Wear 330-331 (2015) 85–92

Contents lists available at ScienceDirect

Wear

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

Contact temperature under three-body dry friction conditions

Horng-Wen Wu [a], Yang-Yuan Chen [a], Jeng-Haur Horng [b,*]

[a] Department of Systems and Naval Mechatronic Engineering, National Cheng Kung University, Tainan, Taiwan, ROC
[b] Department of Power Mechanical Engineering, National Formosa University, Yunlin, Taiwan, ROC

ARTICLE INFO

Article history:
Received 13 September 2014
Received in revised form
15 December 2014
Accepted 27 January 2015

Keywords:
Three-body contact
Contact temperature
Contact load ratio
Particle density
Particle size

ABSTRACT

Particles (wear debris, particle contaminants, or abrasive particles) are often present at contact interfaces. These particles affect the contact temperature and the real contact area between two rough surfaces. In this paper, we used a three-body micro-contact model and contact temperature theory to evaluate particle-to-surface and surface-to-surface contact temperatures between two surfaces with different particle sizes, particle densities, surface roughnesses, relative speeds, and applied loads.

The results show that the values of the particle-to-surface and surface-to-surface temperature rise parameters are highly dependent on the contact load ratio, i.e., the proportion of the total load borne by the contact between the two surfaces. For a given relative speed and applied load, the particle temperature rise parameter value increases with increasing particle size and particle density and with decreasing surface roughness. On the other hand, for a given relative speed, the surface temperature rise parameter value decreases with decreasing applied load and surface roughness and with increasing particle density and particle diameter. For hybrid friction contact conditions, the particle temperature rise parameter value increases almost linearly with an increasing ratio of particle size to surface roughness, x_a/σ, for a given surface roughness and contact load. For a given surface roughness and contact load, the surface temperature rise parameter value remains almost unchanged under hybrid friction contact conditions when x_a/σ is less than 1.0, whereas at x_a/σ values greater than 1.0, the surface temperature rise parameter value decreases as the ratio of particle size to surface roughness increases. The results also show that even for a relatively low load, the particle temperature may be higher than the surface temperature for large debris sizes or high particle densities, suggesting an abnormal wear process. High particle temperatures are believed to play an important role in fatigue, wear, and failure mechanisms. The results indicate that to reduce the interfacial temperature, the larger the contact load is, the smaller the surface roughness value must be. Under hybrid friction contact conditions, the difference between the surface and particle contact temperatures is relatively small.

1. Introduction

When two surfaces slide over each other, roughness of the surfaces and third bodies (particles) cause contact to occur at discrete contact spots, including particle-to-surface and surface-to-surface spots. The contact temperatures at these contact spots are among the factors that cause fatigue, high wear, and failure of materials. Many contact temperature analyses of two-body (surface 1 and surface 2) contact conditions have been proposed. In 1937, Blok [1] and Jaeger [2] demonstrated that a flash temperature equation can be used to predict the occurrence of scuffing. Geeim and Winer [3] reported an increase in the transient temperature rise in the vicinity of micro-contact. In 1994, Tian and Kennedy [4] used Green's function to approximate flash temperatures. Knothe and Liebelt [5] used a Laplace transformation and Green's function to describe the interface between a contact temperature and a temperature field, demonstrating that surfaces with different roughnesses result in different maximum contact temperature rises for wheel–rail systems. In 2009, Bansal and Streator [6] used a linear regression method to obtain the complete temperature and heat partition distributions within an interface and used the results to conduct a detailed thermal analysis of sliding bodies. In 2012, Bansal and Streator [7] extended the Tian and Kennedy formulae to predict the maximum temperature rise for a fairly large range of elliptical ratios. In 2014, experiment data collected by Abbasi et al. [8] showed that railway brake blocks can be made from composite, sinter, or cast iron materials, all of which have highly temperature-dependent physical properties (in a typical temperature range of 0–600 °C). The experimental results showed that cast iron block material exhibits

---

* Corresponding author. Tel.: +886 5 631 5428; fax: +886 5 631 5909.
E-mail address: jhhorng@gmail.edu.tw (J.-H. Horng).

http://dx.doi.org/10.1016/j.wear.2015.01.060
0043-1648/

Nomenclature

A_n, A_{s1s2}, A_{as1}, A_{as2}, a	nominal contact area, total real contact area between surfaces 1 and 2, real contact area of particle and surface 1, real contact area of particle and surface 2, contact radius
C_p	specific heat
d	separation based on asperity heights
E_{s1s2}, E_{as1}	contact elastic modulus of surfaces 1 and 2, contact elastic modulus of particle and surface 1
F_{s1s2}, F_{as1}, F_{total}	force of contact between surfaces 1 and 2, force of contact between particle and surface 1, total contact force
H_{s1}, H_{s2}, h_e	hardness of surface 1, hardness of surface 2, maximum separation of two surfaces with particles that leads to plastic contact
K	thermal conductivity
P, P_e	contact pressure, Péclet number
Q, q	friction heat, heat flux
R_w	thermal distribution factor
T_{s1s2}, $T_{s1s2,ave}$, T_{as1}, $T_{as1,ave}$	surface contact temperature rise, average surface contact temperature rise, particle contact temperature rise, average particle contact temperature rise
V	relative velocity
x_a, x_{max}, x_{min}	particle diameter, maximum particle diameter, minimum particle diameter
σ	standard deviation of surface heights
$\phi_a(x)$	particle Gauss distribution function
η_a, η_d	particle density, asperity density

decreasing wear rates at temperatures higher than 500 °C. However, few reports have investigated the contact temperatures of particles at interfaces.

To analyze the contact temperatures of particles and surfaces at interfaces, the real contact area for three-body contact conditions must first be examined. The mechanisms of contact between two rough surfaces have been studied extensively. The most widely used model is that proposed by Greenwood and Williamson (the GW model) [9]. Pullen and Williamson [10] showed that volume is conserved by a contact area rise in the non-contacting surface under extremely high loading in the plastic deformation state (the PW model). Chang et al. [11] proposed an elastic–plastic micro-contact model (the CEB model) and demonstrated that the GW and PW models are two limiting cases of general elastic–plastic contact. Horng [12] proposed a generalized elliptical elastic–plastic micro-contact model (the H model) that accounts for the directional nature of surface roughness in elliptical contact spots between anisotropic rough surfaces. This model can be simplified to the GW, PW, or CEB models. Kogut and Etsion [13] presented an elastic–plastic asperity model (the KE model) to address the shortcomings of the other models in describing the transition from elastic deformation to fully plastic deformation. In practical situations, wear debris or contaminant particles at interfaces are common. Recently, Horng [14] used a three-body micro-contact model for rough surfaces to describe contact characteristics. This model (the HTB model) has become the basic model for studying contact temperatures in three-body contact situations.

In practical motion devices, particles at interfaces are common. Zhang and Bogy [15], Shen and Bogy [16,17], and Stachowiak [18] discussed the effect of particles in the head disk interface on wear, contact force, and temperature rise. Recently, reports [19,20] have shown that the contact temperature of the third body is the key parameter in the friction, wear, and failure of mating surfaces. In 2013, Haque et al. [21] reported that in a lubricated three-body contact scenario with a diamond-like carbon (DLC) coating, smaller particles are more effectively entrained in the interface, thereby causing higher coating wear than larger particles under mixed lubrication conditions. Qi et al. [22] demonstrated that added sand dust increases the friction coefficient and wear rate under oil-lubricated conditions. In a study of broken ceramic on ceramic interfaces in total hip replacements, O'Brien et al. [23] showed that ceramic particles cause third-body abrasion in joints, greatly accelerating wear and reducing the life of the bearing assembly, which can cause excessive wear of the metal femoral head. In 2014, Ren et al. [24] reported that an increasing particle concentration results in an increased wear rate. However, to date, few have studied contact temperatures in three-body contact situations. Based on three-body contact mechanics and contact temperature theory, a third-body contact temperature analysis was conducted in this study to investigate the effects of particle size, particle density, speed, and applied load on the particle and surface temperature rises of rough surfaces.

2. Microcontact model

Three-body contact geometry is illustrated in Fig. 1. The total contact load (F_{total}) is borne by the particle-to-surface and surface-to-surface contact spots and is a function of the particle-to-surface contact load (F_{as1}) and surface-to-surface contact load ($F_{s1s2-as1}$). The total contact area (A_{total}) is a function of the particle-to-surface contact area (A_{as1}) and the surface-to-surface contact area (A_{as1}). Based on the Horng's three-body microcontact model [14], the total contact load F_{total} and the total contact area A_{total} are given by the following equations:

$$F_{total}=F_{as1}+F_{s1s2-as1}=\frac{\pi H_{s1}H_{s2}\eta_a A_n}{H_{s1}+H_{s2}}\left[\frac{9\pi^2}{4}\left(\frac{H_{s1}^2}{E_{as1}^2}+\frac{H_{s2}^2}{E_{s1s2}^2}\right)\right.$$

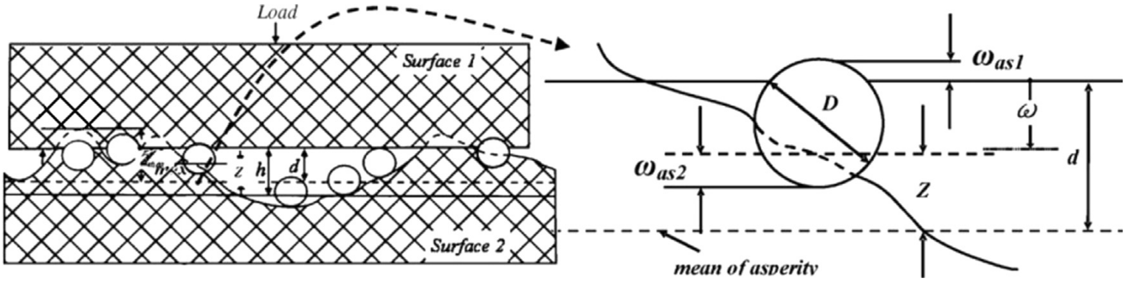

Fig. 1. Geometry of three contacting bodies [14].