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Recent developments in mixed lubrication

Yongbin Zhang

College of Mechanical Engineering, Changzhou University, Changzhou, Jiangsu Province, CHINA
e-mail: engmech1@sina.com

SUMMARY

This paper reviews the advances in the study of mixed lubrication in recent years, both in theoretical modelling and in experiments, especially those marking substantial progress. The advances support the mode of mixed lubrication proposed by the author more than ten years ago which exhibited thinning, mixed and partial films and mixed contacts in modern mixed lubrication under severe operating conditions. The paper outlines recently achieved progress in the field, which revealed new phenomenon such as: the elastoplastic deformation of the surface asperities, the boundary film interfacial slippage, the boundary lubrication effect and the interfacial shear stress effect on the contact surface deformation. Also, the mixed lubrication with designed surface roughness and the load-carrying mechanism of mixed lubrication are reviewed.

Key words: *mixed lubrication, boundary lubrication, surface deformation, interfacial slippage, model, experiment.*

1. INTRODUCTION

Mixed lubrication is a mode of lubrication in which the contact surface roughness effect should be considered or the films are mixed in the contact [1]. More than ten years ago, the author classified the modes of mixed lubrication into three types: the classical mode of mixed lubrication, the “modern” mode of mixed lubrication and the “future” mode of mixed lubrication [1]. It was pointed out that the “future” mode of mixed lubrication should be the direction for subsequent research. Afterwards, new progress has been achieved in both theoretical modelling and experimental studies. It is therefore necessary to give an overview of the main findings that marked the progress in the field. This will certainly be of considerable value for the forthcoming research in this area, as well as for appraising the literature formed during the past period. The present paper aims to accomplish these tasks.

2. THEORETIAL MODELLING OF MIXED LUBRICATION

In Ref. [1], a lot of viewpoints regarding the modelling of advanced mixed lubrication were proposed. They concerned the following content.

2.1 Modelling of the continuum lubricant film lubrication

A non-Newtonian lubricant model was proposed for this kind of modelling in Ref. [1]. It incorporated the following parameters: shear elastic modulus, shear-thinning Eyring stress and shear strength of the lubricant or the contact-lubricant interfacial shear strength. Before Ref. [1], the author and his colleagues used that model to simulate the bahaviour of continuum lubricant in mixed lubrication with mixed hydrodynamic and boundary films in smooth line contacts [2, 3]. That model holds significant values since a non-Newtonian lubricant model is usually demanded in a mixed lubrication modelling.

2.2 Modelling of the boundary lubrication

After Ref. [1], the author put a lot of effort into modelling a physically adsorbed layer boundary lubrication, which practically occurs in mixed lubrication. Several models were proposed.

2.2.1 An effective contact-adhering layer model

By an equivalent treatment method, this model artificially assumed an effective rigid-solid layer adhering at both contact surfaces; between the two surface layers the lubricant was treated as continuum [4, 5].

2.2.2 A real boundary film model

This model considered the rheological behavior of the real boundary film. It considered the boundary lubrication in an asperity contact, as shown in Figure 1 shows [6, 7]. For instance, it gave the Reynolds equation describing the flow of the mobile boundary film in the one-dimensional contact in Figure 1 as:

$$q_{m,bf} = uh\rho_{bf}^{eff} + \frac{S\rho_{bf}^{eff} h^3}{12\eta_{bf}^{eff}}\frac{dp}{dx} \tag{1}$$

where $q_{m,bf}$ is the mass flow rate of the boundary film through the contact, η_{bf}^{eff} and ρ_{bf}^{eff} are the effective viscosity and density of the boundary film, respectively; h and p are the film thickness and pressure, respectively; u is half of the sliding speed, x is the coordinate, and S is the parameter depicting the boundary film non-continuum effect which is here generally expressed as:

$$S(H) = \begin{cases} -1, & for\ \ (H + 2H_{layer})/H_{cr,bf} \geq 1\ \ or\ \ H_{cr,bf} = 0 \\ \left[n_0 + n_1 \left(\dfrac{H + 2H_{layer}}{H_{cr,bf}} - n_3 \right)^{n_2} \right]^{-1}, & for\ \ n_3 < (H + 2H_{layer})/H_{cr,bf} < 1 \end{cases} \tag{2}$$

where $H = h/R$, $H_{layer} = h_{layer}/R$, $H_{cr,bf} = h_{cr,bf}/R$, and n_0, n_1, n_2 and n_3 are constants. Here, $h_{cr,bf}$ is the critical boundary film thickness, and R is the radius of the cylinder.

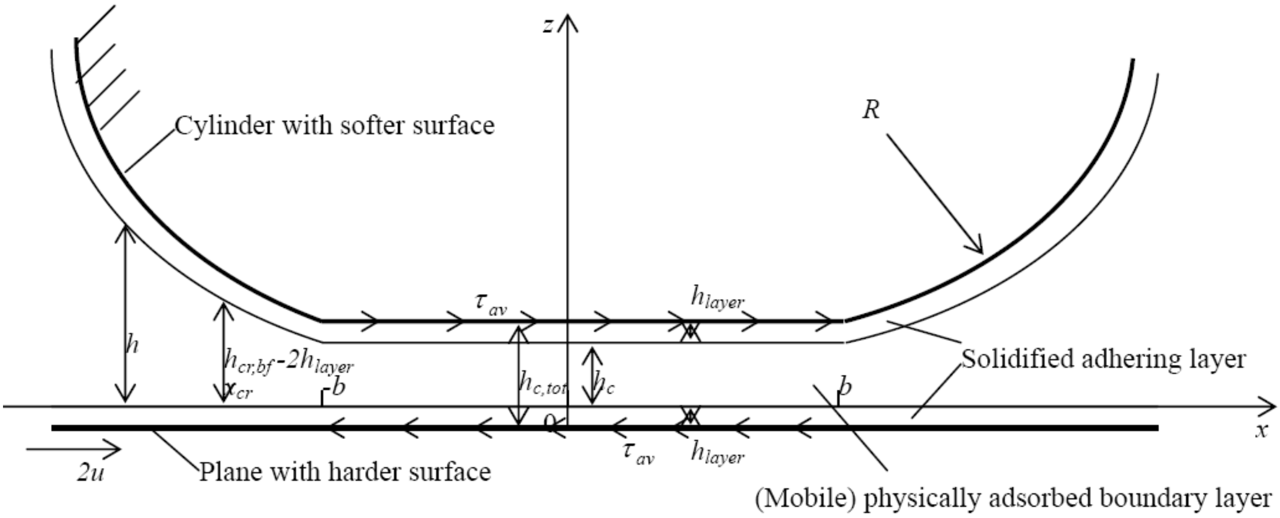

Fig. 1 The physically adsorbed boundary layer lubrication in a one-dimensional contact [6]

2.2.3 Other models considering the boundary film effects

Besides the two aforementioned models, other models were proposed for modelling the boundary lubrication, based on the examination of the boundary film shear elastic modulus and interfacial slippage effects [8-11].

The boundary film slippage in a contact has been well verified by both experiments and molecular dynamics simulations [12-16]. It was agreed that the boundary film slippage was a result of an inefficient momentum transfer at the boundary film-contact interface and that it was determined by the interaction strength between the contact and the boundary film. Normally, the boundary film will unavoidably slip at the contact surface. Actually, before Ref. [1], the author proposed that the pressure within the boundary film should be accurately calculated because any inaccurate calculation of the boundary film pressure may lead to considerable calculation errors in the boundary film thickness [17]. To this end, the author suggested that the boundary film shear elastic modulus and interfacial slippage effects should both be considered in the modelling of boundary lubrication. As a simplified example, the author analytically studied the boundary film shear elastic modulus effect in a one-dimensional micro-step bearing by considering the boundary film interfacial slippage at one contact surface [8, 9]. The selection of the step bearing for analysis was due to its simplicity of configuration and the convenience of the analysis derivation; this selection had actually been done earlier [18]. It was found that the boundary film shear elastic modulus had a considerable influence on the boundary film pressure [8, 9].

It was suggested that, when modelling a mixed lubrication, a boundary film model should normally take into account the boundary film-contact interfacial shear strength and interfacial slippage effect. This should be so because the boundary film interfacial slippage may significantly reduce the local film pressure and, consequently, the local film thickness in mixed lubrication [10, 11]. It was also found that the boundary film interfacial slippage effect was strengthened with the boundary film contact width, but reduced with the increase of the contact surface roughness [19].

It was suggested that in a boundary film model the surface pressure (the solvation and van der Waals pressures) should be incorporated when the boundary film contact width ranges between $10\ \mu m$ and $100\ \mu m$ and the boundary film thickness is below $5\ \mu m$ [20].

Concerning the boundary film model application in mixed lubrication, it was suggested that the actual critical boundary film thickness should usually be significantly lower than the theoretical critical boundary film thickness [21]. Moreover, the reduction of the compound curvature radius of the coupled asperity surfaces tends to significantly reduce the critical boundary film thickness for the boundary film model application [21]. When the interaction between the boundary film and the contact surfaces is weakened, or the contact surface thermoelastic deformation effect is weakened, the value of the critical boundary film thickness is further reduced [21].

2.3 Modelling of the contact surface deformations

In mixed lubrication modelling, the contact surface deformations should be accurately calculated especially when the boundary film occurs in asperity contacts, since this deformation caused by the lubricating film pressure or/and the contact surface thermal expansion is normally comparable with, or even much greater than, the boundary film thickness [10, 11, 20]. A pioneering elastoplastic contact model for a mixed lubrication modeling was published in 2007 [22-24], but it was in fact composed before 2006. The author suggested that in mixed lubrication modelling the contact surface asperities should be treated as elastoplastic [4-7], although the whole contact surface may usually be mainly in a state of elastic deformation due to its hardness [25].

2.3.1 Elastoplastic deformation effect of the contact surface asperities

The author simulated mixed lubrication between two parallel plane surfaces with elastoplastic asperities [22-24]. As the first example, the coupled surface asperities were in direct contact. Depending on the lubricating film thickness, their separations were filled with boundary lubrication film or continuum hydrodynamic film. Through those simulations, important results were obtained concerning the contact stiffness, the load partition in different contacts, the maximum surface temperature rise and the benefits of the truncation of the surface asperities in increasing the contact stiffness and the contact load-carrying capacity, but reducing the maximum surface temperature rise. Soon afterwards, the author wrote an article addressing hydrodynamic lubrication in fully plastic asperity contacts [26]. It was found that the fully plastic deformation of a surface asperity easily resulted in the continuum hydrodynamic film breakdown and in the occurrence of boundary lubrication in an asperity contact in mixed lubrication of a line contact, under heavy load or/and low rolling speed. Afterwards, the author addressed the elastoplastic deformation effect of surface asperities in hydrodynamic lubricated line contacts [25]. It was also found that the occurrence of the plastic deformation of a surface asperity was harmful for the generation of the hydrodynamic load-carrying capacity in an asperity contact. The plastic deformation of an asperity is also very harmful for the lubricating film generation in an asperity contact lubricated with boundary films in mixed lubrication [6, 7]. Therefore, it appears mandatory to incorporate the contact surface plastic deformation into a mixed lubrication model.

2.3.2 Thermal deformation effect of the contact surfaces

In Ref. [1], the author pointed out that the thermoelastic deformation effect of the contact surfaces may be significant for thinning the local lubricating film, especially in mixed lubrication with a local dry contact or local boundary lubrication under severe operating conditions. After that proposal, little research was seen on this subject. Recently, the author carried out an analysis of a lubricated elastoplastic line contact covering issues from boundary lubrication to hydrodynamic lubrication by considering the contact surface thermoelastic deformations [6, 7]. It was found that the thermoelastic deformations of the whole contact surface can result in a drastic collapse of hydrodynamic lubrication film in mixed lubrication of a line contact under high sliding speed and heavy load. This is due to a large value of K_R which is the ratio of the compound curvature radius of the contact surfaces to the contact thermal radius. Furthermore, even the thermoelastic deformations of an asperity contact can have a significant thinning effect on the local lubricating film in mixed lubrication under high sliding speed and heavy load. It was pointed out that the local thermoelastic deformations of the contact surfaces may be intimately related to the local film and contact failures in mixed lubrication under severe operating conditions.

It should be pointed out here that in the future research a mixed lubrication model may be improved if the contact surface thermo-elastoplastic deformation effect is incorporated.

2.3.3 Interfacial shear stress effect on the contact deformation

In a conventional elastohydrodynamic lubrication, the lubricant-contact interfacial shear stress effect on the contact deformation may be neglected [27]. However, in mixed lubrication, such an effect may not be negligible due to the contact deformations caused by the interfacial shear stresses comparable to the lubricating film thickness, especially when the boundary lubrication occurs. The author addressed this effect in line contact mixed lubrication modelling assuming that the interfacial shear stresses mainly occurrs in the Hertzian zone and that it is constant [6].

2.3.4 Designed surface roughness

The designed surface roughness may be considered as an artificially produced surface deformation. Fortunately, mixed lubrication modelling with designed surface roughness was carried out and finally published [28]. It was found that, under conditions of heavy load and high rolling speeds, the truncation of the surface asperities can reduce the maximum surface temperature rise while maintaining the hydrodynamic load-carrying capacity in a mixed elastohydrodynamic contact [28].

3. EXPERIMENTAL STUDY OF MIXED LUBRICATION

Experimental studies on mixed lubrication has been relatively scarse in recent years, although it is very important to verify theoretical modelling. This may be due to the complexity of the problem or restricting conditions for performing experiments. Nevertheless, the author's persistent efforts have yielded some progress in experiments on mixed lubrification.

The author and his colleagues carried out an experiment on sliding friction of a lubricated point contact [29]. It was found that, in mixed lubrication, the asperity contact in boundary lubrication or direct contact may undergo plastic deformation and the boundary film-contact interfacial slippage may normally occur in the asperity contact. It was suggested that the friction model for the practical sliding mixed elastohydrodynamic contact where the asperity contacts are in boundary lubrication or direct contact, should incorporate both the plastic deformation of the asperity contact and the boundary film-contact interfacial shear strength and slippage.

Later, the author and his colleagues carried out an experiment on sliding friction of a lubricated point contact with low surface hardness and different bulk lubricant temperatures [30]. It was found that the reduction of the hardness of the softer contact surface significantly increased the friction coefficient of the contact. This indicated that the asperity contact was nearly in fully plastic deformation. The experiment also verified the existence of boundary film-contact interfacial slippage in an asperity contact. The obtained results also suggested that under high bulk lubricant temperatures the boundary film may locally break through.

4. INDICATION OF THE RESULTS OBTAINED FROM THE MIXED LUBRICATION STUDY

The literature reffered to so far higlights some important points to be considered in future research:

(1) The physically adsorbed boundary layer in an asperity contact cannot be treated as a solid contact. With the movement of the contact surfaces, this boundary layer flows and should be described by the Reynolds equation, which obeys the flow continuity [6, 31]. Furthermore, the stiffness of this boundary layer is much greater than the stiffness of an asperity contact which undergoes elastoplastic deformation [4, 5]. It makes the boundary layer very useful for local lubrication of a contact. In some cases, the boundary layer can even considerably contribute to the load-carrying capacity of the whole contact [4-7].

(2) In mixed lubrication modelling, an asperity contact should normally be treated as elastoplastic. Also, an approach that considers elastoplastic deformation of the contact surface is required for simulating the continuum lubricant lubrication between the coupled rough surfaces in part of the contact.

5. CONCLUSIONS

This paper reviews recent research in mixed lubrication. The review may be of interest to the forthcoming research in this area. Some important points are outlined here:

(1) The boundary lubrication in an asperity contact should be accounted for in modelling. Not only dynamic and non-continuum effects of the boundary film but also boundary film shear elastic modulus and interfacial slippage effects should be considered for giving the local film thickness in an asperity contact accurately. Also, the surface force should be considered when the lubricating film thickness is very low.

(2) The asperity contact in mixed lubrication should generally be considered as elastoplastic. An approach for the boundary lubrication or the continuum lubricant lubrication in an elastoplastic micro contact is essential.

(3) The contact thermal deformation, as well as the interfacial shear stress influence on the contact deformation, should be considered in a fine simulation of mixed lubrication.

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SUVREMENA DOSTIGNUĆA U PODRUČJU MIJEŠANOG PODMAZIVANJA

SAŽETAK

Cilj ovog rada je pružiti pregled najnovijih dostignuća iz područja miješanog podmazivanja, kako iz perspektive modeliranja tako i iz eksperimentalne perspektive, uz naglasak na dostignuća koja predstavljaju značajan napredak u tome polju. Rezultati o kojima će ovdje biti riječ potvrđuju model miješanog podmazivanja kojeg je autor predložio prije više od deset godina, a koji je pokazivao fenomen stanjivanja, miješane i parcijalne slojeve (filmove) i miješane kontakte u modernom mješovitom podmazivanju u grubim uvjetima rada. Ovdje se daje pregled napredaka koji su ukazali na neke nove fenomene poput elastoplastične deformacije površinskih mikroizbočina u dodiru graničnog klizanja međupovršinskog filma, efekta podmazivanja granica te međupovršinskog smičnog naprezanja na deformaciju konktaktne površine. Također je dan pregled miješanog podmazivanja sa zadanom hrapavošću površine te mehanizam nosivosti miješanog podmazivanja.

Ključne riječi: *miješano podmazivanje, podmazivanje graničnih površina, deformacija površine, granično klizanje, model, eksperiment.*