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Combined Effects of Surface Adhering Layer and Surface Elastoplastic Deformation in Hydrodynamic Lubricated Line Contacts with Long-Chain-Molecule Fluids

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1. Introduction

Line contact is popularly existing in mechanical components such as roller bearings, cams and gears. It is often in hydrodynamic lubrication for reducing friction and wear. The hydrodynamic film thickness is the critical parameter for the line contact performance. However, the classical hydrodynamic theory for line contacts is based on the Newtonian fluid and neglects the effect of the adsorbed layer on the contact surface [1].

The physical adsorption of a fluid to a solid surface is a popular phenomenon. Molecular dynamics simulations show that for simple fluids or short-chain-molecule fluids such as water, methane and alcohol, the fluid molecule layers are orientated in some degree to the solid wall in a nanochannel flow owing to the fluid-channel wall interaction, and they flow by the special law determined by the wall slippage, the local density and viscosity enhancements and the discontinuity and inhomogeneity within the layers [2-5]. However, for the fluids with long-chain molecules, there may be only one to several fluid molecule layers on a solid surface [6, 7], which can be considered as a solid layer and wholly moving along with the solid surface. Chan and Horn [8] experimentally observed the hydrodynamic deviation of the octamethylcyclotetrasiloxane (OMCTS) from the Reynolds continuum lubrication theory in the concentrated contact when the surface separation was below 50 nm. They satisfactorily explained this deviation just by assuming the solid layer with the thickness no more than 2.5 nm on the contact surface.

In today's industry, the load, rolling speed and temperature of a line contact are much increased compared to the early industry, and the lubricating film thickness in a line contact can be as low as on the same scale with the thickness of the adsorbed layer [9-11]. To correctly reveal the hydrodynamic lubrication performance of a modern line contact, the new analysis is required by incorporating the effects of the adsorbed molecule layer and the contact elastoplastic deformation. The present study aims to do this work. It addresses on the multiscale hydrodynamic lubrication in line contacts when a long-chain-molecule fluid is used as a lubricant as often occurring on mechanical elements. Here, the adsorbed layer on the contact surface is taken as a solid layer, and intermediate between the two adsorbed layers is the Newtonian fluid. The elastic or elastoplastic deformations of the contact surfaces are considered for different loads. The lubricating film thickness separating the contact surfaces is calculated for varying rolling speeds and loads respectively for the micro and macro steel line contacts when the hardness of the softer contact surface is set as 0.4 GPa. The results show the strong effect of the adsorbed layer in the micro line contact which enhances the lubricating film thickness; While in the macro line contact it is also very significant in the condition of low surface separations and functioned importantly for maintaining the lubricating film.

2. Multiscale Hydrodynamic Lubricated Line Contact with Long-Chain-Molecule Fluids

In mechanical engineering, roller bearings, cam-follower contacts and gear contacts are often lubricated by the hydrocarbon oils with long-chain molecules. In severe operating conditions such as for heavy loads, high rolling speeds and high bulk fluid temperatures, the surface separations in these lubricated line contacts can be lower than one hundred times of the thickness (h_{bf}) of the adsorbed layer on the contact surface, which is normally at least on the 1 nm scale. In itself, owing to the chemical structure of the long chain of the fluid, there are only one to several adsorbed fluid molecule layers on the contact surface which can be wholly taken as a solid layer. Fig. 1 shows this multiscale hydrodynamic lubricated line contact.

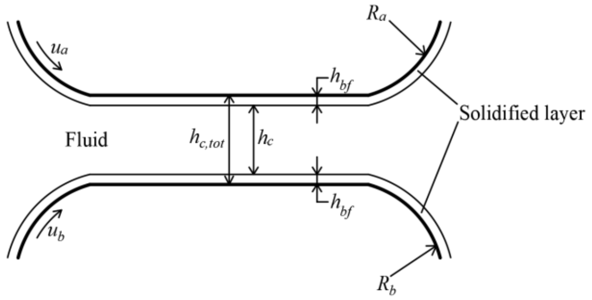

Fig. 1 Multiscale hydrodynamic lubricated elastoplastic line contact with a long-chain-molecule lubricant

3. Calculation of the Lubricating Film Thickness at the Contact Center

The present analysis is based on the following assumptions:

a. the materials of the two contact surfaces are the same and the adsorbed layers on the two contact surfaces are identical;

b. the line contact length is so large that the side leakage is negligible;
c. the fluid is Newtonian;
d. no interfacial slippage occurs;
e. the condition is isothermal and steady-state;
f. the fluid compressibility is negligible.

Fig. 1 directly shows that the (total) lubricating film thickness at the contact center is expressed as:

$$h_{c,tot} = h_c + 2h_{bf}\ , \tag{1}$$

where h_c is the hydrodynamic film thickness of the continuum fluid at the contact center and h_{bf} is the thickness of the adsorbed layer on either of the contact surfaces. The core of the analysis is to calculate h_c.

Zhang [12] suggested that when the dimensionless load (W) of a line contact is no more than $0.6W_{pc}$, where W_{pc} is the critical dimensionless load of the contact for the contact fully plastic deformation, the line contact can be taken as elastic; Otherwise the line contact can be taken as in fully plastic deformation. The equations for calculating h_c are radically different when the contact is in different deformation regimes.

3.1. Elastic contact

When the line contact is mainly in elastic deformation, the dimensionless thickness H_c of the continuum fluid film at the contact center is solved from the following equation [13]:

$$-0.2041\left(lg\frac{W}{H_c}\right)^2+0.8876\,lg\frac{W}{H_c}+$$

$$+lg\left(24.3825GU\right)-\frac{3}{2}lg\,W-1.2725=0$$

$$\text{for } 0.01 \le W/H_c \le 200 \text{ and } W \le 0.6W_{pc}, \tag{2}$$

where $H_c = h_c/R$, $R = R_aR_b/(R_a{+}R_b)$, R_a and R_b are respectively the curvature radii of the upper and lower contact surfaces as shown in Fig. 1, W is a dimensionless load and $W = w/(E_vR)$, U is the dimensionless rolling speed and $U = (u_a{+}u_b)\eta_a/(E_vR)$, and $G = \alpha E_v$. Here, w is the dimensional load per unit contact length, $2/E_v = (1-\nu_a^2)/E_a+(1-\nu_b^2)/E_b$, E_a and E_b are respectively the Young's moduli of elasticity of the upper and lower contact surfaces, ν_a and ν_b are respectively the Poisson's ratios of the two contact surfaces, u_a and u_b are respectively the circumferential speeds of the contact surfaces, η_a is the fluid atmospheric dynamic viscosity, and α is the fluid viscosity-pressure index. Intrinsically, there are two solutions in Eq. (2), but only the minimum solution is the real solution.

3.2. Fully plastic contact

When $W > 0.6W_{pc}$, the line contact is mainly in fully plastic deformation, and the dimensionless thickness H_c of the continuum fluid film at the contact center is solved from the following equation [13]:

$$\left[lg\left(19.15UW^{-3/2}G\right)-1.2791\left(lg\,\lambda-0.60227\right)\right]-$$

$$-\left(0.423404\,lg\,\lambda-2.006847\right)lg\frac{W}{H_c}-$$

$$-\left(0.033444\,lg\,\lambda-0.064543\right)\left(lg\frac{W}{H_c}\right)^2-$$

$$-0.044455\left(lg\frac{W}{H_c}\right)^3-0.042085\left(lg\frac{W}{H_c}\right)^4-$$

$$-\left(4.2692E-3\right)\left(lg\frac{W}{H_c}\right)^5=0$$

$$\text{for } 0.01 \le W/H_c \le 200,\ 30 \le \lambda \le 200$$

$$\text{and } W > 0.6W_{pc}, \tag{3}$$

where $\lambda = W(E_v/\Omega_s)^2$ and Ω_s is the hardness of the softer contact surface. Intrinsically, there are five solutions in Eq. (3), but only the minimum solution is the real solution.

4. Calculation Results

In the calculation, $W_{pc} = 2\Omega_s\sqrt{2\bar{\delta}_{pc}}/E_v$, $\bar{\delta}_{pc}$ is the dimensionless interference when the contact is just in fully plastic deformation under the critical load W_{pc} and $\bar{\delta}_{pc} = 239.22\left(\Omega_s/E_v\right)^2$ [12]. The two contact surfaces are made of steel. The following operational parameter values are chosen: $E_v = 209$ GPa, $\Omega_s = 0.4$ GPa, $h_{bf} = 1.0$ nm.

The values of R are respectively chosen as 50 µm and 10 mm, corresponding to the micro surface asperity contact and the macro line contact respectively.

Fig. 2, a-b show the variations of $H_{c,tot}$ and H_c with the dimensionless load W for different equivalent contact radius R when the different dimensionless rolling speed U is respectively 1.0E-11 and 1.0E-10. For the macro line contact like $R = 10$ mm, if the intermediate continuum fluid film exists, the values of $H_{c,tot}$ are often close to those of H_c and the adsorbed layer effect is negligible; however, when the load is critically heavy, the conventional model gives the values of H_c vanishing, while the present model gives the residual adsorbed layer boundary film with the total thickness 2 nm supporting the load and reducing the friction. For the micro asperity contact like $R = 50$ µm, the adsorbed layer effect is shown to be very significant for the wide load range and it greatly enhances the lubricating film thickness especially for low dimensionless rolling speeds. In a micro asperity contact, the adsorbed layer effect is reduced with the increase of the rolling speed. The results suggest that in a mixed lubrication, when the lubricating film thickness is low, the adsorbed layer effect should be incorporated and the multiscale hydrodynamic approach should be used in simulating the behavior of the lubricated asperity contact.

Fig. 3, a-b show that for the macro line contact with practical dimensionless rolling speeds, if the intermediate continuum fluid film exists, the adsorbed

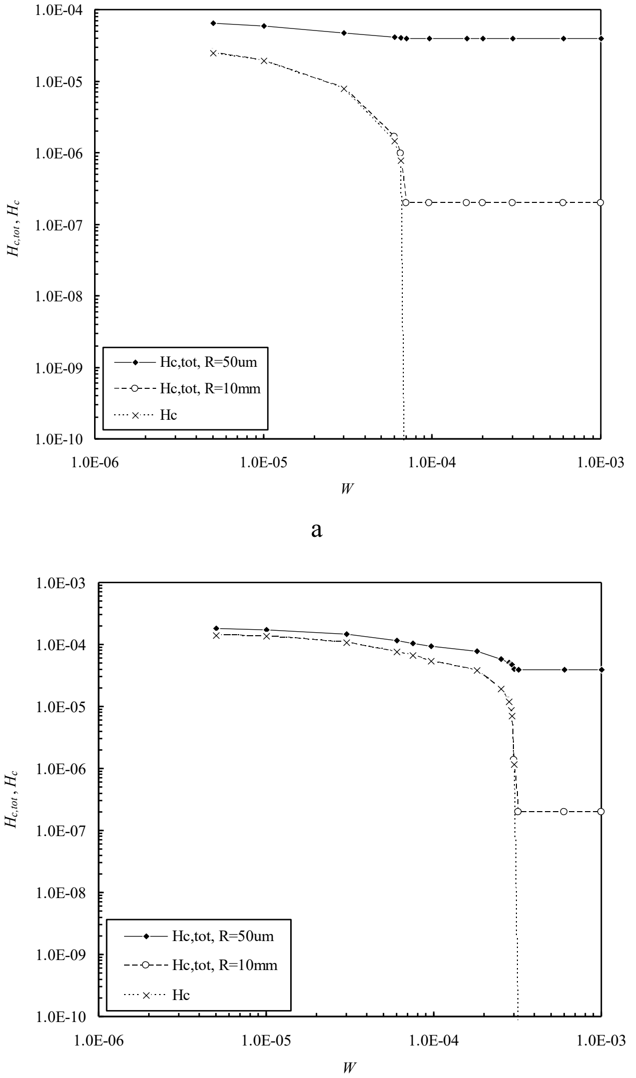

Fig. 2 Dependence of $H_{c,tot}$ and H_c on the dimensionless load W for different equivalent contact radius R and different dimensionless rolling speed U: a – $U = 1.0\text{E-}11$; b – $U = 1.0\text{E-}10$

layer effect is negligible and the value of $H_{c,tot}$ can be directly calculated from the conventional model; However, if the dimensionless rolling speed is so low that the intermediate continuum fluid film vanishes (i.e. $H_c = 0$), the present model still gives the existence of the adsorbed layer boundary film lubricating the contact with the infinite film stiffness under loading. This result is radically different from the conventional model description. For the micro asperity contact, if the dimensionless rolling speed is sufficiently high e.g. $U \geq 5.0\text{E-}10$, the values of $H_{c,tot}$ are close to those of H_c and the adsorbed layer effect is negligible; However, for the dimensionless rolling speeds not so high, the adsorbed layer effect is very significant and it largely increases the lubricating film thickness. The present results indicate the strong effect of the adsorbed layer in a lubricated asperity contact in the condition of low and medium rolling speeds and heavy loads. This effect is very important for maintaining the lubrication of a local asperity contact and avoiding the occurrence of local adhesion and scuffing. The present study suggests the mandatory of the multiscale hydrodynamic approach in the mixed lubrication modeling by incorporating the adsorbed layer effect.

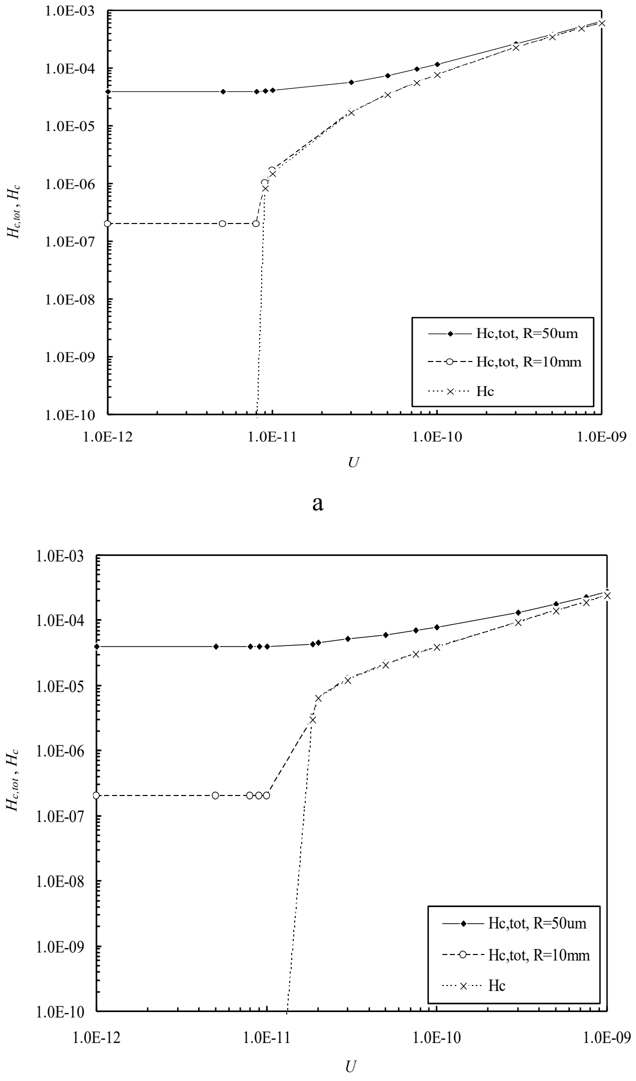

Fig. 3 Dependence of $H_{c,tot}$ and H_c on the dimensionless rolling speed U for different equivalent contact radius R and different dimensionless load W: a – elastic contact, $W = 6.0\text{E-}5$; b – fully plastic contact, $W = 1.8\text{E-}4$

5. Conclusions

The multiscale analysis was made for the hydrodynamic lubrication in the elastoplastic steel line contact lubricated by a long-chain-molecule fluid by incorporating the effect of the adsorbed layer on the contact surface. The (total) lubricating film thickness is the summation of the thicknesses of the adsorbed lubricant molecule layers on the two contact surfaces and the thickness of the intermediate continuum fluid film. For the surface hardness $\Omega_s = 0.4$ GPa and the thickness 1 nm of the adsorbed layer, the dimensionless total lubricating film thickness $H_{c,tot}$ at the contact center was calculated for widely varying loads and rolling speeds and for different equivalent curvature radius R of the contact.

It was found that for the macro line contact like $R = 10$ mm, if the intermediate continuum fluid film exists, the effect of the adsorbed layer is often negligible and the value of $H_{c,tot}$ can be calculated from the conventional elastohydrodynamic lubrication model; However, when the load is sufficiently heavy or the rolling speed is critically low so that the intermediate continuum fluid film vanishes, the present model gives the residual adsorbed layer film with the infinite stiffness supporting the load. For the micro asperity contact like $R = 50$ μm, only for high rolling speeds the adsorbed layer effect is negligible, otherwise it is very significant and largely increases the lubricating film thickness. The present study strongly indicates that in modeling mixed lubrication involving the surface asperity contact, the effect of the adsorbed lubricant molecule layer on the contact surface must be incorporated and the corresponding multiscale lubrication approach is mandatory for correctly evaluating the local contact performance including the local adhesion and scuffing.

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COMBINED EFFECTS OF SURFACE ADHERING LAYER AND SURFACE ELASTOPLASTIC DEFORMATION IN HYDRODYNAMIC LUBRICATED LINE CONTACTS WITH LONG-CHAIN-MOLECULE FLUIDS

Summary

In a line contact, when the surface separation is smaller than one hundred times of the thickness of the adsorbed boundary layer on the contact surface, the hydrodynamics should be considered as multiscale and consisting of both the adsorbed layer flows and the intermediate continuum fluid flow. However, for the fluids with long-chain molecules, there may be only one or several fluid molecule layers on the contact surface, which can be considered as a solid layer. The multiscale hydrodynamic film thickness was calculated for such fluids in the line contact which is respectively elastic or fully plastic under different loads. The results show that in the micro line contact with small equivalent curvature radii (R) such as on the 10 μm scale like the surface asperity contact, the adsorbed boundary layer has a very strong effect on the hydrodynamic behavior, while in the macro line contact such as with R on the 10 mm scale the adsorbed layer effect is eliminated and it is significant only for small rolling speeds or/and heavy loads.

Keywords: adsorbed layer, film thickness, hydrodynamics, line contact, multiscale.

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