International Journal of Solids and Structures 81 (2016) 244–249

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

Adhesive contact of a power-law graded elastic half-space with a randomly rough rigid surface

Fan Jin[a], Wei Zhang[b], Qiang Wan[a], Xu Guo[c,*]

[a] Institute of Systems Engineering, China Academy of Engineering Physics, Mianyang, Sichuan 621900, PR China
[b] Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, FL 32601, USA
[c] State Key Laboratory of Structural Analysis for Industrial Equipment, Department of Engineering Mechanics, Dalian University of Technology, Dalian 116023, PR China

ARTICLE INFO

Article history:
Received 27 July 2015
Revised 20 October 2015
Available online 14 December 2015

Keywords:
Contact mechanics
Adhesion
Power-law graded materials
Rough surfaces
Adhesion hysteresis

ABSTRACT

A theoretical model of a power-law graded elastic half-space in contact with a randomly rough rigid surface is established by combining the Greenwood–Williamson rough contact model and the JKR type adhesion model for power-law graded materials. The rough surface is modeled as an ensemble of non-interacting asperities with identical radius of curvature and Gaussian distributed heights. By applying the JKR type theory for power-law graded solids to each individual asperity of the rough surface, the total normal forces for the rough surface are derived for loading and unloading stages, respectively, and a prominent adhesion hysteresis associated with dissipation energy is revealed. Our results include the solutions for homogeneous materials and Gibson solids as special cases and describe the complete transition between these two limiting situations. A dimensionless adhesion parameter, which influences both the total pull-off force and the energy dissipation due to adhesive hysteresis, is also identified. It is found that a small adhesion parameter results in higher energy dissipation and pull-off force, while a large adhesion parameter leads to lower energy dissipation and pull-off force.

1. Introduction

Modern technological developments have led to considerable interest in functionally graded materials (FGMs) whose properties vary continuously in space (Suresh and Mortensen, 1998). FGMs possess a number of advantages that make them attractive in many physical and biological systems for designing structures with exceptional resistance to deformation, fracture, fatigue and fiction induced damage (Suresh, 2001). For instance, the indentation studies of FGMs show that elastic gradients could offer unprecedented opportunities for materials to achieve improved wear and failure resistance (Giannakopoulos and Suresh, 1997a, 1997b; Jitcharoen et al., 1998). Nowadays, FGMs have been employed frequently in micro-electro-mechanical systems (MEMS) to locally enhance mechanical reliability (Hassanin and Jiang, 2014). It is found that FGMs also play very important roles in biological systems. For example, the adhesion pads on many insects consist of FGMs which exhibit robust flow tolerant adhesion (Sherge and Gorb, 2001; Yao and Gao, 2007; Chen and Chen, 2010). The enamel and dentin layers in teeth are joined over a region of graded material properties which is thought to be very important for reducing stress concentrations (Huang et al., 2007; Niu et al., 2009).

The above applications require a fundamental understanding of the underlying mechanisms and concise theoretical models to characterize the contact and adhesion behavior between surfaces of FGMs. The Hertzian type contact models for power-law graded elastic materials were firstly established in the axisymmetric (Giannakopoulos and Suresh, 1997a, b) and plane strain cases (Giannakopoulos and Pallot, 2000), respectively. Based on these results, the corresponding JKR type models were then developed by Chen et al. (2009a, b) for both frictionless axisymmetric and plane strain cases, and further extended to non-slipping adhesive contact problems (Jin and Guo, 2010, 2012; Guo et al., 2011), and to frictionless adhesion involving any axisymmetric punch shapes (Jin et al., 2013a). Recently, a JKR-DMT transition model for adhesive contact on power-law graded elastic solids was presented based on a double-Hertz model to account for more general material properties (Jin et al., 2013b).

The above mentioned models, however, are mainly focused on smooth contact interfaces. In fact, even a highly polished surface may have surface roughness on multiple length scales. Roughness is believed to be a key factor in design and model of micro-scale surfaces in MEMS (Bora et al., 2005; Toler et al., 2013). Under this circumstance, understanding the adhesive behavior involving both

* Corresponding author. Tel.: +86 411 84707807.
E-mail address: guoxu@dlut.edu.cn (X. Guo).

http://dx.doi.org/10.1016/j.ijsolstr.2015.12.001
0020-7683/

surface roughness and graded materials seems to be a challenging topic. However, the classical rough adhesive contact models for homogeneous solids have been valuable in shedding light on the mechanisms of FGMs. In a seminal paper, Greenwood and Williamson (1966) modeled rough surfaces as an ensemble of non-interacting asperities with identical radius of curvature and height following a Gaussian distribution (GW model), in which the classical Hertz theory was applied to the contact analysis of each individual asperity. The GW approach laid a solid foundation for many subsequent studies, including JKR-based rough model (Fuller and Tabor, 1975) and JKR-DMT transition rough model (Morrow et al., 2003; Zhang et al., 2014). A common conclusion obtained in these multiple asperity contact models is that increasing roughness may result in a monotonic decrease of adhesion. This result was later validated by experiments for large surface roughness, where the interaction between asperities can be ignored (Kim and Russell, 2001; Kesari et al., 2010).

In the absence of adhesion, the GW rough contact model was recently generalized to consider linearly graded elastic rough surfaces (Paggi and Zavarise, 2011). Their results showed that the graded elasticity has an effect on the equilibrium relation between the real contact and load, which lead to quite different contact response from that of a homogeneous surface. More recently, Chen et al. (2014) presented a multi-asperities adhesion model of power-law graded materials and found that the roughness effect and graded material properties can significantly alter the interfacial adhesive strength. Besides, we established a JKR-type adhesion solution between a power-law graded half-space and an axisymmetric rigid punch with sinusoidal undulations (Jin and Guo, 2013). Results showed that simultaneous presence of surface roughness and graded material properties can influence the pull-off force and energy dissipation due to adhesion hysteresis significantly. However, our previous model works well only for small roughness, there is still a lack of adhesion theory of FGMs with large surface roughness.

The main objective of the present study is to develop an adhesive contact model for power-law graded elastic solids involving randomly rough surfaces. Special emphasis is placed on investigating the combined effect of surface roughness and graded elasticity on the total pull-off force and energy dissipation due to adhesion hysteresis. The problem considered here is a generalization of the rough adhesion for homogeneous materials involving both the interfacial toughness (measured by the dissipation energy) (Wei et al., 2010) and strength (measured by the total pull-off force) (Fuller and Tabor, 1975). The remainder of the paper is organized as follows. First, the main results of the double-Hertz theory for a single contact asperity are summarized in Section 2. Based on these results, the adhesion hysteresis and the total pull-off force of the rough contact system are examined in Sections 3 and 4, respectively. A dimensionless adhesion parameter is defined as a key factor in Section 5. Some concluding remarks and discussions are finally provided in Section 6.

2. Rough adhesive contact model

As shown in Fig. 1a, a randomly rough rigid surface is in adhesive, frictionless contact with a power-law graded elastic half-space with a smooth surface. Based on the reference plane of the rough surface defined by the mean asperity height, z measures the asperity height while d represents the distance between the contacting surfaces. Following Greenwood and Williamson (1966), the randomly rough surface can be modeled as an ensemble of non-interacting asperities with identical radius of curvature R and heights following Gaussian distribution with a probability density function

$$\phi(z) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{z^2}{2\sigma^2}\right), \tag{1}$$

where σ is the standard deviation of asperity heights. Lower values of σ correspond to smoother surface, whereas higher values of σ represent rougher surface. As shown in Fig. 1b, each asperity corresponds to a spherical shape. It should be noted that this multiple asperity contact model applies to surfaces with large roughness, in which each individual contact is independent and the interaction between asperities can be ignored (Kesari et al., 2010).

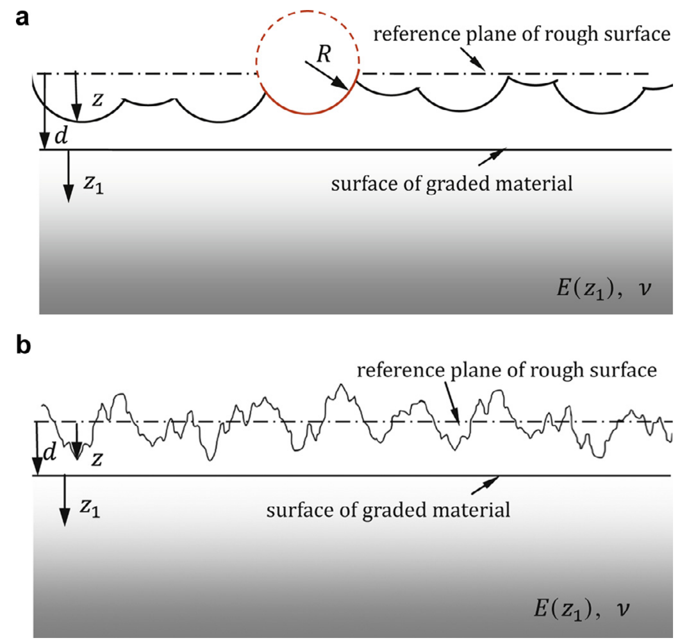

Fig. 1. Adhesive contact between a rigid smooth plane and a power-law graded substrate with rough surface in (a) a real model and (b) a simplified model.

The graded half-space considered here has a constant Poisson's ratio ν and a Young's modulus varying with depth measured from its surface according to the following power-law form

$$E = E_0 (z_1/c_0)^k, \quad 0 < k < 1, \tag{2}$$

where E_0 is a reference modulus, $c_0(>0)$ is a characteristic length of modulus variation and k is the gradient exponent. It is obvious that homogeneous isotropic material is recovered as $k = 0$ while the Gibson solid (Gibson, 1967) is obtained as $k = 1$ and $\nu = 0.5$.

In fact, the present model can be equivalent to the adhesive contact problem between a rigid smooth surface and a graded elastic half-space with a randomly rough surface. In the latter case, the contact asperities are identical but they are themselves graded, in other words, each asperity has the same grading on the Young's modulus from its tip towards the bulk. The latter case is similar to "the locally heterogeneous asperities" which was referred to Case II by Paggi and Zavarise (2011). This grading may take place in an initially homogeneous rough surface which receives a surface treatment or a chemical degradation with modified elastic properties of the asperities as a function of the depth from the exposed surface.

2.1. Approximate JKR solutions for a single contact asperity

According to the concept of GW model, the single asperity contact problem serves as the theoretical basis for establishing the statistical rough contact model. In the presence of adhesive interactions, the JKR type solutions of the normal load (negative when tensile) and the indentation depth (negative when tensile) for a power-law graded elastic solid contacting with a rigid sphere can be summarized as (Chen et al., 2009a; Guo et al., 2011; Jin et al., 2013):

$$P = \frac{2^{2-k}\vartheta}{(1+k)^2(3+k)} \frac{E^* a^{3+k}}{R c_0^k} - \frac{1}{1+k}\sqrt{2^{3-k}\vartheta\pi \frac{E^*\Delta\gamma a^{3+k}}{c_0^k}}, \tag{3}$$