Tribology International 93 (2016) 583–592

Contents lists available at ScienceDirect

Tribology International

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

A mixed lubrication model for studying tribological behaviors of surface texturing

Hui Zhang [a,b], Meng Hua [b,**], Guang-neng Dong [a,*], Dong-ya Zhang [a], Kwai-Sang Chin [c]

[a] Xi'an Jiaotong University, Xi'an, People's Republic of China
[b] MBE Department, City University of Hong Kong, Hong Kong SAR, People's Republic of China
[c] SEEM Department, City University of Hong Kong, Hong Kong SAR, People's Republic of China

ARTICLE INFO

Article history:
Received 22 August 2014
Received in revised form
6 February 2015
Accepted 18 March 2015
Available online 27 March 2015

Keywords:
Mixed lubrication
Surface texturing
Tribological behavior

ABSTRACT

An analytical numerical model is specifically developed to understand the tribological behavior of textured surface in mixed lubrication regime. The model employs the average flow Reynolds equation and an elasto-plastic contact model, established on the basis of finite element analysis, to calculate (i) the hydrodynamic pressure in full film region and (ii) the contact pressure in contact region, respectively. Fast Fourier transform (FFT) method is used to compute the elastic deformation of substrate. It is able to simulate Stribeck curve for the textured surface. Predictions demonstrate surface texturing reducing friction coefficient. Studies on the tribological influence of texture shape, depth, distance and diameter are also performed.

1. Introduction

Surface texturing usually involves the manufacturing of pits, or grooves, or protruding spots in either micro- or nano-scale on the surfaces of mechanical sliding pairs by means of physical or chemical techniques. The technology of such surface texturing has been widely used, in the past decades, in many fields of engineering. Typically, it is applied to automobile cylinders, mechanical seals, slider bearings and computer hard disks [1–6]. The implementation of surface textures on these parts allows: (a) effective reduction of interfacial friction and wear; (b) saving energy from lose; and (c) prolonging the serving life of the components. The three possible mechanisms in improving tribological property of surface texturing are widely recognized as: (i) the promotion of secondary lubrication [7,8], (ii) the assistance in tripping off wear debris [7], and (iii) the creation of micro-hydrodynamic action [9]. Among them, micro-hydrodynamic effect is identified as a major influential mechanism in full film lubrication region. When the relative sliding in the mechanical sliding pairs is at the verge of starting/ending or the sliding pairs are under the condition of being overloaded, the lubrication condition of the tribology system is usually in a mixed or starved lubrication regime, implying direct metal-to-metal contact occurs. The friction and wear in the pairs are subsequently increased, which may then cause vibration, damage and even failure of the mechanical system. Hence, the study on tribological behaviors of surface texturing in mixed or starved lubrication regime is particularly meaningful for optimizing the utilization and the service life of surface texturing in engineering fields. In the mixed lubrication regime, the discontinuity of the lubrication film may susceptibly lead to contact and elasto-plastic deformation of the asperities on rough surface. In the specific lubrication regime, the film in those non-contact regions is so thin that the influence of asperities on hydrodynamic pressure also needs to be suitably addressed.

Studies to establish numerical models for the corresponding mixed lubrication condition have been performed and are available in literature. Particularly, Patir and Cheng [10] derived an average flow Reynolds equation to evaluate the asperity influence on hydrodynamic pressure. Sheu and Wilson [11] developed an analytical model for strip rolling operating in the surfaces with mixed asperities. The analytical model provided an approach to study the regime under the influence of surface roughness. Hu and Zhu [12] formulated a full numerical solution for the condition of mixed elasto-hydrodynamic lubrication (EHL) in point contacts. The approach of their solution is rather simple and robust for computing the contact and hydrodynamic pressure. Wang et al. [13] developed a steady state mixed-TEHD (thermo-elasto-hydrodynamic) model to simulate the operation of journal bearings. Results of their prediction allowed the identification of several important contributing factors in the mixed lubrication. Based on

* Corresponding author.
** Also corresponding author.
E-mail addresses: memnghua@cityu.edu.hk (M. Hua), donggn@mail.xjtu.edu.cn (G.-n. Dong).

http://dx.doi.org/10.1016/j.triboint.2015.03.027
0301-679X/

Nomenclature

A_c	critical contact area from elastic to plastic deformation regime, mm^2
A_{KE}	contact area, mm^2
b, c, m, n	constants determined by contact mode
C_i (x_i, y_j)	influence coefficient at nodal point (x_i, y_j)
d	dimple diameter, μm
E'	effective Young's modulus, GPa
F	applied load, MPa
h	nominal film thickness, μm
h_0	minimum nominal film thickness, μm
h_{lo}	local film thickness, μm
h_p	dimple depth, μm
K	hardness factor
l	distance between two adjacent textures, μm
P (x_i, y_j)	local contact/hydrodynamic pressure at nodal point (x_i, y_j), MPa
P_H	average hydrodynamic lubrication film pressure, MPa
P_{KE}	average contact pressure, MPa
r_p	dimple radius, μm
r_s	effective asperity radius, μm
S_y	material yield stress, MPa
U (x_i, y_j)	local elastic deformation of substrate at nodal point (x_i, y_j), μm
u	sliding velocity of the upper surface, m/s
x_c, y_c	coordinates of the dimple center in x- and y-directions, mm
x_i, y_j	coordinates of grid points in x- and y- directions, mm
η	lubricant viscosity, Pa s
λ	film thickness parameter, $\lambda = h_0/\sigma$
ν	Poisson's ratio
σ	effective roughness, μm
φ_c	contact factor
φ_s	shear flow factor
φ_x	pressure flow factor in x-direction
φ_y	pressure flow factor in y-direction
ω	interference, μm
ω_c	critical interference from elastic to plastic deformation regime, μm

the concept of load sharing, Lu et al. [14] established a mixed EHL model specifically for line contact problems. The model facilitated the investigation of Stribeck-type behaviors for the journal bearings under various loads and with different oil temperatures. Comparison of the experimental results with the predictions using the model is indicatively giving good agreement. Kraker et al. [15] developed a mixed EHL model to simulate the tribological behaviors of water lubricated journal bearings under the condition of constant load. Their model allows computing the contact pressure distribution and the hydrodynamic pressure distribution of journal bearings, which facilitates Stribeck curve to be obtained. Masjedi and Khonsari [16] derived a point-contact EHL model, which includes simultaneous solution to the modified Reynolds and surface deformation equations with the consideration of both bulk and asperity deformations. Results of the model predict the influence of asperities on film thickness, pressure distribution and load bearing capacity.

Although numerical models for studying mixed lubrication are available in literature, application of these existing models to study surface texturing is still very much lacking. Moreover, most of these available numerical models have mainly been developed on the basis of statistic parameters and are feasible to evaluate their global effect only. Hence, their use for detailed analysis of the influence of specific local contact/hydrodynamic pressure, film thickness and contact area seems to have certain difficulty. This paper presents a numerical model to study mixed lubrication for surface texturing. The model combines the average flow Reynolds equation with the K–E (Kogut and Etsion) elasto-plastic contact theory, and is able to describe both the global tribological effect and the local status of contact surfaces.

2. Numerical model

2.1. Generation of virtual rough surface

Based on the autoregressive (AR) model and the technology of digital filter [17–19], rough surfaces with Gaussian distribution (Fig. 1) are thus generated. Comparison of the statistical characters of the Gaussian distribution with the corresponding parameters of the virtual rough surface can thus be performed. Table 1 tabulates the grid arrangements for the model and their associated statistical parameters. Obviously, the small deviation between the theoretical values and the computational results from the three grid arrangements (Table 1) suggests that the virtual rough surface with Gaussian distribution is acceptable and appropriate to be implemented in this study. It is thus implemented or added to the two simulated textured surfaces with a layer of film having a certain thickness to be sandwiched in between.

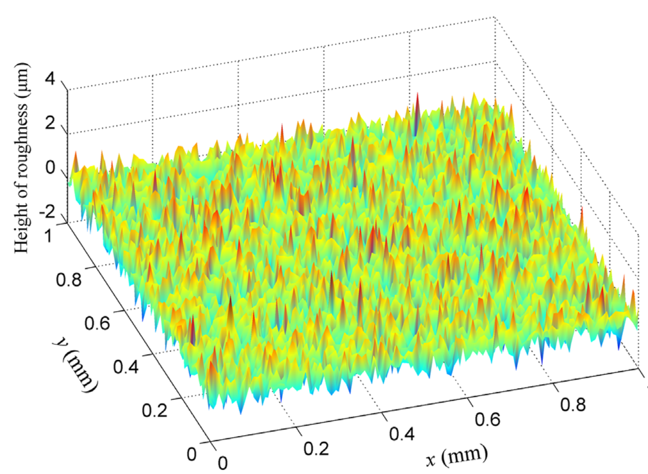

Fig. 1. Virtual rough surface.

Table 1
Comparison of the computational results and theoretical values of Gaussian distribution.

	Mean (μm)	Root mean square deviation (μm)	Skewness	Kurtosis
Theoretical values	0	0.5	0	3
64 × 64 grids	0.0073	0.4960	0.0189	3.0602
128 × 128 grids	0.0032	0.5015	−0.0049	3.0406
256 × 256 grids	5.28e−004	0.508	−0.009	3.0109