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Formation of micro-grooves under impact loading in elliptical contacts with surface ridges

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ABSTRACT

This paper is focused on the effect of impact loading on micro-deformation of asperities in elliptical elastohydrodynamic contacts. Based upon isothermal Newtonian numerical analyses, it is elucidated that a micro-groove, which appears in the ridge under impact loading in elliptical contacts, is brought about by two different mechanisms. One is the smooth surface local pressure difference across the virtual ridge and the other is the macroscopic pressure difference along the ridge. The formation of the micro-groove due to the former mechanism is influenced by the shape, size and orientation of the ridge, and the smooth surface pressure distribution depending on the initial impact gap and loading speed, and that due to the latter is markedly influenced by the loading speed.

1. Introduction

The effect of surface roughness on the rolling/sliding elastohydrodynamic lubrication (EHL) has been investigated in detail, and the results have contributed to the improvement of the performance, reliability and durability of numerous machine elements. The pure squeeze or vertical motion is one of the important relative motions of tribo-pairs. Therefore, numerous important results have been published since Christensen's pioneer work in 1962 [1]. However, the effect of surface roughness on impact elastohydrodynamics has not been necessarily disclosed yet.

In impact EHL, it is well known that the oil is entrapped between surfaces because of the increase of the oil viscosity with pressure, and the film thickness takes the maximum at the center of the contact [1–17] and film shows a dimple shape. Such a central dimple has been obtained under conditions where the initial impact gap is rather large, say 30–100 μm. However, the clearance between the surfaces of some tribo-pairs, for example, rolling element bearings, is much smaller, so that the initial impact gap between the surfaces is also very thin when the rolling element bearing at rest is subjected to some external loads. Furthermore, the external load may not necessarily be constant. The authors have found through direct observations using the optical interferometry technique and numerical analyses that the peripheral oil entrapment occurs when the initial impact gap between the two surfaces is small enough [18–25]. In [24,25], it has been pointed out that the initial impact gap and the size and shape of the circular bump located at the contact center influence significantly the deformation of the bump, and it has also been explained that the deformation of the bump is mainly influenced by the smooth surface pressure distribution.

Generally, the surface finish often gives a strong texture orientation depending on the machining process, and the surface has ridges and grooves. In real situations, furthermore, the contact is generally elliptic. The purpose of this study is to make clear through isothermal Newtonian numerical analysis how the micro-deformations of ridges and grooves are produced when the impact load, which attains the maximum by linear increase, is applied to the lubricated contact surfaces.

2. Method of analysis

The analysis is performed by assuming an isothermal Newtonian fluid in two situations: a spherical steel body impacting a lubricated steel plate and an ellipsoidal steel body impacting a lubricated steel plate. Fig. 1 shows a schematic view of the analytical model used in this study. The major and minor radii of the Hertzian contact ellipse are a and b and $k_e = a/b$ is the ellipticity ratio.

The following semi-paraboloidal ridges and grooves are mainly adopted:

$$\delta(x,y) = \begin{cases} A\sqrt{1-\left(\frac{x-iL}{B}\right)^2} & \left|\frac{x-iL}{B}\right| \le 1 \quad i = 0, 1, 2, \ldots \\ 0 & \text{elsewhere} \end{cases} \tag{1a}$$

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Nomenclature

a	major radius of the Hertzian contact ellipse (m)
A	height of ridge or depth of groove (m)
b	minor radius of the Hertzian contact ellipse (m)
B	base half-width of ridge or groove (m)
E_1, E_2	elastic moduli of solids
E'	equivalent elastic modulus $=2\{(1-\nu_1{}^2)/E_1+(1-\nu_2{}^2)/E_2\}^{-1}$ (Pa)
h	film thickness (m)
h_{00}	rigid central film thicknesss (m)
h_{ini}	initial central impact gap (m)
H	dimensionless film thickness $=h/R_y$
ΔH	dimensionless film thickness difference between contour lines
k_e	ellipticity ratio $=a/b$
L	wavelength of ridges or grooves (m)
m	mass of moving body (kg)
p	film pressure (Pa)
P_H	maximum Hertzian pressure (Pa)
P	dimensionless film pressure $=p/P_H$
R_x, R_y	equivalent radii of contact bodies (m)
t	time (s)
t_0	time required to w_{max} (s)
w_A	applied load (N)
w_{max}	maximum load (N)
x, y	coordinates (m)
x_{out},y_{out}	calculation domain
X	dimensionless coordinate $=x/b$
Y	dimensionless coordinate $=y/b$
α	viscosity–pressure coefficient (Pa^{-1})
ν_1, ν_2	Poisson's ratios of solids
η	viscosity of lubricant (Pa s)
η_0	ambient viscosity of lubricant (Pa s)
ρ	density of lubricant (kg/m^3)
ρ_0	ambient density of lubricant (kg/m^3)

$$\delta(x,y)=\begin{cases} A\sqrt{1-\left(\frac{y-jL}{B}\right)^2} & \left|\frac{y-jL}{B}\right|\le 1 \quad j=0,1,2,\ldots \\ 0 & \text{elsewhere}\end{cases} \tag{1b}$$

where A, B and L are the height or depth, the half-width and wavelength of the ridges and grooves, respectively. In Fig. 1, the case corresponding to Eq. (1a) is schematically illustrated, i.e., the ridges exist along the Y-axis.

The equation of the motion for the spherical or ellipsoidal body can be written as

$$m\frac{d^2h_{00}(t)}{dt^2}=\iint p(x',y',t)dx'\,dy'-w_A \tag{2}$$

where m is the mass of the spherical or ellipsoidal body and w_A is the applied load. $h_{00}(t)$ is the rigid separation between smooth surfaces at the contact center at time t. $h_{00}(0)$ corresponds to the initial central impact gap h_{ini} and the initial speed is assumed to be zero, i.e., $dh_{00}/dt|_{t=0}=0$.

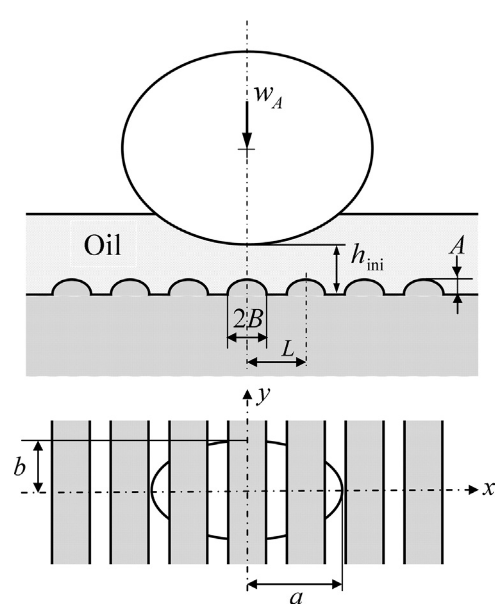

Fig. 1. Schematic view of the analytical model.

The Reynolds equation can be written as

$$\frac{\partial}{\partial x}\left(\frac{\rho h^3}{12\eta}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\rho h^3}{12\eta}\frac{\partial p}{\partial y}\right)=\frac{\partial(\rho h)}{\partial t} \tag{3}$$

The film thickness equation leads

$$h(x,y,t)=h_{00}(t)+\frac{x^2}{2R_x}+\frac{y^2}{2R_y}+\frac{2}{\pi E'}\iint\frac{p(x',y',t)dx'\,dy'}{\sqrt{(x-x')^2+(y-y')^2}}\mp\delta(x,y) \tag{4}$$

Table 1
Contact conditions.

k_e	1	2
R_x (mm)	12.70	36.12
R_y (mm)	12.70	12.70
a (mm)	0.222	0.368
b (mm)	0.222	0.184
p_H (GPa)	1.258	0.915

Table 2
Relation between dimensional and dimensionless quantities.

Dimensional	Dimensionless	
	$k_e=1$	$k_e=2$
Initial impact gap		
h_{ini} (μm)	h_{ini}/R_y	
0.2	0.157×10^{-4}	
2.0	1.57×10^{-4}	
Ridge height		
A (μm)	A/R_y	
0.15	0.118×10^{-4}	
0.25	0.197×10^{-4}	
0.5	0.394×10^{-4}	
Half width of ridge		
B (μm)	B/b	
25	0.113	0.136
Wavelength		
L (μm)	L/b	
75	0.338	0.408