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An adhesive wear model of fractal surfaces in normal contact

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ABSTRACT

A generalized adhesive wear analysis that takes into account the effect of interfacial adhesion on the total load was developed for three-dimensional fractal surfaces in normal contact. A wear criterion based on the critical contact area for fully-plastic deformation of the asperity contacts was used to model the removal of material from the contact interface. The fraction of fully-plastic asperity contacts, wear rate, and wear coefficient are expressed in terms of the total normal load (global interference), fractal (topography) parameters, elastic–plastic material properties, surface energy, material compatibility, and interfacial adhesion characteristics controlled by the environment of the interacting surfaces. Numerical results are presented for representative ceramic–ceramic, ceramic–metallic, and metal–metal contact systems to illustrate the dependence of asperity plastic deformation, wear rate, and wear coefficient on global interference, surface roughness, material properties, and work of adhesion (affected by the material compatibility and the environment of the contacting surfaces). The analysis yields insight into the effects of surface material properties and interfacial adhesion on the adhesive wear of rough surfaces in normal contact.

1. Introduction

Wear plays an important role in many fields of science and technology. The implications of wear can be either beneficial or detrimental to the performance of scientific instruments and engineering components possessing contact interfaces. Since the seminal study of adhesive wear by Archard (1953), several wear mechanisms have been proposed to explain the loss of material from sliding surfaces, including abrasion, corrosion, erosion, contact fatigue, and delamination (Kruschov, 1957; Suh, 1973, 1986). Among various wear mechanisms, adhesive wear is the most common process of material removal encountered over a wide range of length scales. This type of wear is responsible for the failure of many mechanical and electromechanical components whose functionality depends on the tribological properties of contact interfaces. Thus, accurate prediction of the adhesive wear rate in tribological systems is of great technological and scientific importance.

Significant research effort has been devoted to study the dependence of adhesive wear on various factors, such as normal load, sliding speed, interfacial adhesion/friction conditions, and material properties (Lisowski and Stolarski, 1981; Finkin, 1972; Paretkar et al., 1996; Yang, 2003). Archard's wear model has been used extensively to quantify the wear rate of sliding surfaces (Qureshi and Sheikh, 1997; Yang, 2004), develop adhesion models of single-asperity junctions (Rabinowicz, 1980), and perform energy-based analyses of adhering asperities (Warren and Wert, 1990). However, the majority of relationships between adhesive wear rate, sliding speed, and contact area reported in early studies were based on semi-empirical approaches and statistical topography parameters (e.g., mean and variance of the surface heights, slopes, and curvatures) that do not account for the scale dependence of topography parameters, a characteristic feature of multi-scale roughness of engineering surfaces.

To overcome shortcomings with scale-dependent statistical surface parameters (Greenwood and Williamson, 1966) and random process theory (Nayak, 1973) commonly used in contact mechanics, the surface topography in contemporary contact analyses was described by fractal geometry (Majumdar and Bhushan, 1990, 1991; Wang and Komvopoulos, 1994a,b, 1995; Sahoo and Roy Chowdhury, 1996; Komvopoulos and Yan, 1998; Borri-Brunetto et al., 1999; Ciavarella et al., 2000; Komvopoulos and Ye, 2001; Persson et al., 2002; Yang and Komvopoulos, 2005; Gong and Komvopoulos, 2005a,b; Komvopoulos and Yang, 2006; Komvopoulos and Gong, 2007; Komvopoulos, 2008). Because fractal geometry is characterized by the properties of continuity, nondifferentiability, scale invariance, and self-affinity (Mandelbrot, 1983), it has been used in various fields of science and engineering to describe disordered phenomena, including changes in surface topography due to wear and fracture processes. For example, Zhou et al. (1993) used a fractal contact model to examine the

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Nomenclature

a'	truncated contact area or large-base area of spherical segment
a'_C	critical truncated contact area
a'_L	largest truncated contact area
a'_{Li}, a'_{Lk}	largest truncated contact area at the *i*th and *k*th increment of global interference
a'_S	smallest truncated contact area
c_l	lubrication compatibility index
c_m	metallurgical compatibility index
dh	increment of global interference or height of spherical segment
dV_p^i, dV_p^k	wear volume at the *i*th and *k*th increment of global interference
$dV_{e,1}$	volume of an elastic asperity approximated by a spherical cap
$dV_{p,1}$	volume of a fully-plastic asperity approximated by a spherical segment
D	fractal dimension
E^*	effective elastic modulus
E_i	elastic modulus of surface *i* (*i* = A, B)
F_e	total normal force due to elastic asperity contacts
F_p	total normal force due to fully-plastic asperity contacts
F	total normal force
G	fractal roughness
h	global interference
H^*	effective hardness
H_i	hardness of surface *i* (*i* = A, B)
K	adhesive wear coefficient
L	sample length
L_S	smallest characteristic (cut-off) length
m	ridge index
M	number of superposed ridges
n	asperity contact size distribution
N	number of asperity contacts with truncated areas greater than a specific truncated contact area
p_m	mean contact pressure
q	spatial frequency index
q_{max}	maximum value of spatial index
r	real contact radius of an asperity contact
r'	radius of a truncated asperity contact or base radius of spherical cap
r'_S	radius of smallest truncated asperity contact
R	equivalent radius of curvature of spherical asperity
S'	total truncated contact area
S'_e	total truncated contact area of elastic asperity contacts
S'_p	total truncated contact area of fully-plastic asperity contacts
S_a	apparent sample area
V	total wear volume
V_e	total volume of elastic asperities
V_p	total volume of fully-plastic asperities
V_t	total volume of contacting asperities
W_{AB}	work of adhesion of contacting surfaces A and B
x, y	in-plane Cartesian coordinates
z	out-of-plane Cartesian coordinate or surface height function
z_0	equilibrium separation distance of two surfaces

Greek symbols

γ	profile frequency density control parameter
Γ_i	surface energy of surface *i* (*i* = A, B)
δ	local interference, height of a spherical cap, or distance between large base and top of spherical cap at the lower end of a spherical segment
δ_{min}	minimum local interference
ΔF_e	normal force at an elastic asperity contact
ΔF_p	normal force at a fully-plastic asperity contact
μ	Tabor parameter
ν_i	Poisson's ratio of surface *i* (*i* = A, B)
σ	rms roughness of equivalent surface
σ_Y	effective yield strength
$\phi_{m,q}$	random phase generator
ω	spatial frequency of surface profile
ω_h	highest frequency of surface profile
ω_l	lowest frequency of surface profile

dependence of the adhesive wear rate on fractal parameters and material properties, Shirong and Gouan (1999) developed a fractal model of adhesive wear for the running-in stage of sliding, and Sahoo and Roy Chowdhury (2002) studied the effect of adhesion between contacting asperities on the adhesive wear behavior of fractal surfaces subjected to light loads. Although the previous studies have provided insight into the effects of fractal dimension, material properties, and surface adhesion on the loss of material by adhesive wear, the developed wear models are extensions of Archard's model and, therefore, can only be applied to sliding surfaces. However, experimental evidence (Martin et al., 2002) and molecular dynamics simulations (Bhushan et al., 1995) have shown that adhesive wear can occur even in the absence of relative slip between the contacting surfaces. Hence, a comprehensive adhesive wear theory of rough surfaces in normal contact is necessary to bridge this gap of knowledge.

The main objective of the present analysis is twofold. First, instead of an empirical approach based on experimental results and observed trends, an adhesive wear model of rough surfaces in normal contact is derived based on plasticity-induced wear behavior that accounts for adhesion between interacting asperities. Second, the adhesive wear rate and wear coefficient are obtained in terms of the total normal load (global interference), surface topography (fractal) parameters, elastic–plastic material properties, and interfacial adhesion characteristics that depend on the material compatibility and contact environment. Results for representative contact systems with fractal surface topographies reveal the effects of roughness, surface material properties, and interfacial adhesion on adhesive wear.

2. Surface description

Normal contact of two rough surfaces can be analyzed by an equivalent contact model consisting of a deformable rough surface with effective material properties and equivalent roughness in contact with a rigid plane (Greenwood and Williamson, 1966). The effective elastic modulus E^* and hardness H^* of the equivalent surface are given by

$$\frac{1}{E^*} = \frac{1-\nu_A^2}{E_A} + \frac{1-\nu_B^2}{E_B} \quad (1)$$

$$H^* = \min[H_A, H_B] \quad (2)$$

where subscripts A and B refer to the two surfaces in normal contact, and E, ν, and H denote elastic modulus, Poisson's ratio, and hardness, respectively.