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Adhesion between self-affine rough surfaces: Possible large effects in small deviations from the nominally Gaussian case

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A B S T R A C T

It is shown that even small deviations from the ideal Gaussian random roughness case seem to lead to dramatic increase in adhesion of rough surfaces: this could be due to a finite number of asperities, or to a finite tail in the height distribution, particularly realistic at low fractal dimensions *D*, which is the case of most practical interest. It is emphasized that the assumption of a perfect Gaussian heigth distribution, including infinite tails, may be a strong one when studying adhesion in rough surfaces.

1. Introduction

The classical model showing why surface roughness even of extremely tiny amplitude destroys adhesion was due to Fuller and Tabor [9]. Experiments on rubber spheres pressed against roughened Perspex flats showed that less than a micrometer of roughness amplitude reduced the pull-off force of about one order of magnitude with respect to the values obtained with rubber spheres of size of the order of 10 mm against the smooth surface. Fuller and Tabor also explained these results with a generalization of the GW [12] asperity model to the case with adhesion described with the JKR theory [15]. Among the many strong assumptions made by Fuller and Tabor most of which are inherited from the GW model, there is the additional idea to use the analysis for a nominally flat contact with a random distribution of summits, whose limit behavior is the pull-off of aligned summits, and not that of a smooth sphere. In these respects, it is quite surprising that agreement between model and theory was satisfactory. But clearly Fuller and Tabor did not push their experiments to further reduction of adhesion: it is instructive to estimate the number of summits involved in their experiments. If we use the quantities reported in their Table1 for the smooth surface experiments, it appears that the contact area at pull-off was of the order of a little less than 1 mm^2, and the density of summits of the order of few hundreds/one thousand per mm^2: hence, we can estimate an order of about 1000 summits in the nominal contact area. In principle, they could be able to measure a corresponding reduction of 3 orders of magnitude in adhesion, up to just a single asperity in contact at pull-off.

Independently on the number of summits, the *tails* of a distribution are not necessarily Gaussian, although Central Limit Theorem (CLT) suggests a process defined by the sum of many independent components (but nominally of same “size”!) to slowly tend to be Gaussian. However, especially in the multiscale surfaces (“fractal” or “self-affine” in a broad range of wavelength), even if roughness is present from macroscale down to atomic scale, the longest wavelengths inevitably dominates the height distribution,[1] especially at low fractal dimensions, which is by far the case of most common practical interest [23]. Assuming the presence of roll-off in the PSD (Power Spectrum Density) does lead eventually to a much more Gaussian and ergodic process, but not always this is used in simulations (Pastewka and Robbins [21], PR in the following, assume for example very little roll-off, as far as we can judge), and it is also not always measured in experiments. Persson et al. [23] have an extensive set of measurements of rough surfaces, but even with the presence of roll-off, the tails do not extend very far — the question therefore remains open if real surfaces should strictly be assumed Gaussian. Without roll-off, single realization of a surface may look close to a uniform distribution of asperity heights, see eg. Fig. 3 of Ciavarella and Afferrante [7]. While this has very limited effect in the contact without adhesion [27] except in limit cases like in the presence of wear [5], this has not been investigated in the context of adhesion, as far as we know.

In the Fuller and Tabor asperity model, it is the competition between the compressive and tensile loads which gives eventually the pull-off. To illustrate the model, an adhesion parameter is introduced (Δ_c in their paper) which depends on the ratio between the separation at pull-off in the JKR model, δ_c, and the rms amplitude of summit heights h_{rms}

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[1] Notice that a single sinusoid has a distribution which is even singular at the highest and lowest point.

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$$\theta = \frac{\delta_c}{h_{rms}} = \pi^{2/3}\left(\frac{w}{E^*}\right)^{2/3}\frac{R^{1/3}}{h_{rms}} \tag{1}$$

where w is work of adhesion of the surface pair, E^* the plane strain elastic modulus of the contacting materials and R the radius of summits.

We study the Fuller and Tabor model in a discretized version, in order to assess the influence of a finite number of summits, of the non-Gaussian distribution, first in the simple model of a random distribution of summit heights, and then with numerical experiments with self-affine random surfaces generated in principle to be Gaussian.

2. Fuller and tabor (FT) model

The original Fuller and Tabor [9] model introduces adhesion in the Greenwood-Williamson [12] model of a set of independent, identical, spherical summits, using instead of the Hertz equation, those obtained by Johnson et al. [15], which are relevant to large, compliant, spheres, whereas for small summits it is perhaps more appropriate to introduce the DMT model [8], specifically in the form presented by Maugis [18]. The DMT theory doesn't change the Hertzian area vs. remote approach δ relationship. The area of contact is intended to be the "repulsive" part where the Hertzian pressures act, whereas adhesive forces are only outside the contact area and depend on the gap produced by the compressive forces. This results in a total force [18] sum of a Hertzian component and a term independent on remote approach (which also gives the pull-off force $F_c = 2\pi wR$ when $\delta = 0$, although we do not change the definition of θ in (1)), resulting in

$$F = \frac{4}{3}E^*\delta^{3/2}R^{1/2} - F_c \tag{2}$$

where R is the radius of the summit.

Integrating over a distribution of identical summits with a Gaussian height distribution, one obtains area-separation and force-separation as follows

$$\frac{A(t)}{A_0} = \sqrt{\pi/2}\,h_{rms}RD_{sum}I_1(t) \tag{3}$$

$$\frac{F(t)}{N_{asp}F_c} = \frac{\sqrt{2/\pi}}{3}\frac{I_{3/2}(t)}{\theta^{3/2}} - \frac{I_0(t)}{\sqrt{2\pi}} \tag{4}$$

where $I_n(t) = \int_t^\infty d\xi(\xi - t)^n \exp(-\xi^2/2)$, h_{rms} is rms amplitude of summit heights, $t = s/h_{rms}$ is dimensionless separation, D_{sum} the number of summits per unit area (density).

In order to derive reasonable estimates of the quantities involved in an asperity model, there is a well established random process theory for Gaussian surfaces [20], which gives density of "summits" (the asperities), their mean radius, and the rms amplitude of their heights as

$$D_{sum} = \frac{1}{6\pi\sqrt{3}}\frac{m_4}{m_2}; \quad \frac{1}{R} = \frac{8}{3}\sqrt{\frac{m_4}{\pi}}; \quad h_{rms} = \sqrt{m_0\left(1 - \frac{0.9}{\alpha}\right)} \tag{5}$$

where m's and m_4 are the moments of the PSD (Power Spectrum Density) of the surface roughness (here, the moments are relative to the profile spectrum), or else the variance of surface heights, slopes and curvatures, and where α is the Nayak bandwidth parameter defined as $\alpha = m_0 m_4/m_2^2$, ranging from 1.5 (narrow-band) to ∞. We are confusing here the summit rms amplitude with h_{rms}, with simplicity of notation, since the two quantities are very close anyway.

Notice the quantity appearing in the area equation of the Fuller and Tabor model (3), can be estimated as

$$h_{rms}RD_{sum} = \frac{1}{48}\sqrt{\frac{3}{\pi}(\alpha - 0.9)} \tag{6}$$

and was considered to be constant and equal to 0.05 or 0.1, when measuring instruments did not permit to explore a wide spectrum.

Turning back to the Fuller and Tabor model, the load-separation as

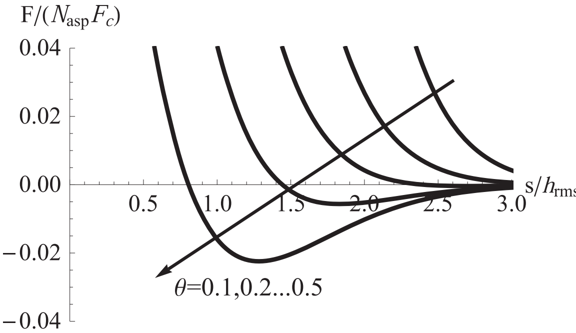

Fig. 1. The dimensionless load $F/(N_{asp}F_c)$ as a function of the normalized separation s/h_{rms} for Gaussian distribution of asperities heights. Notice the force is normalized with respect to the product between the pull-off force of a single asperity and the total number of asperities. Results are given by using in the FT model the DMT-Maugis constitutive law for the single asperity. Plots are presented for different values of the adhesive parameter θ = 0.1, 0.2, 0.3, 0.4 and 0.5, which is higher for the curves more in the tensile (negative) load region.

obtained from (4), is shown in Fig. 1 for different values of the adhesion parameter θ (higher θ corresponds obviously to the curves more in the tensile region). According to the definition of "stickiness" given by PR, here the transition to this regime seems to occur (reading it at realistically small contact areas, where one can use numerical codes with accuracy) at a value of θ between 0.3 and 0.4.

It is clear from Fig. 1 that increasing the adhesion parameter leads to a minimum (pull-off) at increasingly low separations. However, the asperity models give a poor description of the geometry of random surfaces when, say, $t < 1$ (see [11]) if the bandwidth parameter α is large ($\alpha > 20$), which means that the region of validity is a priori rather limited in terms of θ. It is unclear how strong this limitation is, as there is presently no estimate on the order of error made by the asperity model, with the exception of the PR, which we shall use indeed for comparative purposes.

When θ is very high, the Fuller and Tabor model predicts the pull-off of a set of N_{asp} independent asperities. On the contrary, if full contact is established or a smooth contact is considered, pull-off may occur only at the theoretical adhesive van der Waals strength, unless we postulate the existence of flaws at the interface in analogy, for example, to Johnson [16] or Afferrante et al. [1]. As remarked by Fuller and Tabor, when using for the rms amplitude a value of the order of atomic spacing, the model surprisingly shows indeed this order of magnitude of adhesion, and we shall discuss this limit in details when comparing with PR. Furthermore, for high adhesion parameter, it has been suggested that roughness may possibly increase stickiness rather than decrease it [10] and this could be in conflict with asperity models. This effect has been found clearly in very special regular surfaces in the JKR regime having either axisymmetric or 1D regular roughness [13], but is much less pronounced for less regular ones [14] — this, incidentally, means that a purely 1D random roughness could behave extremely differently form a 2D one, and results specific to 1D profiles [4] could trigger this mechanisms and should not be translated to a true 2D roughness. Notice Carbone et al. [4] predicts a possible contribution to adhesion due to roughness-induced increase of the true contact area. Also the finite dimensions and boundary configurations of the contacting bodies can play a crucial role in affecting stickiness [19].

On the other hand, when θ is very low, the predicted pull-off occurs at very high separations, where one may also doubt that the small number of asperities in contact will follow the Gaussian distribution.

In order to shed light into this problem, we shall investigate distributions of asperities generated independently on any actual random process surface, to discuss two effects in a simple configuration: the finite number of asperities, and the absence of tails in the distribution. Since both lead to very significant deviations from the ideal Fuller-Tabor model, we then investigate self-affine nominally "Gaussian" surfaces.