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The effect of surface roughness characteristics on the elastic–plastic contact performance

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A B S T R A C T

Rough surface elastic–plastic contact performance is investigated in this paper. First, a computer program is developed to generate rough surfaces with given parameters; Then, the elastic–plastic contact model is developed based on minimization of complementary energy and semi-analytical method; finally, contact analysis for rough surfaces are conducted. The results show that kurtosis and skewness have significant effects on the contact performance under light-medium load; for heavy load condition and small skewness, the contact characteristic parameters change slightly along with kurtosis. Comparing with elastic contact, the low contact pressure and large contact area are predicted in elastic–plastic contacts.

1. Introduction

Different machining processes may produce surface topography with different characteristics, which may significantly affect the performance of tribological interface. During past decades, many rough surface contact models have been developed, in most of which, Gaussian surface height distribution was assumed. However, the assumption of Gaussian distribution for surface heights is not accurately practical. In fact, the surface height distribution produced by most of the common machining processes approximately conforms to non-Gaussian distributions [1–3]. For example, turning and shaping produce a positively skewed rough surface, while grinding, honing and milling produces negatively skewed rough surfaces with high kurtosis. The real rough surface can be mathematically approximated by a stochastic process. For a Gaussian rough surface with prescribed autocorrelation function (ACF), two surface roughness parameters are used to represent its characteristics—the standard deviation of surface heights Rq (or rms), and the correlation length β (β_x, β_y for an anisotropic surface); for a non-Gaussian rough surface, two additional parameters are needed to characterize the surface, skewness (Sk) and kurtosis (K). The skewness and kurtosis are the third and fourth moments of the distribution function. A Gaussian surface has a kurtosis of 3. If $K>3$, the surface contains relatively fewer high peaks and low valleys, while $K<3$ corresponds to more high peaks and low valleys over the surface. Bendat [4] proved that the ACF with an exponent-cosine form can express many random phenomena in the real word. Patir [5] proposed a numerical procedure to generate Gaussian and non-Gaussian rough surface with prescribed statistical properties and the given ACF by applying linear transformation to random matrixes. Gu and Huang [6] used two-dimensional auto-regressive model with the assumed ACF matrix of exponential form to generate non-Gaussian rough surface. In recent years, as a fast and convenient tool, filter and Fast Fourier Transform (FFT) were used to generate rough surfaces. Hu and Tonder [7] firstly proposed finite impulse response (FIR) filter based approach to generate a rough surface, in which FFT algorithm was applied to speed up the computation process. Lately, Wu [8,9] improved the filter based method to generate Gaussian and non-Gaussian surface with the given skewness, kurtosis and ACF or spectral density. The generated rough surface can be conveniently used in contact models to analyze the contact behaviors.

In 1966, Greenwood and Williamson [10] investigated the elastic contact of rough surface with the assumption of spherical asperity tips and a Gaussian distribution of asperity heights, they indicated the existence of 'elastic contact hardness'. Since then, different shapes of asperities [11–13] were assumed to represent the rough surface. Further improvements to the GW model were made by many researchers, such as Onions and Archard [14], Chang et al. [15], and Zhao et al. [16]. In CEB model developed by Chang et al. [15], the sphere is still in elastic Hertz contact until a critical interference is reached. The volume conservation of the sphere tip is assumed in CEB model. However, this model leads to the discontinuity from elastic contact to plastic contact. Zhao et al. [16] modified this model based on contact mechanics theory in

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Nomenclature

a_c	critical Hertz contact radius
A	contact area
A_c	critical contact area
E	elastic modulus
E^*	effective elastic modulus
E_T	tangent modulus
$\mathbf{g}$	surface gap
$h_{r,s}$	the coefficient of finite impulse response filter
$\tilde{\mathbf{h}}$	geometrical interference between two surfaces
$\mathbf{h}_0$	initial body separation
$\mathbf{k}$	influence coefficient matrix relating pressure to surface displacement
K	given kurtosis
K_1	input kurtosis of Johnson's system
$\mathbf{p}$ or p	contact pressure
p_H	maximum Hertz contact pressure
P	dimensionless contact pressure, p/p_H
R	auto-correlation function
rms or Rq	standard deviation of the rough surface height
$S_{k,l}$	spectral density
$\boldsymbol{S}$	influence coefficient related plastic deformation with plastic strains
Sk	given skewness
Sk_1	input skewness of Johnson's system
$\boldsymbol{T}$	influence coefficient of pressure to stress
$\mathbf{u}_e$ or u_e	surface elastic deformation
$\mathbf{u}_p$ or u_p	surface plastic deformation
W	load
W_c	critical load
x, y, z	coordinates
Z	rough surface
β_x, β_y	correlation length in x and y direction
$\boldsymbol{\delta}$	approach between two surfaces
$\boldsymbol{\varepsilon}^p$	plastic strain
η	Gauss series
η'	non-Gauss series
ν	Poisson's ratio
$\boldsymbol{\sigma}$	stress in subsurface
σ_s	yield stress
$\boldsymbol{\sigma}^p$	stress caused by plastic strain
$\boldsymbol{\sigma}^0$	stress due to contact pressure directly
φ	phase angle component of rough surface
ω	interference
ω_c	critical interference

conjunction with the continuity and smoothness of variables across different modes of deformation, and they obtained more complete results after comparing with GW and CEB model. Some researchers [17,18] also used mathematical methods to modify the CEB model. The abovementioned statistical models mainly concentrated on the statistical parameters; however, the interactions between the asperities were ignored. Jeng and Wang [19] developed an elastic–plastic microcontact model which considered the ellipticity, the continuity and smoothness of variables across different modes of deformation. However, this study still did not considered the interactions between the asperities. Later, Jeng and Peng [20] investigated the effects of asperity interactions on the mean surface separation and the real contact area in detail. They also used the non-Gaussian rough surface to investigate the effect of different skewnesses and kurtosises. The significant effect of asperity interactions is found. The effects of skewness on the mean surface separation are more pronounced than those of kurtosis.

On the other hand, finite element analysis (FEA) has been becoming a common method to analyze the contact problem. Kucharski et al. [21] solved elastic–plastic contacts of rough surfaces by FEA and gave the empirical relationship between the contact load and the contact area. Liu et al. [22] also used FEA to analyze the elastic–plastic contact problems for rough surfaces, but it was only limited to line-contact problem. Kogut and Etsion [23] analyzed the elastic–plastic adhesion problem for spherical micro-contact by the FEA. They showed substantial differences in the local separation and in the adhesion force comparing with CEB adhesion model [24]. Sahoo and Ali [25] studied the elastic–plastic adhesive contact of non-Gaussian rough surfaces, in which an improved elastic–plastic model was used based on accurate FEA of an elastic–plastic single asperity contact. The results indicated that adhesion indices and skewness values can strongly influence loading–unloading behavior. Poulios and Klit [26] also used the finite-element model to study the elastic–plastic contact problem with real surface topography. The results showed that the plasticity would have significant influence on the calculated area and mean contact pressure. Some researchers also used commercial finite element software to study plastic contact problems. Kogut and Etsion [27] used the ANSYS™ to solve the elastic–plastic contact problem of a sphere and a rigid flat, and they also showed the relationship between the dimensionless interference and contact area and pressure. Jackson and Green [28] also used ANSYS™ to investigate elastic–plastic hemispherical contact against a rigid flat. They fitted the results to empirical formulae for a wide range of interferences and materials in order to use in other applications.

Recently, semi-analytical method (SAM) has been well developed for solving contact problems. In order to use the SAM, the relationship between pressures or shear tractions and displacements on surface and stresses in subsurface should be known first. In the elastic contact, the surface displacement due to pressure or shear tractions can be obtained from the Boussinesq–Cerruti solutions [29]. The influence coefficients relating pressures and shear tractions to stresses can be found in works [30–32]. In order to speed up the related calculations, the discrete convolution—Fast Fourier transform (DC-FFT) [33] approach is widely used. It can reduce the computation complexity from $M\times N\times L$ to $\ln M\times\ln N\times\ln L$. Polonsky and Keer [34] used the conjugate gradient method (CGM) to solve rough contact problems for elastic contacts. The method can converge for arbitrary rough surfaces, but does not consider the influence of plastic deformation. In the aspect of plasticity, Chiu [35] first derived the analytical expressions relating unit initial strain in a cuboid to the residual stresses and displacements in an infinite space in 1977. In following year, Chiu [36] derived the expressions for half space by using an imaginary initial strain to enable the surface to be a free surface. In 1987, Mura [37] first proposed the concept of eigenstrain which is a kind of inelastic strain, such as the thermal expansion, phase transformation, plastic deformation and misfit strain. The plastic strain is a typical eigenstrain, and the eigenstress and eigen-displacement is the residual stress and displacement. Jacq et al. [38] proposed an elastic–plastic model to investigate the elastic–plastic point contact problem using SAM based on Chiu's formulation. The advantage of this model over FEA is the sharp reduction of calculation time especially in a fine mesh. However, the solution of residual stress was relatively complex, and little results for surface topography were shown. Kim et al. [39], Chen et al. [40] and Wang et al. [41]