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Plastic deformation and contact area of an elastic–plastic contact of ellipsoid bodies after unloading

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Abstract

This paper presents theoretical and experimental results of the residual or plastic deformation and the plastic contact area of an elastic–plastic contact of ellipsoid bodies after unloading. There are three regime responses of the deformation and contact area: elastic, elastic–plastic and fully plastic. Experimental investigation is presented in order to validate the proposed model. A new technique is introduced to measure the plastic deformation and plastic contact area. Very good correlation is found between the theoretical prediction and the experimental results.
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1. Introduction

Most of engineering surfaces are rough so that when such surfaces are pressed together there will always be some contact at the tips of the micro-protrusions which are called asperities to support the normal load. The real area of contact is therefore smaller than the nominal contact area of the contacting surfaces. Deformation occurs in the region of the contact spots, establishing stresses that oppose the applied load. If the deformation is in the same order as the topography of the surfaces, the response to the normal load may be strongly related to the height and size of the asperities [1,2]. For an elastic–plastic deforming material the plasticity may be initiated either at the surface (asperities) or in the bulk depending on the contact condition. This problem is of particular interest to tribologists and engineers with respect to the functional properties of devices. Depending on the desired functional performance specific contacting surfaces may be designed.

The analytical and numerical modeling for estimating the actual contact deformation and contact area for the contact of surfaces have been studied by many researchers. Greenwood and Williamson [3] studied the contact between a rough flat surface and a rigid flat. They assumed that the rough flat surface is covered with spherical asperities and the heights of the asperities are represented by a well-defined statistical distribution function (i.e. Gaussian). The contact analysis is based on the Hertzian theory [4] where the asperities deform elastically. This elastic asperity-based model has been extended by other researchers, for instance, to the contact of rough curved surfaces [5], the contact of two nominally flat rough surfaces [6], the contact of rough surfaces considering a distribution of the radii of the asperities [7] and elliptic paraboloidal surfaces [8]. However, the aforementioned models are devoted to the elastic contact situation.

Abbot and Firestone [9] introduced the basic plastic contact model, which is known as the profilometric model or surface micro-geometry model. In this model the deformation of a rough surface against a smooth rigid flat is assumed to be equivalent to the truncation of the initial rough surface at its intersection with the flat so that the contact area is simply the geometrical intersection of the original profile. The mean contact pressure is equal to the flow pressure or the indentation hardness of the softer body. For high loads

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Pullen and Williamson [10] proposed a volume conservation model for the fully plastic contact of a rough surface based on the experimental results. Kucharski et al. [11] confirmed this model by finite element analysis.

In order to bridge the two extreme models, elastic and fully plastic, Chang et al. [12] developed an elastic–plastic contact model (CEB) based on volume conservation of the plastically deforming asperities. In the CEB model the deformation mode changes from the elastic to the fully plastic contact regime without transition, whilst Johnson [13] showed, based on the analysis of the indentation of a sphere on a plane, that there is a large transition regime from the elastic to the fully plastic state. This transition is included in modeling the contact of rough surfaces by Zhao et al. [14]. Kogut and Etsion [15] performed a detailed finite element analysis on the elastic-plastic contact of a sphere and a rigid flat. The empirical coefficients for the dimensionless relations for contact load, contact area and mean contact pressure as a function of contact interference have been formulated. However, the analysis is limited up to the onset of the fully plastic state. A similar work has been done recently by Jackson and Green [16], which includes the fully plastic contact regime. To incorporate the effect of the anisotropy of the asperities Horng [17] and Jeng and Wang [18], for instance, extended the model of [12,14], respectively, to the elliptical contact situation. There is no experimental validation of most of the proposed elastic–plastic asperity contact models. A new elastic–plastic elliptical asperity contact model has been developed by Jamari and Schipper [19] based on the experimental results.

Almost all the contact models are devoted to the loading situation. There are only few models, such as Vu-Quoc et al. [20] and Li et al. [21] that consider the unloading situation of the contacting bodies. These models studied the different stages of the unloading process; however, these models have several shortcomings. In the Vu-Quoc model several difficult to obtain constants were introduced and the model was applied to only in the beginning of the elastic–plastic contact regime for a certain material while in the Li model it is very difficult to determine the actual radius of the contacting bodies at the unloading stage. Furthermore, there is no experimental validation of the proposed models. A rigorous analysis of unloading elastic–plastic spheres has been conducted by Mesarovic and Johnson [22]. They found that although the unloading was elastic the pressure distribution was not Hertzian. An expression for the pressure distribution during elastic unloading based on a rigid punch decomposition was derived and has been verified by Wu et al. [23] by finite element analysis. However, the explicit expression to calculate the plastic deformation or geometrical changes after unloading is not presented.

A complete loading/unloading sequence of contacting bodies results in a permanent plastic deformation when the applied load reaches over the critical load. A permanent change of the asperity is formed as a result of the plastic deformation. The change of the surface topography due to plastic deformation is particular of interest in some tribological application, such as, running-in. Therefore, the present study offers a new plastic deformation model of elliptic elastic–plastic asperity contact. In this study, attention will be paid only to the complete loading and unloading process rather than studying the unloading stages itself. Experimental validation has been performed to validate the proposed model. As an illustration, Fig. 1 shows the plastic deformation of the loading/unloading of a Phosphor-bronze sphere ($H = 2.72$ GPa, $E = 115$ GPa and $\upsilon = 0.35$) with a diameter of 3.175 mm in contact with a Sapphire flat ($H = 190$ GPa, $E = 430$ GPa and $\upsilon = 0.26$) at $\omega/\omega_c = 25$, where H is the material hardness, E is the elasticity modulus, υ is the Poisson's ratio, ω is the contact interference and ω_c- is the critical interference where first yield occurs. Plotted are the loading curves of Hertz [4] and JS model [19] and the unloading curve of Li model [21].

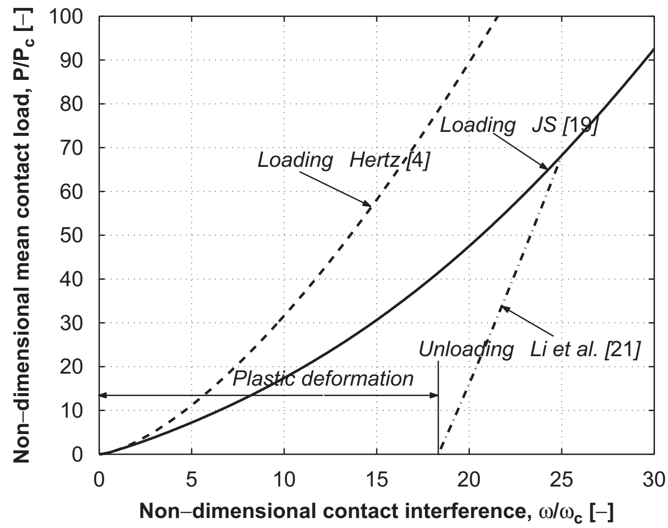

Fig. 1. Non-dimensional load versus non-dimensional interference curves during loading–unloading of a sphere against a rigid flat.

2. Theoretical background

The same as for the loading of an elastic–plastic contacting asperity, the unloading does have three different contact regimes as well i.e. elastic, elastic–plastic and fully plastic.

2.1. Elastic contact unloading

It is widely accepted that the elastic unloading process is assumed to follow the Hertzian analysis. Therefore, in the elastic contact regime there is no difference between loading and unloading contact behaviour. Consequently, the residual contact interference or plastic deformation in this regime, ω_{ue}, and the plastic contact area, A_{ue}, are:

$$\omega_{ue} = 0, \tag{1}$$

$$A_{ue} = 0. \tag{2}$$

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