What parameters control adhesive pull-off stresses and the work of adhesion?

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Using computer simulations, we investigate how the adhesive pull-off stress $\sigma_\mathrm{p}$of nominally flat contacts depends on a variety of parameters including elastic properties, interfacial interactions (magnitude as well as range), and the parameters defining the roughness of the rigid indenter. Results are analyzed in terms of various dimensionless quantities. A large correlation is found between $\sigma_\mathrm{p}/\sigma_\mathrm{m}$, where σ_m is the maximum local pull-off stress, and $\gamma_\mathrm{adh}/\gamma_\mathrm{ela}$, which is the ratio of surface energy and the areal elastic energy density needed to make full conformal contact between the solid bodies. The analyzed thin sheets generally require a larger work of adhesion than their semi-infinite counterparts, when all parameters but the elastomer thickness remain unchanged. Yet, simple models of thin sheets, in particular those with only one interfacial dimension, tend to require small pull-off stresses, because thin sheets are easily peeled off a substrate. Treating the interface as two-dimensional enhances the pull-off stress of thin sheets. This increase does not appear to result from the larger relative contact area of the thin sheets but rather originate from the peculiar adhesive hysteresis of saddle points.

Keywords: contact mechanics, nominally flat surfaces, adhesion, pull-off stress

1. Introduction

Recent years have seen a fierce debate on what parameters control the stickiness of surfaces. Simple but rigorous energy-balance arguments undoubtedly show that adhesion for typical surfaces is "killed" in macroscopic system due to the roughness at long wave lengths [1]. In contradiction to this insight, Robbins and Pastewka [2] identified a stickiness criterion, which only depends on properties that are predominantly determined at the small scales. It was derived by arguing that stickiness starts to set in when the relative contact area at zero external pressure is non-negligible and the predicted trends were confirmed by preliminary simulations of one of the current authors (MHM) [3]. This contribution attempts to resolve the controversy by computing pull-off stresses for a large variety of adhesive contacts and by analyzing the results in terms of appropriate dimensionless quantities.

Of particular interest is also the question at what point thin sheets stick better than thick elastomers made up of the same material. On one hand, thin sheets can easily acquire a larger contact area and thus greater adhesive interaction than semi-infinite solids, because they conform much more easily to the long wavelength surface undulations than thick elastomers do. On the other hand, they can be peeled off more easily. This latter argument explains why simulations of thin sheets, in which roughness consists of a single sinusoidal wave, finds them to be lifted off relatively easily. Our simulations add to the reasons for why the "real-life" thin sheets tend to stick better to surfaces than their thick counter parts.

2. Methods

The Green's function molecular dynamics (GFMD) method is employed to study the adhesive contact between an elastic layer and rough, rigid contact. The topography of rigid substrate ranges from single roughness to multi-scale roughness in 1D and 2D domain. In addition, the elastic layer is treated from semi-infinite solid to finite thickness sheet. Interactions between substrate and elastomer are modeled by a Morse potential. The pull-off stress is defined as the maximum stress during a quasi-static detachment of the contact.

3. Results and discussion

As shown the left of Figure 1, the reduced pull-off stress of semi-infinite elastomers in contact with randomly rough indenters can be collapsed on a master curve. For thin sheets, we find that the pull-off stress in a two-dimensional contact can be enhanced by finite sheet thickness, while it is generally reduced in line contacts. The effect is particularly strong when saddle points are in contact at the pull-off instability.

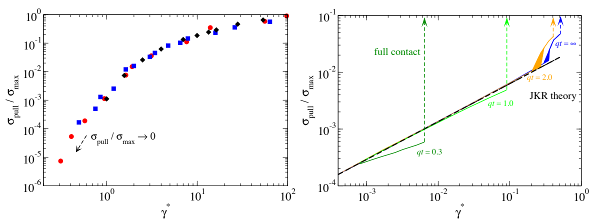

Figure 1: Reduced pull-off stress for a semi-infinite elastomer in contact with a randomly rough indenter as a function of reduced surface energy (*left*) and for finite-thickness elastomers in contact with a single-wavelength indenter with 90° rotational symmetry (*right*). Different symbols and line colors indicate different roughness parameters and elastomer thicknesses, respectively.

4. References

[1] Tiwari, A. et al., "The effect of surface roughness and viscoelasticity on rubber adhesion", Soft Matter 13, 19, 2017, 3602-3621.

[2] Pastewka, L. and Robbins, M. O. "Contact between rough surfaces and a criterion for macroscopic adhesion", Proc. Natl. Acad. Sci. USA, 111, 9, 2014, 3298-3303.

[3] Müser, M. H., "A dimensionless measure for adhesion and effects of the range of adhesion in contacts of nominally flat surfaces", Tribol. Int. 100, SI, 2016, 41-47.