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Loading–unloading normal stiffness model for power-law hardening surfaces considering actual surface topography

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ABSTRACT

Contact surfaces widely exist in the engineering applications and their contact behaviors strongly affect the mechanical performance. The normal contact stiffness, as an important contact parameter, is studied during loading and unloading process. The normal stiffness of single asperity contact is calculated based on the contact between a power-law hardening hemisphere and a rigid flat under full stick condition and the shoulder–shoulder contact form. The actual surface topography is considered efficiently to build the stiffness model of contact surfaces. The stiffness predicted by the proposed model is verified by the experiments.

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1. Introduction

Contact is ubiquitous in engineering applications, such as MEMS [1], head–disk interface [2], connectors [3], gears [4] and so on. The contact behaviors have great influence on friction [5], wear [6], and conduction of heat and electricity [7]. As one of the important parameters affecting contact behavior, contact stiffness needs to be studied in detail. However, all actual surfaces are rough on a microscopic scale and consist of asperities having different radii and heights. When they are compressed together, the contact is discontinuous and only occurs at discrete points. Consequently, the contact force and deformation vary nonlinearly and the mechanism of the contact stiffness is extremely complicated.

Two approaches are commonly used to explore the stiffness. One is the experimental approach, where the stiffness can be identified utilizing novel techniques such as ultrasonic assessment [8], digital image correlation [9], modal analysis [10] and virtual fields method [11]. The other approach is to build the theoretical contact model and derive the contact stiffness further. There are several kinds of contact models, e.g. statistics model, deterministic model, fractal models and finite element (FE) models. The statistics model was proposed originally by Greenwood and Williamson [12], and improved by many subsequent researchers [13–15]. The deterministic model [16,17] considered all actual geometrical characteristics of the asperities on contact surfaces. The concept of fractals was presented by Mandelbrot [18], and was introduced to describe surfaces and to build the fractal models [19–21] later. By comparison, the FE model is more precise to study single asperity contact which is the base of the surfaces contact. Kogut and Etsion [22] provided an accurate solution to study the contact between an elastic–plastic sphere and a rigid flat. They concluded that the evolution of the contact could be divided into three distinct stages ranging from elastic to plastic, and proposed empirical equations to calculate the contact parameters (contact force and contact area) which were negligibly affected by the ratio of Young's modulus to yield strength E/Y_0. Jackson and Green [23] provided a more accurate FE model with finer meshes and acquired another generalized expressions for contact parameters. They concluded contact parameters were affected by the deformed contact geometry. Shankar and Mayuram [24] studied the effect of the yield strength and the tangent modulus on the transition behaviors of materials from elastic–plastic to the fully plastic case. They derived new empirical relations of the contact parameters and validated them with an experiment. However, these FE models [22–24] only dealt with the loading case but neglected the unloading process. Actually, unloading also plays an important role in many applications, such as MEMS micro switches [25], head–disk interaction in magnetic storage systems [26] and so on. Etsion et al. [27] studied the unloading process of an elastic–plastic loaded sphere in contact with a rigid flat. They gave the dimensionless expressions for the unloading load-deformation relation and the residual interference after complete unloading. This expression was generalized and independent of specific materials or radii of the sphere. Kadin et al. [28] improved this model to consider the effect of adhesion during unloading. Jackson

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Nomenclature

A	contact area
A_c	critical contact area at yielding inception
A_{max}	maximum contact area before unloading
A^*	dimensionless contact area
A^*_{max}	dimensionless maximum contact area
a	contact radius
d	mean separation of two surfaces
E	Young modulus of the hemisphere
E'	combined Young's modulus of two materials
E_T	tangent modulus of the hemisphere
F_n	normal force of contact surfaces
f	contact force
f_c	critical load at yielding inception
f_{max}	maximum contact force
f_n^L	normal components of contact force during loading
f_n^U	normal components of contact force during unloading
f^*	dimensionless contact force
f^*_L	dimensionless contact force in loading process
f^*_{max}	dimensionless maximum contact force
f^*_U	dimensionless contact force in unloading process
K_n	normal stiffness of contact surfaces
k_n^L	normal stiffness in loading process
k_n^U	normal stiffness in unloading process
n	strain hardening exponent
P	normal pressure of contact surfaces
K_n	normal stiffness of contact surfaces
R	radius of the hemisphere
R_s	sum of radii of summits of asperity on surface 1 and 2
$R_{v,1}$, $R_{v,2}$	radii of summits of asperity on surface 1 and 2
$R_{v,1}(r)$, $R_{v,2}(r)$	radii at the contact point of asperity on surface 1 and 2
$R_{v,s}(r)$	equivalent asperity radius at contact point
r	tangential offset of two contact asperities
S	nominal contact area
w	contact interference
w_1	interference defined in Greenwood and Tripp
w_c	critical interference at yielding inception
w_{max}	maximum contact interference before unloading
w_{res}	residual contact interference after fully unloading
w^*	dimensionless contact interference
w^*_{max}	dimensionless maximum contact interference
w^*_{res}	dimensionless residual contact interference after fully unloading
Y_0	virgin yield strength of the hemisphere
z_1, z_2	heights of summits of asperity on surface 1 and 2
α	contact angle
δ_n	change of normal relative deformation of asperities
η	asperity density
λ	error between theoretical models and experiments
μ_x	average value of x, $x=E, Y_0, \nu, n; R, z, \eta$
ν	Poisson's ratio
σ_x	standard deviation of x, $x=E, Y_0, \nu, n; R, z, \eta$
ψ	plasticity index of contact materials

[29] studied the residual stress and deformation in hemispherical contacts during loading and unloading. Jackson [30] predicted the residual deformation of impacting elastic-perfectly plastic spheres during unloading.

Almost all the above FE models were built on the assumed frictionless contact condition. Nevertheless, friction widely exists in the practical applications and the frictionless assumption has been proved invalid in dry contact of dissimilar materials experimentally by McGuiggan [31] and Ovcharenko et al. [32]. Recently, full stick condition was employed in many studies. Brizmer et al. [33,34] analyzed the effect of two contact conditions (frictionless and full stick) on the elasticity terminus and the elastic–plastic properties of a spherical contact, and compared contact parameters under these two conditions. They found contact parameters were not much sensitive to contact conditions and were independent of the ratios E/Y_0, but they were affected by Poisson's ratio ν. The contact area and the mean contact pressure showed good correlation with the experimental results given by Ovcharenko et al. [35]. Zait et al. [36] studied the unloading process of a spherical contact under full stick condition, and proposed the residual profile of the sphere and residual von Mises stresses within the sphere. The theoretical results accorded well with the experiments.

It can be seen from the literature review that many contact models have been developed and modified recently. However, some problems still should be improved further. First, all the aforementioned FE models investigated the contact between a rigid flat and a linear hardening sphere with tangent modulus as 2% of Young's modulus. But power-law materials [37–39] are rarely considered, whose hardening law is more appropriate to be described by power function. And the contact stiffness for power-law hardening materials is an important parameter to study the static and dynamic characteristics of the mechanical equipment made of this kind of materials. Secondly, many FE models simplified the asperity contact as the contact between a rigid flat and a sphere. In this work, considering many asperities were in contact with others obliquely, a shoulder–shoulder asperity contact form [40] was employed. Finally, to investigate the contact of rough surfaces, many models employed a statistical description of rough surfaces [41], or special sinusoidal surfaces [42], or other incomplete description of the real topographies with the same summit radii [43]. By comparison, the deterministic method could describe the surface contact more accurately, as they considered the asperity locations and actual geometry parameters more completely.

In this study, a normal stiffness model for power-law hardening surfaces during loading and unloading process is proposed. The contact model of a single asperity pair is built at first, based on the contact between a power-law hardening hemisphere and a rigid flat under stick condition. Then a modified shoulder–shoulder asperity contact form is employed to establish the stiffness model of single asperity contact. To consider the effect of the actual surface details, the locations and geometrical characteristics of asperities of real metallic specimens are analyzed, with which the asperities are generated to simulate the real contact between surfaces. After that, the stiffness of contact surfaces is derived by summing the components of each single asperity pair. The predicted results are testified by the experiments.

Two hypotheses are taken for simplification in this work: (i) the asperities are in contact with each other independently, and (ii) the deformation of substrate which the asperities attach to is ignored.

2. Contact model of a single asperity pair

The model is built on the contact between a power-law hardening hemisphere and a rigid flat under full stick condition,

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