Mechanics of Adhesion and Friction in Soft Materials (Sponsors: AFOSR, NSF CAREER/PECASE)

1. Mechanics of Wavy Surface Adhesion and Friction: Understanding and controlling adhesion and friction of soft materials, particularly in the presence of roughness, is of importance in a variety of technological applications, as well as in insect locomotion. In order to reveal the role of surface roughness/waviness in such applications, **Guduru** developed a theory of wavy surface adhesion and friction of soft materials by idealizing the roughness as sinusoidal waviness [2.1-2.2]. The theory considers the canonical problem of adhesive and frictional contact between a rigid circular cylinder (plane strain) or a sphere (axisymmetric) and a soft half space with sinusoidally wavy surface [Fig. 1a]. Closed form solutions are obtained for the detachment force and contact displacement (for the axisymmetric case) as a function of the contact radius. It can be viewed as a generalization of the JKR theory of adhesion to wavy surfaces. The salient features of the solutions are as follows: **(i)** During detachment, the contact area recedes in a series of stable-unstable jumps. In other words, the contact edge behaves like a crack tip that gets pinned/de-pinned as it recedes. The unstable jumps dissipate mechanical energy, which results in a substantial increase in the interface toughness [Fig. 1b]. **(ii)** Pinning of the contact edges results in an increase in the detachment force compared to the case of no waviness. Depending on the wavelength and amplitude of the waviness, the increase in the detachment force can be an order of magnitude

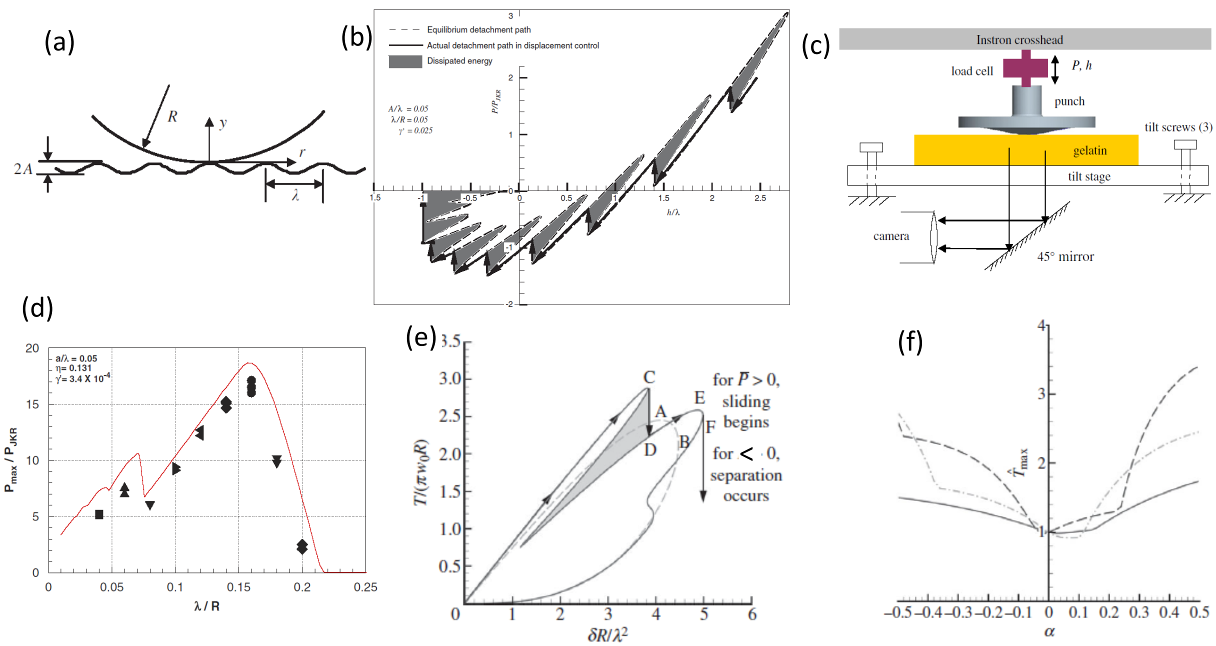

Figure 1. (a) Schematic illustration of the adhesion problem being modeled, between a rigid punch and a wavy elastic half space. (b) The force-displacement relation for the wavy surface adhesion problem, revealing that detachment proceeds in alternating stable and unstable segments. The unstable part dissipated energy (shown as the shaded area). The detachment force also increases; the relative increase in the detachment force as a function of the wavelength is shown in (d) as the red curve for an amplitude to wavelength ratio of 0.05. (c) Experimental setup to validate the theory. (d) Comparison of the theoretical predictions with the experimental results; very good agreement can be seen. (e) Tangential force vs. lateral displacement for a wavy surface. The dashed line is for the case of no waviness. For a fixed normal force, the contact area evolves through unstable jumps indicated by the arrows. (f) Enhancement in sliding resistance due to waviness (normalized with the case of no waviness). The abscissa is the normalized amplitude of the waviness. Different curves correspond to different values of the ratio of the waviness wavelength to the radius of the punch. Note the large enhancement in the sliding resistance due to the geometry induced instabilities!

higher [Fig. 1b and 1d]. **(iii)** An experimental investigation was carried out in the axisymmetric geometry in which the wavelength and amplitude of the waviness were varied systematically [Fig. 1c] and excellent agreement was seen between the experimental measurements and the theoretical predictions [Fig. 1d]. It is worth noting that the enhancement in adhesive strength due to waviness is a consequence of the structural instabilities arising from the interaction between the elastic response of the material and and surface geometry alone; no chemistry is involved! **(iv)** To understand the role of surface waviness on friction, **Guduru** considered the sliding resistance of a rigid sphere on a soft elastic material with axisymmetric waviness [2.3]. When the sphere is loaded laterally under a fixed normal force, the contact edge is subjected to mixed-mode loading. The theory predicts that, as the lateral loading increases, the decrease in contact area involves unstable jumps; and each unstable jump dissipates mechanical energy [Fig. 1e]. The additional energy dissipation increases the peak force required for gross sliding of the interface compared with that of a flat surface [Fig. 1f]. Thus, surface instabilities constitute a potent mechanism for enhanced sliding resistance on the surface of a soft material owing to surface waviness-induced instabilities.

2. Adhesion Enhancement due to Concave Surface Geometries: It has been recognized that several biological attachment devices are concave in shape and that such a shape enhances adhesion strength. Here, an analytical model is developed for the pull-off force required to separate a rigid axisymmetric concave punch from an elastic half-space (Fig. 2a) with the goal of understanding how concave shapes seen in both biological and man-made adhesive systems can outperform other geometries [2.4]. Closed form solutions are obtained for the detachment force as a function of the concave shape parameters by considering two modes of failure of the interface: crack like failure beginning at the outer edge of the contact and cohesive failure at the center when the interface strength is reached. The main feature of the solution is that significant enhancement in adhesion strength (compared with that of a flat punch) is predicted for both spherical and elliptical concave punch profiles (shown in Fig. 2b). Increasing the degree of the concavity initially increases the resulting pull-off force, but for higher depths the contact interface will separate before pull-off forces higher than those for the flat punch are achieved. Experiments were performed with elliptical concave punches on a soft substrate and the results were found to agree with the theoretical predictions very well (Fig. 2b); the maximum pull-off forces measured are within 80% of the predicted optimum pull-off force. These findings emphasize the benefits of concave geometries for designing interfaces which enhance adhesion through geometry alone.

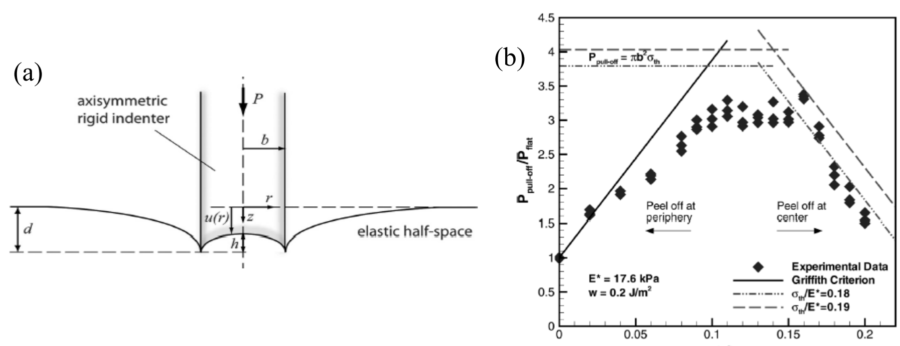

Figure 2. (a) Geometry of the concave punch contact problem. An axisymmetric rigid indenter with radius *b* and maximum depth of concavity *h* is pressed into an elastic half-space with load *P* such that the displacement under the indenter is described *u(r)* with maximum displacement *d*. (b) Experimental results (symbols) for adhesion strength as a function of the depth of concavity, along with theoretical predictions (lines).

3. Relevant Publications

1. P.R. Guduru. "Detachment of a Rigid Solid from a Wavy Elastic Surface - Theory." *Journal of the Mechanics and Physics of Solids* 55: 445-472, 2007.
2. P.R. Guduru and C.Bull. "Detachment of a Rigid Solid from a Wavy Elastic Surface - Experiments." *Journal of the Mechanics and Physics of Solids* 55: 473-488, 2007.
3. J.F.Waters and P.R. Guduru. "A Mechanism for Enhanced Static Sliding Resistance due to Surface Waviness." *Proceedingds of the Royal Society* A. 467: 2209-2223 (2011).
4. J.F.Waters, H.J. Gao, P.R. Guduru, "On Adhesion Enhancement due to Concave Surface Geometries." DOI: 10.1080/00218464.2011.557325, *The Journal of Adhesion,* (2011).
5. J.F. Waters, P.R. Guduru. Mode-mixity-dependent adhesive contact of a sphere on a plane surface. *Proceedings of the Royal Society*, A., 466: 1303-1325 (2010).
6. J.F.Waters, J. Kalow, H.J.Gao, P.R.Guduru. "Axisymmetric Adhesive Contact under Equi-biaxial Stretching." Submitted to *Journal of Adhesion* (2011).
7. J.F. Waters, S. Lee, P.R. Guduru. "Mechanics of axisymmetric wavy surface adhesion: JKR-DMT transition solution." *International Journal of Solids and Structures* 46: 1033-1042 (2009).
8. H. Yao, S. Chen, P.R. Guduru, H. Gao. "Orientation-dependent adhesion strength of a rigid cylinder in non-slipping contact with a transversely isotropic half-space." *International Journal of Solids and Structures* 46: 1167-1175, 2009.
9. H. Yao, P.R. Guduru, H.J. Gao. "Maximum strength for intermolecular adhesion of nanospheres at an optimal size." *Journal of the Royal Society of Interface* 5: 1363-1370, 2008.
10. H. Yao, G. Della Rocca, P.R. Guduru and H. Gao. "Adhesion and Sliding Response of a Biologically Inspired Fibrillar Surface: Experimental Observations." *Journal of the Royal Society Interface*. 5: 723-733, 2008.