Cranfield, Bedfordshire, UK
Email: m.teodorescu@cranfield.ac.uk

Carmel Majidi
Princeton Institute for the Science and Technology of Materials
Princeton University
Princeton, New Jersey, USA

Homer Rahnejat
Wolfson School of Mechanical and Manufacturing Engineering,
Loughborough University,
Loughborough, Leicestershire, UK

Ronald S. Fearing
Department of Electrical Engineering and Computer Sciences
University of California
Berkeley, California, USA

ABSTRACT

A multi-scale mathematical model is used to study the effect of surface roughness on the adhesion and friction of microfibers engaged in side contact. Results are compared to closed-form analytic approximations derived from linear elastic contact mechanics.

INTRODUCTION

By introducing nanostructure, researchers have fabricated adhesive and high friction materials from otherwise non-sticky, stiff materials (see Fig. 1(a)). Such work has been inspired by the adhesive system of gecko lizards, which is composed entirely of a stiff polymeric material, which has an elastic modulus $E > 1$ GPa. The use of intrinsically stiff, non-sticky material is essential for controlling grip and preventing contamination. Adhesion, however, requires the material to conform to surface roughness. This is achieved by structuring the material into an array of elastic microfibers. If sufficiently slender, the fibers will bend over and adhere to the opposing substrate along their sides. Energetically stable side contact occurs when the interfacial forces exceed the elastic restoring forces for fiber bending and cross-sectional deformation.

Previously, the side contact mode of adhesion and friction was studied with simplified analytic approximations that ignored the effects of surface roughness and preload [1-3]. Here, a more complete, multi-scale model is introduced to compute the contact area for various preloads and roughness. Preliminary results are compared with estimates from the analytic approximations where the nominal work of adhesion W_{ad} is replaced with an effective work of adhesion W_{eff} that accounts for the change in contact due to surface roughness [4].

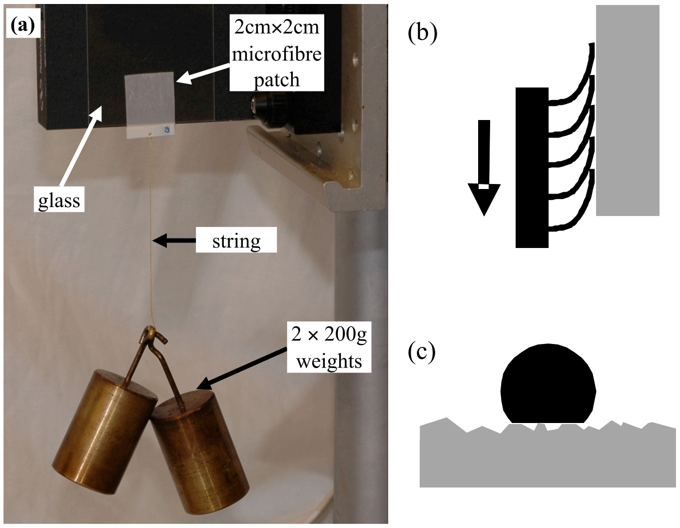

Figure 1 (a) 4 cm^2 array of vertically aligned polypropylene microfibers (20 μm long, 0.3 μm radius, 42 x 10^6 cm^{-2} density) supporting a 400 gram weight in shear [1]; (b) microfibers adhere through side contact; (c) equilibrium cross section of microfiber engaged in side contact with a rough substrate.

MATHEMATICAL MODEL

Majidi *et al.* [2,3] showed that for a microfiber with radius R=0.3μm, length L=20μm, in the absence of surface roughness, the side contact length c, can be obtained from:

$$EI\{\phi'(L-c)\}^2 = 6\left\{\left(1-\nu^2\right)R^2W_{ad}^4/(\pi E)\right\}^{1/3} \tag{1}$$

where ϕ=dv/ds, v=v(s) denotes the lateral deflection of the fiber, E and ν are the modulus of elasticity and Poisson's ratio.

For contact with a nanorough surface, W_{ad} is replaced with the effective work of adhesion W_{eff} obtained from [4]. The current analysis predicts the adhesion force and the limiting value for the friction force (at equilibrium), of a fiber-glass contact for a unit length (1µm) of the rough fiber. Regardless of their physical scale, contacting surfaces are covered by roughness features. Therefore, the interaction between two surfaces can be seen as the summation of individual interactions between asperity tip-pairs. In the first approximation, asperity tips may be considered spherical. If two asperities are in direct contact, the force of adhesion and the limiting value for the tangential force can be predicted by the JKR model [5]:

$$\begin{cases} p_a = 4E^*a^3/(3R_e) - (8\pi a^3\Delta\gamma E^*)^{0.5} \\ f_a = \pi\tau_0 a^2 \end{cases} \tag{2}$$

where p_a is the adhesion force, f_a is the limiting value of the tangential force, R_e is the equivalent radius of a pair of asperities, E^* is the equivalent modulus of elasticity for the contact, a is the contact radius for an asperity and τ_0 the interfacial shear strength (10MPa [1]). The prediction f_a is approximate since the derivation assumes there is no coupling between adhesion and tangential forces [5].

A thin film of water condenses between two surfaces in close proximity [6]. This can be neglected in macro-scale applications. However, in micro-scale it can play a significant role. If the distance between two non-contacting asperities is smaller than the thickness of the condensed water layer, a nano-scale meniscus bridge would form. At very small separations, hydration pressure between the two opposing asperities is also encountered [7]. Therefore, the total attractive/repulsive force and the corresponding shear force can be expressed as [8,9]:

$$\begin{cases} p_h = -2\pi R_e\gamma_{lv}\left(\cos\theta_1 + \cos\theta_2\right) + 2A_m\gamma_i e^{-(D-z)/\lambda_0}/\lambda_0 \\ f_h = A_m\eta U/\delta \end{cases} \tag{3}$$

where A_m=πr^2 is the cross section of a liquid bridge, $\lambda_0 \approx 1.5\ nm$, $1/(1/r_1 + 1/r_2) = \gamma V/RT\log(p/p_s)$, $r_1 \approx r_2 = r$, $\gamma_i \in [10 \div 50]$ mJ/m^2, $\theta_{1,2}$ contact angles, η dynamic viscosity [7].

Equations (2) and (3) predict the forces between two opposing asperities. To account for the interaction between two rough surfaces, a normal distribution of asperity heights can be assumed. Therefore, the probability for an asperity to have a height between z and $z+dz$ is: $\phi(z)=\exp(-z^2/2\sigma^2)/(2\pi)^{0.5}$ [10]. For N asperities per unit area the interaction between two surfaces is [8]:

$$p(z) = N\int_{-L}^{d}(p_a + p_h)\phi(z)dz\ ; \qquad f(z) = N\int_{-L}^{d}(f_a + f_h)\phi(z)dz \tag{4}$$

Equation (4) is solved numerically. Because the fibers are fabricated in-situ, their surface topography is strongly influenced by the fabrication technique. In practice, the surface roughness is in the nano-scale range. For the current model, the method proposed by Carbone *et al* [4] to describe surface features was carefully adapted.

The shape of the elastic contact is obtained as:

$$h_{i,j} = x_{i,j}^2/2R + h_{ref} + \delta_{i,j} \tag{5}$$

where R is the fiber radius (~0.3µm), $h_{i,j}$ is the local deformed gap, h_{ref} is the gap between the undeformed fiber profile and glass, $\delta_{i,j}$ =$(\sum\sum D_{i\,j}^{k\,l}\, p_{kl})/\pi E^*$ is the contact deflection, D is the influence coefficient matrix [8], (i,j) is the location on the computational grid and (k,l) is the location of the applied pressure grid.

Figure 2 shows the pressure applied on the contact. It should be noted that the predicted pressure represents the average value for the rough profile, from which individual asperities are compressed or stretched.

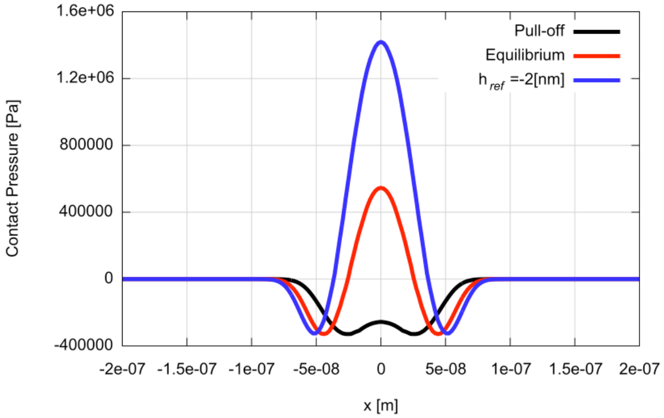

Figure 2 Contact pressure and deflection during detachment.

RESULTS AND DISCUSSION

The contact pressure (figure 2 b) can be either attractive or repulsive. Thus, depending on the geometry of the gap, the total force applied on the contact (P=∫∫$pdxdy$) can be either negative (overall attractive) or positive (overall repulsive). However, the limiting value of the friction force (F=∫∫$fdxdy$) can only be positive.

Teodorescu and Rahnejat [8] have shown that the contact load between two surfaces is different during attachment and detachment. This is due to adhesion and repulsion between individual asperities, as well as the localized contact deflection.

Figure 3 shows the contact load (during attachment and detachment), as well as the limiting value of the friction force during detachment. In practice, following the preload stage, the fiber rests in an equilibrium position and generates the limiting value of the friction force.

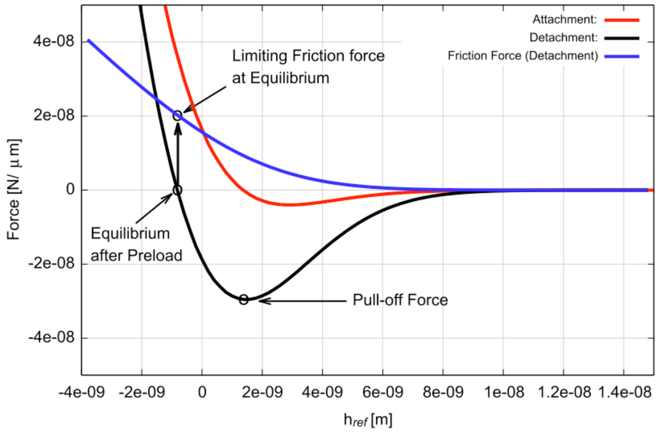

Figure 3 Forces during attachment and detachment of a lateral section of the fiber (1µm length and σ=3nm surface roughness)

Figure 4 shows the contact force and the limiting value of the friction force for several possible cases of surface roughness. For smaller roughness the adhesive component is significantly higher, but the limiting value of the friction force appears to be less affected. However, for a full prediction, the coordination between the contact force and friction force should be considered.

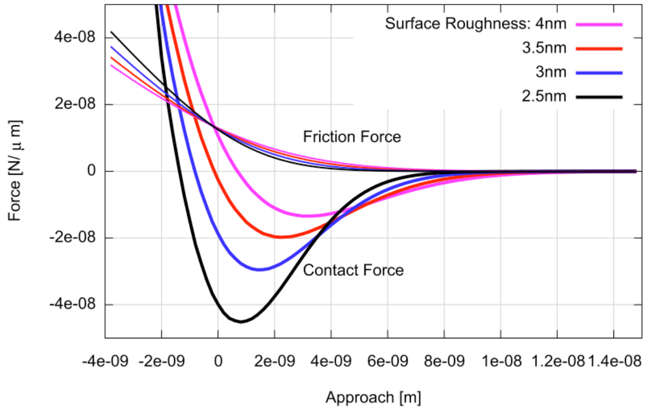

Figure 4 Contact Forces and limiting value of the Friction Forces for σ=2.5…4nm

Figure 5 shows variations of contact forces and limiting friction forces. In this representation, the expected limiting friction force is the intersection between the curve and the axis. Therefore, for identical fibers, limiting friction can double if the fiber becomes very smooth.

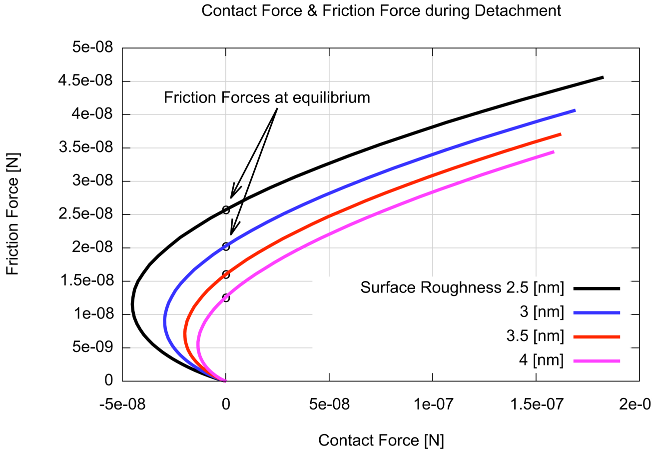

Figure 5 Friction force vs. Contact Force for $\sigma = 2.5 \div 4nm$

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