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Effective work of adhesion in loading and unloading soft contacts

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Lately Dalvi and co-authors have experimentally measured the adhesion of soft spheres with rough substrates with roughness measured down to nanometers. They have shown good correlation between a corrected version of the Persson & Tosatti theory and the apparent work of adhesion during loading obtained experimentally. We show that unloading data would show similar correlation with the Persson-Tosatti's simple criterion, but for a much larger effective work of adhesion, which therefore becomes not an "intrinsic" property, although it may partly depend also on viscoelastic effects. We provide a new criterion inspired by the theory of Guduru, which gives reasonable estimates for both loading and unloading.

Keywords: adhesion, rough contact, hysteresis

1. Introduction

After some debate, the scientific community has found some consensus that it is the longest wavelength spectral content of roughness which is responsible for reducing adhesion at the macroscale. The simplest parameter to be considered is hence the height root mean square roughness. Nevertheless, already Fuller and Tabor found that a tiny amount of roughness may result in enhancing adhesion. Much later Guduru found a different mechanism for adhesion enhancement with respect to the smooth case, during unloading, in the case of a sphere pressed against a wavy substrate with a single axisymmetric waviness. Here we reconsider the recent experiments published by Dalvi et al. [1]. They used soft elastic polydimethylsiloxane (PDMS) hemispheres (2 to 3 mm diameter) having Young's elastic modulus in the range from 0,7 to 10 MPa, in contact with four different polycrystalline diamond substrates with roughness from 4 to 126 nm.

2. Methods

The PT theory [2] is originally devised as a criterion based on a energy balance

$$\frac{\Delta\gamma_{app}}{\Delta\gamma} = \frac{A_{true}}{A_0} - \frac{1}{\alpha(\zeta)} \qquad (1)$$

where $\Delta\gamma_{app}$ is the apparent work of adhesion, $\Delta\gamma$ is the intrinsic work of adhesion, A_{true} is the real contact area considering roughness, which is important to account only at high magnification, A_0 is the nominal contact area and $\alpha(\zeta) = \frac{\Delta\gamma}{U_{el}}$ where U_{el} is the elastic strain energy to flatten the roughness and $\zeta = \lambda_L/\lambda_s$ is the magnification, being λ_L and λ_s the longest and the shortest wavelength in the surface representation.

3. Results

Here the full set of experimental data of Dalvi et al. [1] is considered, i.e. both at approach and at retraction. Fig. 1 shows that the criterion based on the PT theory give a very poor correlation with the experimental data (PT, Dalvi, NoA_{true}) while the criterion inspired by the Guduru theory (MG) gives a coefficient of determination of 0.9 giving a unique intrinsic work of adhesion valid at both loading and unloading equal to $\Delta\gamma = 57.4$ mJ/m^2.

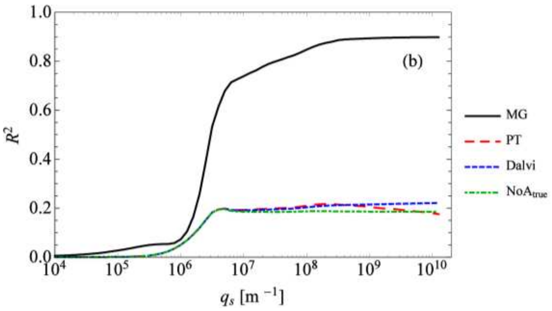
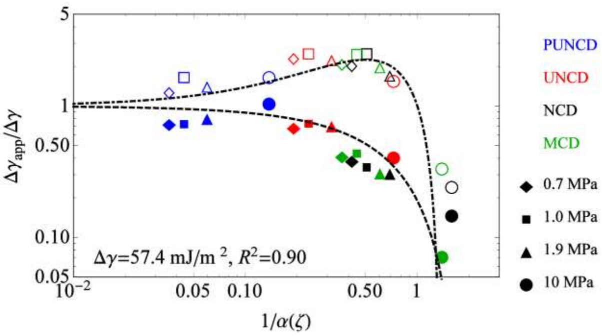


Figure 1: Dimensionless apparent work of adhesion versus the generalized Johnson parameter $1/\alpha(\zeta)$ Filled (empty) symbols for experimental data at approach (retraction).



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4. References

[1] Dalvi, S., et al., "Linking energy loss in soft adhesion to surface roughness", PNAS, 116(51), 2019, 25484-25490

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