Tribology International 126 (2018) 270–282

Contents lists available at ScienceDirect

Tribology International

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

The study of anisotropic rough surfaces contact considering lateral contact and interaction between asperities

Zhiqiang Gao, Weiping Fu *, Wen Wang, Weichao Kang, Yanpeng Liu

School of Mechanical and Precision Instrument Engineering, Xi'an University of Technology, Xi'an, 710048, PR China

ARTICLE INFO

Keywords:
Anisotropy
Lateral contact
Interaction
Stiffness

ABSTRACT

Interfacial performances are dissimilar due to the different surface topographies and materials. The aim of this paper is to study the effect of the surface topography on the contact force, contact area and contact stiffness. The distributions of the contact azimuthal angles and the contact angles were introduced in the model to build an anisotropic interface model, which includes the asperity lateral contact and the interaction. The simulation results indicate that the normal contact force, real contact area and contact stiffness decrease with the increasing separation. The standard deviations of asperity heights and asperity contact angles have significant influences on the contact of rough surfaces, while the interfacial anisotropy does not influence the contact performances in the normal direction.

1. Introduction

A machine is constituted by the different parts that are manufactured by various machine tools. The various processing methods make different surface topographies, and it is wide consensus that surface roughness plays an important role in the contact behavior. According to the existing contact models [1–5], a tested consequence of two rough surfaces contacting is that the actual contact area of the interface is smaller than the area of contact surfaces because the contact only occurs on asperities. Therefore, the contact form between the upper and lower asperities, the interaction between adjacent asperities, and the probability distribution of asperities may have important effects on the contact performance. A large number of models [6–10] were proposed to analyze the interface behavior of contacting asperities.

Greenwood and Williamson [11] presented an elastic contact model (the GW model) based on the Hertz theory, and they assumed the rough surface is composed by the different height spherical asperities. Moreover, they discovered the height distribution obeying the Gaussian distribution. Later, Chang et al. [2] proposed a model that extends the GW model from the elastic stage to the fully plastic stage (the CEB model). Zhao et al. [12] studied the problem of the elastic-plastic asperity deformation, which used the mathematical fit method to obtain the elastic-plastic stage (the ZMC model). Kogut and Etsion [13] also studied the contact problem of the elastic-plastic asperity deformation using the finite element analysis method (the KE model), which has been widely used. Another finite element model [14] was subsequently built by Etsion who found the relation between the loading-unloading force and the deformation in the elastic-plastic stage (the Etsion model). Jackson and Green [15] account for a varying geometrical hardness effect using a finite element analysis for an elastic-plastic sphere in contact with a rigid flat surface (the JG Model). However, the above models are based on the assumption of an equivalent rough surface contacting with a smooth rigid surface. So, the stick-slip at the shoulder of asperities is ignored by those models when the upper and lower asperities contact in the lateral form, which is also called the shoulder-to-shoulder contact in other documents [16] [17].

Jäger [18] studied the lateral contact between two elastic spheres, and proposed a method of how to estimate energy dissipation due to friction at the lateral contact. Nevertheless, this model just fit for the elastic asperity. Later, Faulkner and Arnell [19] proposed a statistical model that incorporates the sliding lateral contact of two, three-dimensional, elastic-plastic, hemispherical asperities. Jackson et al. [20] analyzed the sliding lateral contact between spheres using the semi-analytical and the finite element simulation, respectively. Sepehri and Farhang [16] studied the contacting characteristics of two rough surfaces (the SF model), which assumed the asperities are the parabolic body and considered the elastic-perfectly plastic stage. This model studied the effect of the normal component force and the tangential component force on the interfacial deformation, respectively. Abdo and Farhang [1] proposed an elastic–plastic contact model for rough surfaces

* Corresponding author.
E-mail address: weipingf@xaut.edu.cn (W. Fu).

https://doi.org/10.1016/j.triboint.2018.01.056
Received 25 September 2017; Received in revised form 5 January 2018; Accepted 25 January 2018
Available online 21 May 2018

based on plastic asperity concept, which involves asperity shoulder-to-shoulder contact (the AF model). Mulvihill et al. [21] investigated a finite-element model of the sliding lateral contact of cylindrical and spherical metal asperities, and predicted the sliding friction coefficients. Shi et al. [22] developed a three dimensional model of two identical elastic–plastic spherical asperities in contact, which characterizes the initial contact offset with polar angle and azimuthal angle, but this model not includes the contact of rough surfaces. Most of those lateral contact models are using the deformation of the normal component to derive the displacement of the tangential component according to the relation between the spacing of the upper-lower asperities and the asperity contact angle, or using the finite-element method. Although, those above-mentioned models proposed some methods to solve the lateral contact problem, the stick-slip between the upper and lower asperities is still neglected by those models when a pair of asperities contacts in the shoulder-to-shoulder contact. In the current model, a normal force can be resolved into a normal and tangential component forces. Some classical models [2,4,11,13,15] of the normal contact can be used to analyze the normal component, and the Mindlin's model [23], Eriten's model [24] and BKE model [25] are employed to solve the problem of the tangential component.

For the study of the interaction between adjacent asperities, Ciavarella, Greenwood and Paggi [26] reinterpret the asperity theories to formulate an improved GW model with the inclusion of interaction between adjacent asperities, but they ignored the elastic-plastic stage. Later, Zhao et al. [27] based on the ZMC model [12] built an interactive model, which considers the interaction between the adjacent asperities using the Saint-Venant's principle [28,29] and Love's formula [30], and it's valid for the elastic, elastic-plastic and full plastic stages (the ZC model). Jeng et al. [31] uses the ZC model to take account of the effects of asperity interactions on the mean surface separation and real contact area of rough surfaces containing elliptical asperities with Gaussian and non-Gaussian height distributions, and indicates that the effects of asperity interactions become more pronounced as the effective radius ratio of the asperities increases. Chandrasekar et al. [32] studied a normal contact of nominally flat rough surfaces with an improved analytical model of asperity interaction using a finite element method, and they proposed that the asperity spacing (density) is shown to be an important roughness parameter in determining the effects of asperity interaction. Moreover, they give an elastic–plastic contact formulation for line-hardening materials to consider the heavy loading condition. Bin et al. [17] proposed an analytical interaction model of multi-asperity contact for the power-law hardening materials, and consider the contact of a rigid flat and a rough power-law hardening surface under the stick contact condition.

About the study of the anisotropic rough surfaces contacting, Longuet-Higgins [33] studied the random ocean surfaces' statistical geometry and introduced the two-dimensional random process using the techniques of random process theory. Nayak [34,35] found that the shape and orientation of asperities are the basic parameters for the contact of the engineering surfaces. Greenwood and Williamson [11] and Chang et al. [2] assumed that all of the asperities are spherical and that the distribution is isotropic. In reality, most machined surfaces have the orientation with respect to the direction of motion of the cutting tool relative to the work pieces. So, the anisotropic roughness must be considered. However, the analysis of random, anisotropic, Gaussian surfaces is extremely complicated since at least seven parameters are required to define the surfaces [36]. Misra et al. [37,38] introduced a contact orientation distribution in the interface model. Finally, they described the effects of inherent anisotropy and the induced anisotropy of the interfaces and extremely simplified the anisotropic model.

According to the analyses of existing models, there still have lot of deficiencies in the studies of the mechanical interface. For example, most of models are based on the assumption of an equivalent rough surface contacting with a smooth rigid plane, which ignores the effects of the friction between the upper-lower asperities, and the influences of the interaction between adjacent asperities are often to be neglected by most models. Furthermore, a lot of models assume that the rough surfaces are the isotropic rough surfaces, therefore the grain direction of surfaces machined is not considered. Aiming at above problems, the current work builds a combined model that includes the lateral contact between the upper and lower asperities, the interaction of adjacent asperities and the anisotropy of two rough surfaces contacting.

2. The asperity lateral contact model

Microscopically, the real machined surface is very rougher, and it's covered by innumerable asperities. When two rough surfaces contact, there are mainly lateral contact between upper and lower asperities in the interface. The existing researches, however, are mainly based on the assumption that a smooth rigid plane contacts with an equivalent rough surface. Therefore, the friction at the shoulders of asperity is always neglected, which makes the serious errors. The lateral contact case is introduced by the proposed model, and this section will give a particular introduction.

2.1. The assumption of the asperity lateral contact model

Microscopically, the machined surface can be assumed that: (1) it's constituted by a lot of 3-D spherical asperities with various radii and different height; (2) the asperity height is assumed as the Gaussian distribution. Moreover, the peak-to-peak contact between the upper and lower asperities can be assumed as a particular lateral contact case that the contact angle and the contact azimuth angle both equal to zero.

Fig. 1 shows the force analysis on an asperity when a pair of asperities contacts under the normal force F_i. The normal force F_i can be divided into three component forces, which are the normal component force F_{in}, the tangential component force $F_{i\tau}$ and the horizontal component force F_{is}, respectively. φ and θ express the contact angle and the contact azimuthal angle, respectively. The Coordinate system OXYZ is the global Coordinate system. The Z-axis direction is the normal direction that is perpendicular to the interface, and the XOY-plane is parallel to the interface. The Coordinate system O′X′Y′Z′ is the local coordinate system. The Z′-axis direction is the direction of the normal component. The X′-axis direction is the direction of the tangential component, and the Y′-axis direction is the direction of the horizontal component.

According to the decomposition synthesis theorem of force, the normal component force, the tangential component force and the horizontal component force can be obtained by

$$F_{in} = F_i \cos\varphi \tag{1}$$

$$F_{i\tau} = F_i \sin\varphi \sin\theta \tag{2}$$

and

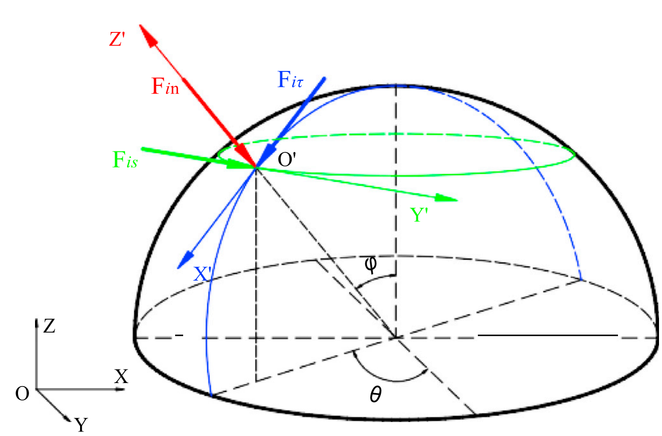

Fig. 1. The force analysis of an asperity.