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An engineering approach for rapid evaluation of traction coefficient and wear in mixed EHL

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ABSTRACT

An engineering approach is introduced for estimating the traction coefficient and the wear rate in elastohydrodynamic lubrication of rough surfaces without the need of extensive numerical simulations. The method suggested by Tian and Kennedy is extended to the mixed EHL to estimate the temperature rise. This temperature rise is then used together with the formulas for the film thickness and asperity load to evaluate the traction coefficient and the wear rate for different input conditions. The results from this method are compared to those from numerical simulations.

1. Introduction

A numerical model was recently developed by the authors to treat the elastohydrodynamic lubrication of rough surfaces for both line-contact EHL [1] and point-contact EHL [2] obtained by solving the modified Reynolds equation [3] and the elasto-plastic asperity micro-contact equations [4]. Based on these studies, expressions were provided to predict the central and minimum film thickness in dimensionless form. Also predicted was the asperity load ratio which is the percentage of the load carried by the surface asperities. These formulas are summarized below.

Line-contact EHL [1]:

$$H_c = h_c/R = 2.691W^{-0.135}U^{0.705}G^{0.556}\left[1+0.2\bar{\sigma}^{1.222}V^{0.223}W^{-0.229}U^{-0.748}G^{-0.842}\right]$$
$$H_{min} = h_{min}/R = 1.652W^{-0.077}U^{0.716}G^{0.695}\left[1+0.026\bar{\sigma}^{1.120}V^{0.185}W^{-0.312}U^{-0.809}G^{-0.977}\right]$$
$$L_a = 0.005W^{-0.408}U^{-0.088}G^{0.103}\left[\ln(1+4470\bar{\sigma}^{6.015}V^{1.168}W^{0.485}U^{-3.741}G^{-2.898})\right] \tag{1}$$

Point-contact EHL [2]:

$$H_c = h_c/R = 3.672W^{-0.045\kappa^{0.18}}U^{0.663\kappa^{0.025}}G^{0.502\kappa^{0.064}}(1-0.573e^{-0.74\kappa})\times\left[1+0.025\bar{\sigma}^{1.248}V^{0.119}W^{-0.133}U^{-0.884}G^{-0.977}\kappa^{0.081}\right]$$
$$H_{min} = h_{min}/R = 1.637W^{-0.09\kappa^{-0.15}}U^{0.711\kappa^{-0.023}}G^{0.65\kappa^{-0.045}}(1-0.974e^{-0.676\kappa})\times\left[1+0.141\bar{\sigma}^{1.073}V^{0.149}W^{-0.044}U^{-0.828}G^{-0.954}\kappa^{-0.395}\right]$$
$$L_a = 10W^{-0.083}U^{0.143}G^{0.314}\left[\ln(1+\bar{\sigma}^{4.689}V^{0.509}W^{-0.501}U^{-2.90}G^{-2.870})\right] \tag{2}$$

In Refs. [1,2,5], we conducted a set of verifications to show the agreement between the results of these expressions and the published data in the literature for both smooth [6–9] and rough surfaces [10,11]. It should be noted that in the statistical treatment of the mixed EHL context, the film thickness is equal to the distance between the mean lines of two rough surfaces. Therefore, the above formulas evaluate the overall effect of the surface roughness on film profile. In Eqs. (1) and (2), for both central and minimum film thickness, the part of the expression outside the brackets represents the smooth-surface film thickness, while the part inside the brackets represents the effect of surface roughness on the film thickness. This part contains the surface roughness term as the standard deviation of the asperities heights, as well as the surface hardness term which is appeared due to the plastic deformation of the asperities. The interested reader is referred to Refs. [1,2] for more information.

These expressions offer an easy-to-use procedure for estimating the EHL parameters without the need of performing extensive numerical simulations. Although these formulas are based on isothermal simulations, at moderate rolling velocities, the central film thickness, h_c, and the asperity load ratio, L_a, are not significantly affected by the sliding-induced heat generation. In fact, it is only the minimum value of the film thickness, h_{min}, that experiences a significant drop [12]. Consequently, if the rolling speed is moderate, the formulas for h_c and L_a can still be used at large slide-to-roll ratio values.

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Nomenclature

a_χ	diameter of area associated with an adsorbed molecule, m
b	half Hertzian width, $\sqrt{8RF/\pi BE'}$, m
B	contact length, m
c_p	specific heat, J/kg K
E'	effective Young's modulus, $1/E'=0.5[(1-\nu_1^2)/E_1+(1-\nu_2^2)/E_2]$, Pa
E_a	heat of oil's adsorption on surface, J/mole
f	traction coefficient
f_c	asperity friction coefficient
f_d	dry friction coefficient
F	total normal load, N
F_f	traction force, N
$(F_f)_a$	asperity traction force, N
$(F_f)_h$	hydrodynamic traction force, N
G	dimensionless material number, $E'\alpha$
h	film thickness, m
h_c	central film thickness, m
h_{min}	minimum film thickness, m
H	dimensionless film thickness, h/R
H_c	dimensionless central film thickness, h_c/R
H_{min}	dimensionless minimum film thickness, h_{min}/R
k	thermal conductivity, W/m K
K	dry wear coefficient
K_T	temperature–viscosity coefficient, K^{-1}
L_a	asperity load ratio (in percentage)
p	average contact pressure, $F/2bB$, Pa
p_a	average asperity pressure, Pa
p_h	average hydrodynamic pressure, Pa
p_e	Peclet number, $u_s \cdot b \cdot \rho \cdot c_p/2k$
q	total heat flux, W/m^2
q_a	asperity part of heat flux, W/m^2
q_h	hydrodynamic part of heat flux, W/m^2
R	equivalent contact radius, $[1/R_1 \pm 1/R_2]^{-1}$, m
R_g	gas constant, J/mole K
S	slide-to-roll ratio, u_s/u_r
t_0	fundamental time of molecule's vibration in the adsorbed state, s
T_s	surface temperature, K
T_0	inlet temperature, K
ΔT	temperature rise, K
u_r	rolling speed, $(u_1+u_2)/2$, m/s
u_s	sliding speed, $\lvert u_1-u_2\rvert$, m/s
U	dimensionless speed number, $\mu_0 u_r/E'R$
ν	Vickers hardness, Pa
V	dimensionless hardness number, ν/E'
w	load per contact length, F/B, N/m
W	dimensionless load number, $F/BE'R$ in line contact and $F/E'R^2$ in point contact
Z	viscosity–pressure index
α	pressure–viscosity coefficient, m^2/N
Λ_{lim}	limiting shear stress coefficient
κ	ellipticity parameter
μ	lubricant viscosity, Pa s
μ_0	inlet viscosity, Pa s
ρ	density, kg/m^3
σ	standard deviation of the surface heights, m
$\bar{\sigma}$	dimensionless surface roughness number, σ/R
τ_{avg}	average shear stress of the lubricant, Pa
τ_{lim}	limiting shear stress, Pa
Ω_{dry}	dry wear volume, m^3/s
Ω_{lub}	lubricated wear volume, m^3/s
ψ	fractional film defect

Development of a general expression capable of predicting the traction coefficient in EHL applications is a difficult task because it largely depends on the lubricant viscosity. The shear rate also plays a significant role here, and different lubricants may show completely different traction behaviors. More importantly, the viscosity is drastically influenced by the contact temperature rise. In contrast to numerous publications on the thermal EHL of smooth surfaces (see for example [13–22]), reports on the treatment of the thermal mixed EHL are scarce. With growing interest in field of rough EHL in recent years, a few studies also concentrated on the thermal effects in the mixed EHL [11,23–30]. In a recent paper, we conducted a full numerical simulation for the mixed thermo-elastohydrodynamic lubrication (mixed TEHL) to predict the behavior of traction coefficient [12]. Based on extensive set of results, a curve-fit expression was derived for predicting the traction coefficient for a specific type of lubricant (SAE 30).

Deriving an expression for prediction of the wear in the mixed EHL is also a challenging job since it requires the knowledge of the asperity load ratio and the temperature rise [31]. Although the load ratio can be predicted by the curve fit formulas [1,2], the temperature rise is still an unknown parameter.

In the current study, we report a simple but realistic approach for estimating the traction coefficient and the wear rate in elastohydrodynamic lubrication of rough surfaces without the need of performing extensive numerical simulations. A simplified method is adopted to estimate the temperature rise with the consideration of heat generation by both the solid and the lubricant. The estimated temperature rise is utilized together with the results from the isothermal formulas (Eq. (1)) to evaluate the traction coefficient and the wear rate in the mixed EHL.

2. Model

In this section, it is first shown how the temperature rise within the mixed EHL contact can be evaluated. Next, the traction coefficient and the wear rate are approximated using this method.

2.1. Temperature rise

To estimate the temperature rise due to the sliding in the mixed EHL regime, the theory by Tian and Kennedy [32] is used here. In their study, the temperature rise within the sliding bodies is analytically obtained. Although the method was originally developed for dry contact, where the asperity friction is the heat source, in the current study the fluid shear heating is treated as a heat source in a similar fashion. The method described here is for line-contact EHL, but it can be extended to point contact.

According to Tian and Kennedy [32], the flash temperature within the contact area of a moving square-shape heat source against a semi-infinite body is obtained as

$$\Delta T = \frac{2lq}{\sqrt{\pi}[k_1\sqrt{1+Pe_1}+k_2\sqrt{1+Pe_2}]} \tag{3}$$

where q is the average heat flux and l is the half contact length along the sliding direction which is here equal to the Hertzian half width of contact $\left(b=\sqrt{8RF/\pi BE'}\right)$. Note that for point contact, an expression for the elliptical heat source should be utilized. In Eq. (3), parameters k_1 and k_2 represent the thermal conductivity of the contacting surfaces, and Pe_1 and Pe_2 are their corresponding Peclet numbers.