Tribology International 95 (2016) 132–138

Contents lists available at ScienceDirect

Tribology International

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

Thermo-mechanical contact between a rigid sphere and an elastic–plastic sphere

Wenping Song [a], Longqiu Li [a,*], Andrey Ovcharenko [b], Frank E. Talke [c]

[a] Harbin Institute of Technology, Harbin, China
[b] Western Digital Corporation, San Jose, USA
[c] University of California, San Diego, USA

ARTICLE INFO

Article history:
Received 30 May 2015
Received in revised form
15 October 2015
Accepted 10 November 2015
Available online 1 December 2015

Keywords:
Thermo-mechanical contact
Spherical contact
Plowing
Flattening

ABSTRACT

The mechanical and thermal response of a rigid sphere sliding over an elastic–plastic sphere with radius larger than that of the rigid sphere, namely, plowing contact model, are investigated using a finite element method. Dimensionless solutions for the maximum values of contact force, friction force, contact area, residual interference, and interfacial temperature rise are obtained as a function of dimensionless contact time. A detailed comparison is performed with the results between the plowing contact model and the flattening contact model in which an elastic–plastic sphere flattened by a rigid sphere with radius larger than that of the elastic–plastic sphere.

1. Introduction

Contact mechanics is important for design of mechanical and electromechanical components, such as gears [1], hard disk drives [2] and micro-switches [3]. In many studies involving spherical contacts, two different models of spherical contact have been used. One is the flattening model, where a rigid sphere is sliding over an elastic–plastic sphere with a radius smaller than that of the rigid sphere. The other one is the so-called plowing model, where a rigid sphere is sliding over an elastic–plastic sphere with a radius larger than that of the rigid sphere. These two models look similar at first glance. However, the contact characteristics of both models are quite different, especially in the elastic–plastic and the fully plastic deformation regimes.

In many publications, a hard indenter plowing into a soft flat has been used to study frictional behavior of the plowing process [4–9]. During plowing, sliding motion of the indenter is resisted by both adhesive friction and plowing friction, imposed by the elastic–plastic deformation of the soft flat [4]. Liu et al. [5] analyzed a diamond conical indenter sliding on the surface of a deformable metal, assuming that the deformation was perfectly plastic. On the other hand, elastic recovery was observed experimentally at the rear edge of an indenter during scratching tests by Bucaille et al. [6]. Considering the elastic recovery, Lafaye et al. [7,8] provided a solution for plowing friction of a conical tip. The authors found that a tip with a large radius of curvature leads to a small plowing component of friction. Kamminga and Janssen [9] studied a diamond spherical indenter plowing into a CrN coated steel to investigate the effect of substrate and contact condition on adhesive and plowing components of friction. It was observed that the adhesive component of friction is determined by the surface condition.

Taking into account the combined effect of thermo-mechanical stress, Ye and Komvopoulos [10] studied the mechanical and thermal response of an elastic sphere sliding over an elastic–plastic layered flat under normal and tangential loading. The stress and strain fields were investigated, as well as the interfacial temperature rise. Thermo-mechanical contact of an elastic–plastic sphere sliding on an elastic–plastic layered flat was studied by Gong and Komvopoulos [11]. The effect of friction coefficient, sphere radius and repetitive sliding on stress and temperature distributions was studied. Song et al. [12] developed a thermo-elastic–plastic transient contact model to study the contact between slider and disk asperity in hard disk drives. They found that both plastic deformation and high interfacial temperature induced by slider/asperity contacts can cause head degradation. Universal solutions for transient contacts between a rigid sphere and a moving flat were provided by Ovcharenko et al. [13]. Plowing was observed during transient impact which led to large contact force and high interfacial temperature.

In the above literature review, no investigation was found dealing with the thermo-mechanical transient response between

* Corresponding author.
E-mail address: longqiuli@hit.edu.cn (L. Li).

http://dx.doi.org/10.1016/j.triboint.2015.11.019
0301-679X/

two spherical asperities in the presence of plowing friction. It is the goal of this investigation to fill this gap and develop a three-dimensional model for the thermo-mechanical transient contact between two spheres. The thermo-mechanical response for the plowing model is investigated and universal solutions are obtained for maximum values of contact parameters. A detailed comparison is made between the plowing model and the flattening model studied in Ref. [14].

2. Modeling

Fig. 1 shows a schematic of flattening and plowing models of an elastic–plastic sphere in contact with a rigid sphere. For the flattening model (Fig. 1(a)), R_1/R_2 is in the range of $10 \leq R_1/R_2 \leq 100$, where R_1 and R_2 represent the radii of the rigid and elastic–plastic spheres, respectively [14]. The ratio of R_1/R_2 is chosen to be in the range of $0.01 \leq R_1/R_2 \leq 0.1$ for the plowing model (Fig. 1(b)). An interference ω is preset during the transient contact. A constant velocity V_x is applied to the rigid sphere while the base of the elastic–plastic sphere is kept stationary. In this paper, the thermo-mechanical response of the plowing model is studied and compared with the flattening model analyzed in Ref. [14].

Fig. 2 shows a typical plowing model of a small rigid sphere sliding over a large elastic–plastic sphere solved using a finite element method. This plowing model is somewhat different from the flattening model reported in Ref. [14], in which the radius of the rigid sphere is larger than that of the elastic–plastic sphere. Similar to Refs. [12–14], the thermal and mechanical analysis during the transient contact is performed in LS-DYNA, a commercially available finite element solver [15]. The momentum equation is solved by an explicit time integration scheme [15].

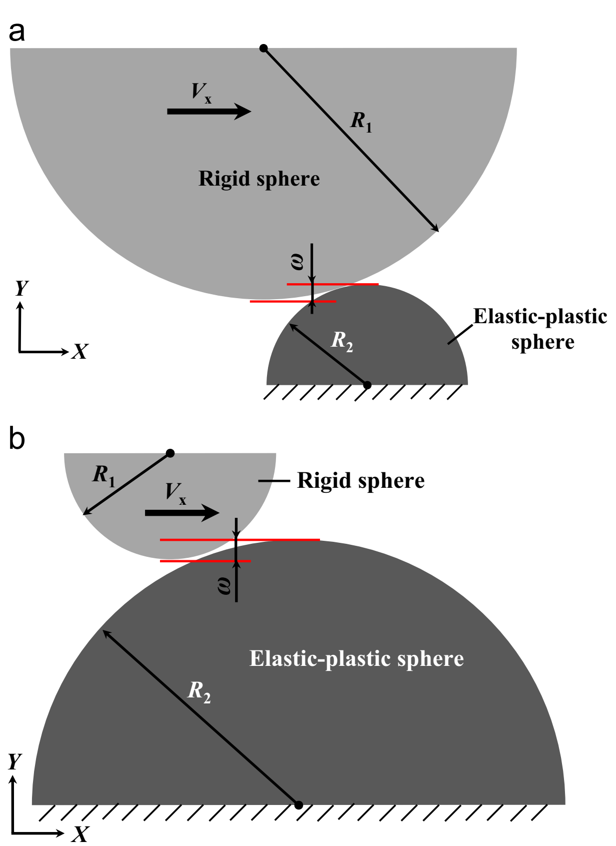

Fig. 1. Schematic of (a) flattening model [14] and (b) plowing model of an elastic–plastic sphere contacting with a rigid sphere.

During the plowing process, the generated frictional energy is converted to the thermal energy. In the current study we do not consider convection, radiation, and the heating caused by plastic deformation. The thermal equilibrium equation is solved by a backward integration scheme [15]. In addition, the temperature at the opposing nodes of the contact interface is assumed to be the same to fulfill the Block's postulate [16].

In the elastic-deformation regime, the difference between the numerical results solved by the finite element model and the analytical results of dynamic Hertzian theory was found to be less than 3%. The detailed information related to the finite element model (i.e., meshing, boundary conditions and validation) is not provided in this work to avoid redundancy while it can be found in Ref. [14].

3. Background

3.1. Critical parameters for normalizing numerical results

In order to compare the results of this investigation with results of the flattening model presented in Ref. [14], the critical parameters used in Ref. [14] (i.e., critical load P_c, critical interference ω_c, critical contact area A_c and critical temperature rise ΔT_{max_c}) are used to normalize the numerical results of the plowing model in this study. The critical parameters are given by

$$P_c = \frac{\pi^3}{6} C_\nu^3 Y \left(R(1-\nu^2)\frac{Y}{E} \right)^2 \quad (1)$$

$$\omega_c = \left[C_\nu \frac{\pi(1-\nu^2)}{2} \left(\frac{Y}{E} \right) \right]^2 R \quad (2)$$

$$A_c = \pi \omega_c R \quad (3)$$

$$\Delta T_{max\_c} = \frac{1.31 a_c \mu p_c V_x}{k_{ep}\sqrt{1.2344} + k_r \sqrt{1.2344 + Pe_r}} \quad (4)$$

where $C_\nu = 1.234 + 1.256\nu$, $R = 1/(1/R_1 + 1/R_2)$, E, Y and ν are the Young's modulus, yield strength and Poisson's ratio of the elastic–plastic sphere, respectively. In Eq. (4), the critical pressure $p_c = P_c/A_c$, the critical contact radius $a_c = \sqrt{A_c/\pi}$, μ is the friction coefficient, k_{ep} and k_r are the thermal conductivity of the elastic–plastic sphere and the rigid sphere, respectively. Peclet number of the rigid sphere Pe_r is defined as

$$Pe_r = \frac{V_x a_c \rho_r C_r}{2k_r} \quad (5)$$

where ρ_r and C_r are the thermal density and specific heat of the rigid sphere, respectively. The details about the critical parameters can be found in Ref. [14].

3.2. Thermo-mechanical flattening of a deformable sphere by a rigid sphere

In our previous study [14], the flattening of an elastic–plastic sphere by a rigid sphere is investigated. The dimensionless maximum contact force P_{max}/P_c, the dimensionless maximum friction force Q_{max}/P_c, the dimensionless maximum contact area A_{max}/A_c, the dimensionless maximum residual interference $\omega_{max\_res}/\omega_c$ and the dimensionless maximum temperature rise $\Delta T_{max}/\Delta T_{max\_c}$ are given as functions of the dimensionless interference ω/ω_c

$$\frac{P_{max}}{P_c} = (-0.6\,\mu + 1.423) \left(\frac{\omega}{\omega_c} \right)^{1.263} \quad (6)$$

$$Q_{max} = \mu \cdot P_{max} \quad (7)$$