International Journal of Mechanical Sciences 104 (2015) 104–111

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Adhesive rough contacts near complete contact

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ARTICLE INFO

Article history:
Received 11 May 2015
Received in revised form
3 October 2015
Accepted 12 October 2015
Available online 18 October 2015

Keywords:
Roughness
Adhesion
Fuller and Tabor's theory
Fractals

ABSTRACT

Classical asperity theories predict, in qualitative agreement with experimental observations, that adhesion is always destroyed by roughness except if the roughness amplitude is extremely small, and the materials are particularly soft. This happens for all fractal dimensions. However, these theories are limited due to the geometrical simplification, which may be particularly strong in conditions near full contact. We therefore introduce a simple model for adhesion which aims at being rigorous near full contact, where we postulate there are only small isolated gaps between the two bodies, as an extension of the adhesive-less solution proposed recently by Xu, Jackson, and Marghitu (XJM model) (Xu et al., 2014) [1], using the JKR theory for each gap. The results confirm recent theories in that we find an important effect of the fractal dimension. For $D<2.5$, the case which includes the vast majority of natural surfaces, there is an expected strong effect of adhesion. Only for large fractal dimensions, $D>2.5$, it seems that for large enough magnifications a full fractal roughness completely destroys adhesion. These results are partly paradoxical since strong adhesion is not observed in nature except in special cases.

1. Introduction

Adhesion between elastic bodies was relatively unexplored until the last few decades, and this is reflected in the very marginal role it has in the otherwie very comprehensive book of Johnson [2], despite Johnson himself is one of the authors of one of the most important papers on adhesion (on adhesion of elastic spheres, the JKR theory, Johnson et al., [3], which has over 5000 citations at present). This is obviously because until sufficiently accurate and high-resolution technique were developed, adhesion was hard to measure, because of roughness, it was commonly observed and explained, destroys the otherwise very strong field of attraction between bodies, which should in principle make them stuck to each other at the theoretical strength of the material. JKR theory itself was developed having in mind the special cases where adhesion can indeed be measured at the macroscopic scales, using very soft materials like rubber and gelatin spheres, clean and with extremely smooth surfaces. Today, there is however interest in both scientific and technological areas also at small scale, where very smooth surfaces for example in information storage devices result in adhesive forces playing a more crucial role than in more conventional tribological applications. On the other hand, when people have started to study adhesion in Geckos, which adhere to just about any surface, being it wet or dry, smooth or rough, hard or soft, with a number of additional extraordinary features (self-cleaning, mechanical switching), interest is emerging on how to reproduce these capabilities in "gecko inspired synthetic adhesives". The interest stems on the fact that adhesion cannot be produced on hard rough surfaces, and therefore only the strikingly complex hierarchical structure of the gecko attachment can produce the macroscopic values of load that Gecko can sustain.

This makes one wonder why the multiscale nature of surface roughness also could not show an effect of adhesion enhancement. Indeed, at least one model of adhesion of solid bodies (that of Persson and Tosatti, [4], PT in the following), does show adhesion persistence and even enhancement. There seems to be a qualitative difference for surfaces with fractal dimensions below 2.5, which turns out to be the case in most if not the totality of the commonly observed rough surfaces (Persson, [5]). In general however, it is hard to measure strong adhesion, despite the van der Waals interactions in principle are orders of magnitude larger than atmospheric pressure — this "adhesion paradox" (Pastewka and Robbins, [6], Persson et al., [7]) has been linked to surface roughness, but the explanations of the paradox have been different, the latest very interesting one being due to Pastewka and Robbins [6], which is a very promising parameter-free theory that shows how adhesion changes contact area and when surfaces are sticky — but mostly in a regime near small contact areas. Pastewka and Robbins [6] conclude that *"For most materials, the internal cohesive interactions that determine elastic stiffness are stronger than adhesive interactions, and surfaces will only stick when they are extremely smooth. Tape, geckos, and other adhesives stick because the*

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http://dx.doi.org/10.1016/j.ijmecsci.2015.10.005
0020-7403/

effect of internal bonds is diminished to make them anomalously compliant". This conclusion seems in qualitative agreement with the classical asperity theory, except that Pastewka and Robbins use in their model quantities related to slopes and not to heights and show no explicit strong dependence on fractal dimension, being therefore in quantitative disagreement with previous theories (including the one we are about to develop).

Persson [8,9] introduced more elaborate version of the theory, which solves the partial contact problem also, and the coupling of the two aspects (effective energy due to roughness in full contact, and its use in a partial contact with a diffusion model) makes the limit behavior for very short wavelengths difficult to capture, and motivated us to search a possibly simpler, more traditional picture.

The traditional asperity model of Fuller and Tabor [10], today is not considered to be adequate because of its many assumptions on geometry and absence of interaction, showed that adhesion and pull-off force is reduced very easily at macroscopic scale by roughness, quantified by a ratio between roughness amplitude and single asperity separation at pull-off. Even extremely tiny amounts of roughness amplitude reduce the pull-off force to values orders of magnitude lower than the nominal value of aligned asperities which is the reference value for FT theory. The original FT theory was applied to experiments on rubber spheres on rough Perspex flats and despite this qualitatively different geometry, seemed to be able to provide a good agreement with the experiments, within the limits of their accuracy. Pastewka and Robbins [6] show instead in their Fig. S3 various orders of magnitude higher adhesion in their numerical experiments than what expected by FT theory. In the mean time, the only case where FT theory seemed contradicted by experimental evidence, was in some measurements of adhesion in highly viscoelastic solids (Fuller and Roberts, [11], Briggs and Briscoe [12]). These experiments indeed showed an enhancement of adhesion with roughness, which was not expected in the pure elastic FT model. More recent evidence comes from the cleverly designed experiments using a two-scale axisymmetric problem with roughness between gelatin and Perspex flat rough plates, by Guduru and his group (Guduru [13], Guduru et al. [14], Waters et al. [15]). They showed clearly that an elastic JKR analysis explains the strong increment of pull-off forces observed (an order of magnitude increase), and that this comes with irreversible energy dissipated in many jumps of the force–area curve.

In this paper, we shall try therefore a new model for a rough surface, completely different from either asperity models, and PT model (or Persson [8,9]). The model is based on the very simple idea which could be attributed to Bueckner [16]: namely, that the gaps in an otherwise full contact are cracks that cannot sustain finite stress intensity factors in the case of pure mechanical contact without adhesion, or that can sustain the appropriate stress intensity factor corresponding to the toughness K_{Ic} (in terms of surface energy, $G_c = K_{Ic}^2/E$), in the case of adhesion. This technique was used recently for the case without adhesion by Xu et al. [1] (XJM theory), who in turn extended a methodology adopted by Johnson et al. [17] for a deterministic sinusoidal 3D contact, both near full contact but without adhesion. Greenwood [18] further discusses the XJM theory, in particular as regarding the assumption of parabolic distribution of tensile pressures near the asperity full contact pressure summits. Here, we shall therefore develop a method for a random rough surface to the case with adhesion.

2. Preliminary remarks on a single sinusoid contact

Before embarking into the full rough surface case, it is crucially important to understand qualitatively the mechanics of adhesion near full contact. At a risk to make this paragraph a little disconnected to the rest of the paper, the best strategy is to start from the relatively simple behavior of a single sinusoidal contact, as studied quantitatively by Ken Johnson under the JKR regime assumption (Johnson, [19]). Taking therefore a sinusoid with λ wavelength, h amplitude, in contact against a flat surface, and considering materials with combined plane strain elastic modulus E^*, $p^* = \pi E^*(h/\lambda)$ is the compressive mean pressure to flatten the sinusoid and achieve full contact without adhesion. In the adhesive case, curves of area–load are described in Fig. 1, where we have considered the case of a 1D profile for simplicity because it is fully analytical. The curves depend on a parameter

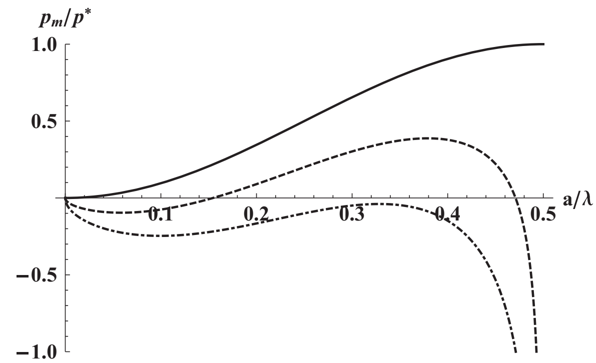

Fig. 1. The relationship between p/p^* and contact area ratio a/λ for Johnson's JKR solution of the single 1D sinusoidal adhesive contact problem. The change from the pure contact case $\alpha = 0$ (solid line) to adhesive case $\alpha = 0.3, 0.6$ (dashed and dot-dashed line, respectively).

$$\alpha = \sqrt{\frac{2\lambda\Delta\gamma}{\pi^2 h^2 E}} \tag{1}$$

where $\Delta\gamma$ is the surface energy, and the other symbols have already been introduced.

Starting from the case of "low adhesion" (for $\alpha < 0.6$), we can describe the behavior during loading as follows. The curve has two extremes, a minimum and a maximum: under zero load, the contact jumps into a state of contact given by the intersection of the curve with the load axis. Upon further increase of the load, it follows the stable curve, until it jumps into full contact at the maximum. At this point the strength is theoretically infinite (more precisely, the theoretical stress of the material) unless we postulate the existence of some flaw of trapped air, as Johnson suggests, and which gives a bounded tensile pressure for pull-off after loading above the curve at the maximum. If instead we do not load above the maximum, we have a more regular unloading without the "need" to postulate flaws, and the loading curve is followed in a stable manner until a minimum is reached which was not visible during loading. This defines pull-off in essentially a Hertzian regime since the contact area is small with respect to wavelength.

Turning now to higher values of adhesion parameter α, we reach a "critical" value of adhesion of about $\alpha = 0.6$, for which the surfaces will spontaneously snap into full contact at zero load. What matters in particular to the present investigation is that the original contact curve (that without adhesion) changes sharply shape when adhesion is introduced, since the negative pressure region appears which is crucial to understand pull-off loads, and the transition towards infinite tension is also introduced. However, our model will not use the sinusoid as a basic element and therefore the analogy stops here.

3. The model

In the classical random process theory, since surfaces are described as random variables, the pressure to cause full contact,