Tribology International 96 (2016) 202–216

Contents lists available at ScienceDirect

Tribology International

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

Numerical studies on the surface effects caused by inhomogeneities on torsional fretting

Yanyan Huang [a], Zhanjiang Wang [b,*], Qinghua Zhou [c]

[a] College of Materials Science and Engineering, Chongqing University, Chongqing 400030, China
[b] State Key Laboratory of Mechanical Transmission, Chongqing University, Chongqing 400030, China
[c] School of Aeronautics and Astronautics, Sichuan University, Chengdu 610065, China

ARTICLE INFO

Article history:
Received 16 July 2015
Received in revised form
19 December 2015
Accepted 23 December 2015
Available online 31 December 2015

Keywords:
Torsional fretting
Inhomogeneities
Semi-analytical method
Fast Fourier transform

ABSTRACT

This research explores the influence of inhomogeneities on the torsional fretting via a newly developed semi-analytical method with considering the load history. The disturbances of elastic fields caused by inhomogeneities are modeled based on Eshelby's equivalent inclusion method. Solutions are achieved iteratively through considering the coupling of surface tractions and subsurface inhomogeneities. The influences of a single inhomogeneity are investigated, revealing that the presence of an inhomogeneity causes significant surface effects on the torsional fretting. Further, the influences of inhomogeneity distribution parameters on the torsional fretting performance are quantified, demonstrating the capability of the proposed method.

1. Introduction

Fretting, defined as the oscillatory movements of small amplitudes occur along the contact interface between two objects, may affect the service life of a material due to rapid crack formation and surface wear. For a ball-on-flat contact configuration, fretting can be categorized as four basic modes: tangential, radial, rotational, and torsional, according to the relative motion directions [1]. Among them, torsional fretting presents as the relative motion induced by reciprocating torsion under alternating load, which is one of the main contact modes existed in many engineering and natural systems, such as spinning balls against raceways and retention rings, a ball joint connecting a control arm to the steering knuckle, ball and socket in mammal shoulder and hip joints, artificial hip and knee joints involving rolling and sliding during walking [2]. Therefore, it is important to analyze torsional contact quantitatively and to understand the failure mechanisms induced by torsional fretting.

A torsional contact problem is complex when the contacting bodies are under a limited torque insufficient to cause full sliding. As early as 1951, Lubkin [3] firstly proposed a concept that the contact surface was composed by two parts: stick zone and slip zone. The analytical solutions of surface shear tractions and moment as functions of the radius of stick during a loading process based on two loaded elastic spheres with identical materials were derived. Torsional contact-related problems have been widely studied since then. Deresiewicz [4] extended Lubkin's solution and more useful solutions with considering an oscillating torque of fixed amplitude were obtained. Keer [5], Hills and Sackfield [6] proposed a set of analytical solutions for the stress fields induced by surface shear traction during a loading process. Recently, the analytical solution for torsional contact is still attractive to many research scholars [7–9]. On the other hand, many beneficial experimental studies on torsional fretting have also been conducted. Briscoe et al. [10,11] investigated the fretting wear behavior of poly (methylmethacrylate) (PMMA) substrate contacting against steel balls experimentally, and found that contact zone kinematic conditions, including torsional fretting, rotational fretting, etc., play a major role in determining the wear resistance of the PMMA. Systematic experiments on torsional fretting were carried out by Cai and colleague [2,12–14] to explore the wear performance of materials like LZ50 steel, PMMA, Ti6Al7Nb alloy, etc. More recent experimental works were reported in Refs. [15,16].

Quantitative analyses on the torsional contact are critical to understanding the mechanisms of torsional fretting fatigue. Advancement of computational methods and increase in computational power allow the development of more realistic numerical models. As a typical full numerical method, finite element method (FEM) was used by Cuttino and Dow [17] to study elliptic contact involving torque, and by Segalman et al. [18] to verify their model for the torque-twist angle relationship. However, the FEM is time

* Corresponding author. Tel.: +86 18502376952; fax: +86 23 65105721.
E-mail address: wangzhanjiang001@gmail.com (Z. Wang).

http://dx.doi.org/10.1016/j.triboint.2015.12.028
0301-679X/

Nomenclature

a	Hertzian contact radius, mm
c	stick zone radius, mm
C_{ijkl}, C^*_{ijkl}	elastic moduli of the matrix and inhomogeneity, MPa
$C_p^{u_x}$,$C_p^{u_y}$,$C_p^{u_z}$	influence coefficients relating pressure to surface displacements, mm/MPa
$C_{q_x}^{u_x}$,$C_{q_x}^{u_y}$,$C_{q_x}^{u_z}$,$C_{q_y}^{u_x}$,$C_{q_y}^{u_y}$,$C_{q_y}^{u_z}$	influent coefficients relating shear tractions to surface displacements, mm/MPa
E_1	Young's modulus of the half space, GPa
E_2	Young's modulus of the loaded sphere, GPa
E_i	Young's modulus of the inhomogeneity, GPa
$E(k)$	complete elliptical integral of the second kind
$E(\phi, k')$	incomplete elliptical integral of the second kind
$F(\phi, k')$	incomplete elliptical integral of the first kind
F_x, F_y	applied tangential load along the x, y direction, N
g	surface gap, mm
G_1	shear modulus of the half space, GPa
G_2	shear modulus of the sphere, GPa
h_0	initial gap, mm
H	depth of the cuboidal inhomogeneity, mm
H	influence coefficient matrix relates the eigenstrain to the surface displacement, mm
I_c, I_{stick}, I_{slip}	contact, stick and slip regions
$K(k)$	complete elliptical integral of the first kind
M_z	torque along the z direction, N mm
p	maximum Hertzian pressure, MPa
p_h	maximum Hertzian pressure, MPa
q_r	radius of the spherical inhomogeneity, mm
q_x, q_y	radius of the spherical inhomogeneity, mm
r	radius of the spherical inhomogeneity, mm
r_x, r_y, r_z	semi axes of the ellipsoidal inhomogeneity, mm
R	radius of the loaded sphere, mm
s_x, s_y	Eshelby tensor relating the eigenstrain to the disturbed strain
S_{klmn}	Eshelby tensor relating the eigenstrain to the disturbed strain
u_x, u_y, u_z	surface displacements in three directions caused by surface tractions, mm
u_x^*, u_y^*, u_z^*	perturbed surface displacements in three directions caused by eigenstrains, mm
W	normal load, N
x, y, z	space coordinates, mm
δ_x, δ_y, δ_z	rigid displacements parallel to the x, y, and z direction, mm
ΔE	energy dissipation per cycle, N mm
θ	twist angle
ε_{kl}^0	strain caused by surface tractions
ε_{ij}^*	eigenstrain
μ_f	friction coefficient
ν_1	Possion's ratio of the half space
ν_2	Possion's ratio of the loaded sphere
ν_i	Possion's ratio of the inhomogeneity

Special symbols

*	convolution

consuming when solving contact problems for tribological components, where the contact regions are much smaller than the contact bodies. In recent years, semi-analytical methods (SAMs) have proven more efficient than the FEM in solving contact problems. The SAMs combine the advantages of numerical and analytical methods. The fundamental solutions are analytical responses to a unit excitation, usually in the form of a Green's function, and the final results are obtained from the superposition of the fundamental solutions. The influence coefficient, which relates a response to an excitation in a unit cell, is obtained from those fundamental solutions. By using the SAMs, Wang et al. [19] considered the effects of a tangential load and a twisting moment and found that the coupling of a normal load, a tangential load and a twisting moment makes the contact behavior much more complex. Partial slip contacts of dissimilar materials under coupled normal and tangential loads were also studied with the SAMs [20–23]. The effects of loading path were not considered for the above studies. Leroux and Nélias [24], Gallego et al. [25] and Wang et al. [26] established more general fretting algorithms involving the loading path.

In the above works, the materials of contacting bodies were assumed homogeneous. However, inhomogeneities, defined as domains having properties different from those of the surrounding material (matrix) [27], are inevitably existed in many engineering materials. The presence of inhomogeneities can significantly alter torsional contact performance of materials due to their produced disturbances to the elastic field. The modeling of the influence of inhomogeneities on the elastic field of materials were explored by some researchers since the pioneering work by Eshelby [28,29]. In his work, the well-known equivalent inclusion method (EIM) was proposed innovatively to solve the stress field of an ellipsoidal inhomogeneity with replacing the inhomogeneity by an equivalent inclusion subjected to a properly selected eigenstrain distribution. The EIM can be effective in handling degenerated two-dimensional (2D) plane inhomogeneities [30,31] and three-dimensional (3D) multiple inhomogeneities [32,33]. Recently, the EIM was introduced to deal with heterogeneous contact problems [34]. Moreover, integrated with a rolling-contact fatigue (RCF) life prediction model, the EIM was applied to investigate the RCF lives of composites [35].

Non-metallic inhomogeneity plays a major role in affecting the contact mechanism of materials. External loads can make the inhomogeneities interact with the matrix, resulting in localized stress concentrations and unexpected deformations on the surface, which further modifies the surface traction distribution [17]. Such an interaction between the surface tractions or deformations and inhomogeneities under contact loads must be fully considered for heterogeneous torsional contact problems. In order to better understand the influence of inhomogeneity on torsional contact of heterogeneous materials, a general model based on a semi-analytical method is developed by using the EIM and fast Fourier transform (FFT) algorithms. The load history can be taken into account in the new model. Inhomogeneity beneath the surface is set as ellipsoidally shaped. With different combinations of the three principal axes, an ellipsoidal inhomogeneity can conveniently represent various shapes, such as spheres, flat cracks, and cylindrical microwires. It is expected that the simulation results can shed light on the nature of the fretting phenomena in tribological components.

2. Numerical modeling of torsional contact for heterogeneous materials

Typical point contact problems are investigated. Heterogeneous torsional fretting is simplistically modeled as torsional contact