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Analytical asperity interaction model and numerical model of multi-asperity contact for power hardening materials

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ABSTRACT

In the present work, an analytical interaction model of multi-asperity contact for the power-law hardening materials is proposed. The real surface topography including the asperity locations, heights and radii of summit is considered. Meantime, a numerical model is built based on the finite element method, to study the contact of a rigid flat and a deformable rough surface which is simplified and reconstructed with the measured original surface using the wavelet transform. The analytical results are close to the numerical results. Finally, the effect of the power-law hardening material properties on the asperity interaction is studied.

1. Introduction

Contact widely exists in many engineering applications such as the microelectromechanical systems (MEMS) [1,2] and bolted connections [3]. The contact behaviors affect the product performances greatly, which need to be studied in detail. However, all surfaces are rough in the microscopy scale, leading to the surface contact discontinuous and irregular. Thus it is a challenging work to reveal the contact mechanism. The pioneer Greenwood and Williamson model (GW model) [4] employed the Hertz contact theory and the statistical description of asperity heights, to bridge the contact of asperities in microscale and the macroscale surface contact. They regarded that the heights z of almost all asperities on rough surfaces distributed in the range of $\mu-3\sigma_s$ and $\mu+3\sigma_s$ according to Gaussian distribution, where μ and σ_s are the mean plane and the standard deviation of asperity heights respectively. All asperities were assumed having identical radii, which might not be able to represent the real surface topography quite accurately. Many subsequent works [5,6] modified the GW model and simplified the rough surfaces contact as the contact between a rigid flat and a rough surface. A corresponding schematic of the contact at a separation d between the mean plane of asperity heights and the rigid flat is shown in Fig. 1. Considering material layers close to the surface have often contamination and different microstructures as compared to the bulk, some researchers [7–9] studied the contact by considering graded elastic or plastic rough surfaces.

Nevertheless, the asperity interaction was always ignored for a long time, which is not realistic since all asperities are attached to the substrate, and the interaction effect through the continuous substrate is ineluctable. Recently, researchers have studied the asperity interaction. Zhao and Chang [10] computed the asperity deformation due to a uniform contact pressure acting outside the territory of the asperity, and considered it as the asperity interaction effect. They found that the asperity interaction significantly affected the mean surface separation and micro-contact load redistribution. Iida and Ono [11] investigated the surface contact with the improved GW model including the asperity interaction. They treated the asperity contact as an elastic point contact, but this assumption was no longer valid when the contact load was high. Ciavarella et al. [12] proposed a discretized GW model to consider the interaction effect in the first-order sense, namely for each asperity, a displacement affected by the Hertzian pressures on the other asperities would be imposed. Then Ciavarella et al. [13] continued to modify the GW theory with the inclusion of interaction between asperities considering the contact pressures distributed uniformly over the nominal area. They assumed elastic asperity contact and treated the substrate level as the mean plane of asperity heights. However, the substrate determined in this way cannot be continuous due to the peaks and valleys under the mean of the asperity heights. To overcome this defect and assume the substrate as a continuum, Chandrasekar et al. [14] presented a new definition for the substrate level based on the shortest asperity recently. They assumed the asperity spacing as a constant decided by the asperity density, and studied the effect of the asperity

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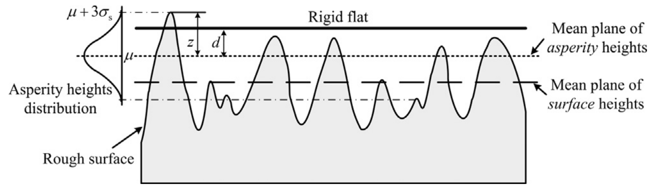

Fig. 1. Schematic of the contact between a rigid flat and a rough surface at a separation d. The distribution of the asperity heights z accords with the Gaussian distribution, whose mean plane and standard deviation are μ and σ_s respectively.

spacing on the interactive contact load. Also, they adopted elastic–plastic contact formulations for line-hardening materials to consider the heavy loading condition. Yeo et al. [15] treated the asperity interaction as the substrate deformation caused by a Hertzian pressure on the elastic flat half-space, considering the actual topography to some extent with the identical asperity radii assumption. Vakis [16] established a statistical summation model considering asperity interaction, in which interaction deformations of non-contacting asperities were computed according to the probability that they had taller neighbors around. The influence of order of the asperity interaction on the contact force was explored.

Meanwhile, the finite element (FE) method is also another effective means to study the surface contact including the asperity interaction effect. Komvopoulos et al. [17] simulated a two-dimensional (2-D) contact between relatively smooth and machined surfaces as that between an elastic half-space and a rigid rough surface consisting of cylindrical asperities using the FE model. Gao et al. [18] also developed a 2-D contact between a flat rigid platen and an elastic–perfectly plastic solid with a sinusoidal surface to analyze the contact between elastic–plastic solids. Recently, the three-dimensional (3-D) models have been established as the FE method develops. Eid and Adams [19] established a two-asperity model with two connected neighboring deformable hemispheres to study the interaction. Through changing the geometrical relations of two hemispheres, the influence of asperity interaction on the contact force and area were revealed in detail. Chandrasekar et al. [14] utilized a FE model of 25 spheres on a flat to consider the rough surface topography characteristics. They studied the influence of asperity spacing on the contact load and the asperity interaction. However, the number of the asperities in a real surface is much more than 25, and the specially patterned surface cannot represent the real surface topographies. Medina et al. [20] produced a GW style rough surface on which the asperities were generated at random locations with random heights and uniform radius. With it, they built a numerical model to calculate the contact area and the tangential stiffness, and compared with the analytical results including the interaction effect. Megalingam and Mayuram [21] established a "deterministic" FE contact model to study the contact parameters. The key points were created with the rough surface altitudes generated by the Gaussian random numbers, and were connected by the splines. Then the coon's patches formulation was used to make the rough surface. It was a relatively effective way to consider the actual topography characteristics, but for the high accuracy case, the randomly generated heights still could not reflect all the real features of rough surfaces.

As mentioned above, most asperity interaction models concerned the elastic materials, or elastic–plastic materials with line-hardening plastic characteristics. However, few researchers studied the interaction effect for power-law hardening materials. Furthermore, the effect of the power-law hardening material properties on the asperity interaction was also not considered by most people. So it was necessary to study the multi-asperity contact problem for this kind of materials with the analytical and numerical models. While for the existing analytical models, some used the integrals to consider the rough surface contact, and some others considered the topography with the same radius or same asperity spacing assumption. In contrast, it would be more accurate to consider all actual detailed geometrical characteristics of asperities, consisting of their locations, heights and radii of summit. For the numerical (FE) models considering the contact between the rigid flat and the deformable rough surface, it should be the first work to construct the rough surface. Some of the existing works regarded the rough surface as a specially patterned surface with a few asperities, and some generated the rough surface with random numbers following Gaussian distribution. These were effective ways to reveal the surface characteristics to a certain extent. By comparison, the reconstruction technique based on the real topography was a more efficient and accurate way to reflect the geometrical characteristics of the surface such as roughness [22]. Wavelet transform (WT) has the advantage of fast computation with localization in both space and frequency domains. With the multi-resolution signal decomposition method, WT could be applied to the hierarchical analysis of rough surfaces to obtain the low frequency information which is related to the contact behaviors. Thus WT was a powerful tool to simplify and reconstruct rough surfaces.

In this work, an analytical asperity interaction model for power-law hardening materials is developed. The interaction effect is considered with the substrate deformation caused by the asperity contact. The substrate level, as an important factor influencing the interaction effect, is defined as the base of the shortest asperity where a continuum of solid material starts [16]. To consider the real surface topography, all actual detailed geometrical characteristics of asperities are taken into account, consisting of their locations, heights and radii of summit. A numerical model is also proposed to account for the contact between a rigid flat and a deformable rough surface using the FE method. The rough surface is simplified and reconstructed with the measured original surface using the wavelet transform. The simplification and reconstruction process can make the FE analysis efficiently and precisely. The contact parameters (contact force and contact area) predicted by the analytical model are close to those predicted by the numerical model. The effect of the properties of power-law hardening materials on the interaction is studied with the proposed analytical model.

2. Analytical asperity interaction model

2.1. Topography measurement and asperity analysis

The isotropic elastic–plastic materials were investigated in the present work, whose plastic behavior obeys J_2 flow theory together with isotropic hardening model and satisfies a power hardening law reconstructed by the classical Ramberg–Osgood curve. The constitutive law was given as follows [23]:

$$\xi = \begin{cases} \sigma/E, & \sigma \le Y_0 \\ (Y_0/E)(\sigma/Y_0)^{1/n}, & \sigma > Y_0 \end{cases} \tag{1}$$

where σ and ξ are the stress and the strain respectively, E means the Young's modulus, Y_0 represents the yield strength and n is the stain hardening exponent.

AlZn6CuMgZr (ISO) aluminum alloy, as a typical power-law hardening metallic material, was taken as an example to build the analytical interaction model. The material properties are listed as following: Young's modulus $E=71.7$ GPa, yield strength $Y_0=528$MPa, stain hardening exponent $n=0.21$, which were obtained by the tensile test with the tensile testing machine (Instron 8801, Instron Co., USA). The Poisson's ratio ν is 0.33.

A milling surface was prepared, and the topography was measured by white light interferometer (WYKO NT9300, Veeco Instruments Inc.,