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Mechanics of a Novel Shear-activated Microfiber Array Adhesive

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ABSTRACT

Elastic rod theory and principles of contact mechanics motivate the development of a novel, shear-activated, microfiber array adhesive. Unlike with conventional Pressure Sensitive Adhesives (PSAs), the microfiber array and backing are composed entirely of a stiff, glassy polymer (polypropylene, elastic modulus E = 1 GPa) and an externally applied shear load is required to achieve contact with a substrate. Results from a Shear Power Test on glass indicate an interfacial shear strength of 5 kPa over 4 cm^2, consistent with the theoretical prediction and a factor of 1000 greater than a smooth polypropylene sheet of similar thickness.

INTRODUCTION

Motivated by principles of rod theory and contact mechanics, scientists and engineers are developing a new class of microfiber array adhesives [1]. Still in its early stages, this emerging field aims to introduce adhesives that are pressure-sensitive, directional, reusable, biocompatible, temperature resistance, and self-cleaning. An example of adhesion with a microfiber array is presented in Figure 1. Unlike a conventional Pressure Sensitive Adhesive (PSA), this adhesive is composed entirely of a stiff, glassy polymer (polypropylene, elastic modulus E = 1 GPa). High elastic modulus correlates with high wear resistance and low tack and so may be essential for reusability and self-cleaning.

The polypropylene fibers shown in Figure 1 have a radius R = 0.3 μm, length L = 20 μm, and density D = 42×10^6 fibers/cm^2 and are on a 35 μm polypropylene backing. Unlike the ultrahigh friction arrays presented in [2], these samples have a naturally planar backing. Hence, intimate contact is possible without needing to press the sample into a glass substrate [3]. However, such contact does require an applied shear load. Once this shear load is removed, the sample spontaneously delaminates from the substrate and can be easily removed.

This unique shear-activated adhesion property follows from elastic rod theory and contact mechanics. Here, a model is derived that predicts shear strength based on the mechanics and geometry of the microfibers and the interfacial properties between the microfiber tip and substrate. Design criteria are presented to determine the appropriate microfiber geometry for shear-activated adhesion with any selected material.

MODEL

The remarkable adhesion demonstrated in Figure 1 is explained by a shear-activated adhesion model similar to that used by setal arrays in a natural gecko adhesive [4]. In their undeformed configuration, the vertically aligned microfibers exhibit considerable compliance in compression (by buckling, see [5]) but are stiff in tension. While compressive compliance is sufficient for ultrahigh friction [2], pure shear adhesion also requires tensile compliance particularly in the presence of interfacial gaps, which may result from substrate roughness, fiber length variation, backing curvature, or misalignment.

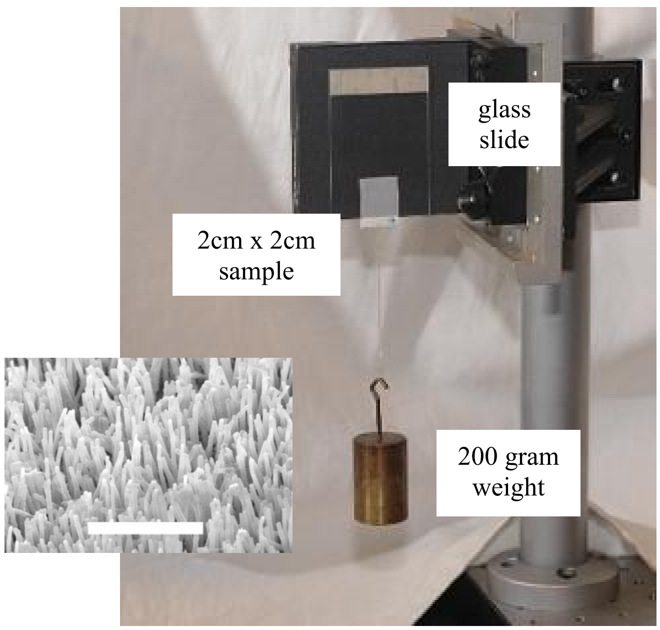

Figure 1 2cm x 2cm array of vertically aligned polypropylene microfibers supporting 200 grams in pure shear; (inset) SEM image of microfibers (bar = 20 μm)

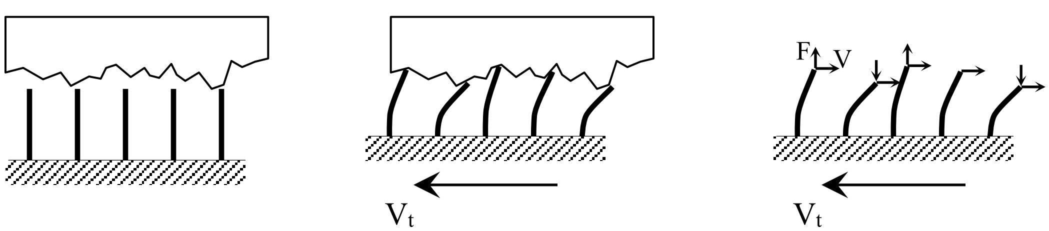

Figure 2 (a) Microfiber array and rough substrate with no external load; (b) external shear load V_t ; (c) free body diagram of array.

As illustrated in Figure 2(a), contact between the array and substrate is generally poor in the absence of externally applied forces. For simplicity, it is assumed that the fibers have equal length and a planar backing and that the interfacial gaps are due to substrate roughness alone. For stiff materials ($E \geq 1$ GPa) like polypropylene, the fibers are virtually inextensible and so overcoming the interfacial gaps and achieving complete contact requires the fibers to bend, as illustrated in Figure 2(b). A free body diagram of the complete system is presented in Figure 2(c). Here, each contacting fiber is subject to an interfacial shear force V and normal force F. For some fibers, F is tensile (i.e. $F > 0$) while for others it is compressive ($F < 0$) or equal to zero. Under a pure shear load V_t, the net normal force is zero (i.e. $\sum F = 0$) and the net shear force acting on the fiber tips is $\sum V = V_t$.

During sliding, V is approximately equal to

$$V = \tau A_r \tag{1}$$

where τ is the interfacial shear strength per unit area of contact and A_r is the real area of contact between the fiber tip and substrate. Assuming a rounded tip, A_r is obtained from Johnson-Kendall-Roberts (JKR) theory:

$$A_r = \pi\left\{\frac{3(1-\nu^2)R_t}{4E}\left(-F + 3\pi W_{ad}R_t + \sqrt{-6\pi F W_{ad} R_t + (3\pi W_{ad} R_t)^2}\right)\right\}^{2/3} \tag{2}$$

where ν is Poisson's ratio, R_t is the tip radius of curvature, and W_{ad} is the work of adhesion per unit area of contact [6].

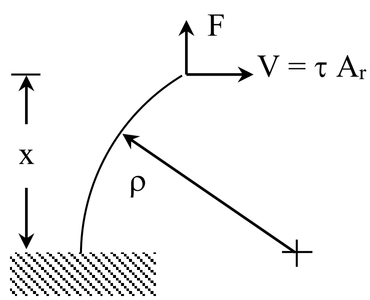

Figure 3 Free body diagram of an individual fiber of length L.

As illustrated in Figure 3, it is assumed for simplicity that the deformed fiber follows a circular arc of radius ρ. The total potential energy of the fiber is thus

$$U = \frac{EIL}{2\rho^2} - F\rho\sin\left(\frac{L}{\rho}\right) - \tau A_r \rho\left\{1 - \cos\left(\frac{L}{\rho}\right)\right\}, \tag{3}$$

where L is the fiber length, $I = \pi R^4/4$ is the area moment of inertia, and R is the cross-sectional radius of the fiber. For a prescribed value of F, $dU/d\rho = 0$ at equilibrium. Noting that

$$\sin\left(\frac{L}{\rho}\right) \approx \frac{L}{\rho} - \frac{1}{6}\left(\frac{L}{\rho}\right)^3 \text{ and } \cos\left(\frac{L}{\rho}\right) \approx 1 - \frac{1}{2}\left(\frac{L}{\rho}\right)^2, \tag{4}$$

the fiber curvature at equilibrium is approximately

$$\rho_{eq} = \frac{6EI + 2FL^2}{3\tau A_r L}. \tag{5}$$

The corresponding height of the fiber tip is

$$x = \rho_{eq} \sin\left(\frac{L}{\rho_{eq}}\right) \approx L - \frac{L^3}{6\rho_{eq}^2}. \tag{6}$$

The maximum height of a sheared fiber corresponds to x evaluated when $F = F_0$, where F_0 is the maximum tensile load that the substrate can transfer to the fiber tip before the tip spontaneously detaches. According to JKR theory [6],

$$F_0 = 1.5\, \pi\, W_{ad}\, R_t\,. \tag{7}$$

The largest interfacial gap that the fiber tip can cross is thus on the order of

$$\Delta = x\big|_{F=F_0} - x\big|_{F=0}. \tag{8}$$

DESIGN CRITERIA

Substituting equations (2) and (5 – 7) into (8) yields

$$\Delta = 8.86\tau^2 L^5 \left\{\left(\frac{2^{1/3}}{EI}\right)^2 - \frac{1}{\left(2EI + \pi W_{ad} R_t L^2\right)^2}\right\}\left\{\frac{\left(1-\nu^2\right)W_{ad} R_t^2}{E}\right\}^{4/3}. \tag{9}$$

That is, for all the fibers to make contact under a pure shear load, the amplitude of the substrate roughness (or fiber length variation, backing waviness, etc.) must be less than or equal to Δ. As shown in equation (9), Δ is a function of fiber length L, radius R, tip curvature R_t, elastic modulus E, interfacial work of adhesion W_{ad} and interfacial shear strength τ. Alternatively, (9) may be used to select the appropriate microfiber geometry for a prescribed substrate roughness and material.

Approximating the average sliding resistance of each contact as $V = \tau\, (A_r)_{F=0}$, the total interfacial shear strength will be

$$S = 18.36 D\tau \left\{\frac{\left(1-\nu^2\right)W_{ad} R_t^2}{E}\right\}^{2/3}, \tag{10}$$

where D is the fiber density. Previously, it had been shown that fibers have a propensity to adhere to one another if spaced too closely together. In order to avoid fiber clumping, the density cannot exceed the critical value [7]

$$D_{cr} = \frac{1}{4}\left\{ R + \frac{L^2}{\sqrt{3EI}}\left[\frac{(1-\nu^2)R_t^2 W_{ad}^4}{\pi E}\right]^{1/6}\right\}^{-2} . \tag{11}$$

Consider, for example, the polypropylene microfiber array presented in Figure 1. For polypropylene, E = 1 GPa and $\nu = 0.4$, and on glass, $\tau = 10$ MPa and $W_{ad} = 30$ mJ/m^2 [8]. For simplicity, it is assumed that the fiber tips are hemispherical, such that $R_t = R$. For maximum density without clumping, S is calculated for $D = D_{cr}$ using equations (10) and (11). These results are plotted in Figure 4 for fibers of radius $R \leq 1$ μm and length $L \leq 40$ μm. Figure 4 also shows the corresponding critical roughness amplitude Δ.

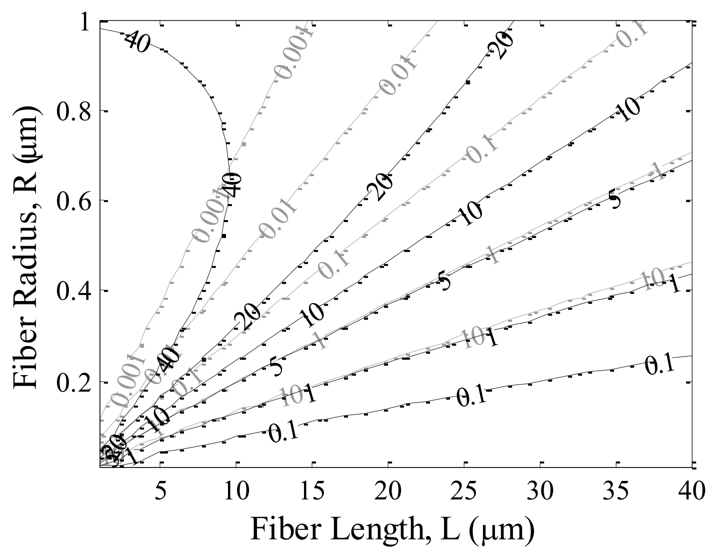

Figure 4 (black) Estimated shear strength S (kPa) of fiber array in complete contact with a substrate (density $D = D_{cr}$); (gray) maximum allowable amplitude Δ (μm) of interfacial roughness for complete contact between fiber array and substrate during sliding.

It is apparent from Figure 4 that fiber geometries with greater shear strength correlate with a lower tolerance for interfacial roughness. For example, lower aspect ratio fibers allow greater packing density and hence exhibit S > 10 kPa. However, such fibers also exhibit less compliance during sliding on account of their large bending stiffness and thus cannot conform to surfaces with roughness Δ > 100 nm.

For L = 20 μm and R = 0.3 μm, the estimated shear strength is close to S = 5 kPa and the allowed interfacial roughness for complete contact is approximately Δ = 1 μm. Interestingly, this is consistent with the experimental result presented in Figure 1, where the arrays support a 5 kPa shear load with a fiber length variation on the order of 1 μm. It should be noted that the experimentally tested fibers have a density of $D = 42 \times 10^6$ cm^{-2}, well above the critical density of $D_{cr} = 7.7 \times 10^6$ cm^{-2}, which explains the mild amount of clumping observed under SEM. Moreover, the fiber tips are toroidal rather than hemispherical and so JKR theory may not be applicable.

CONCLUSION

A mathematical model is introduced that explains the shear-activated adhesion of vertically aligned microfiber arrays. The model is based on elastic rod theory and JKR contact mechanics. Three important design criteria (9 – 11) are presented that relate microfiber geometry (R, L, R_t, D), mechanical properties (E, ν), and interfacial properties (W_{ad}, τ) with total interfacial shear strength (S) and the maximum allowable amplitude (Δ) of substrate roughness, array backing waviness, or fiber length variation.

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