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Hydrodynamic Performance of Square Shape Textured Parallel Sliding Contacts Considering Fluid-Solid Interfacial Slip

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Abstract. Hydrodynamic lubrication performances of square shape textured parallel sliding contacts are investigated under the influence of slip at the fluid-solid interface based on a CFD (computational fluid dynamic) approach. A Navier-slip length model is adopted to formulate the fluid-solid interfacial slip. In order to model slip, the enhanced user-defined-function (UDF) in the FLUENT commercial package is developed. The slip in the fluid-solid interface is controlled by applying a hydrophobic property on a certain zone of a textured surface. Four arrangements of placement of fluid-solid interfacial slip are discussed in detail in terms of pressure, load support, friction force and friction coefficient. In addition, such performances of hydrophobic textured contact are also compared with that of optimal conventional (untextured) one. In general, the results suggest that the hydrophobicity of surface textured parallel contact enhances the load support and reduces the friction. Also, a particular care must be taken in choosing the slip placement within the textured surface to achieve an optimal improvement in the parallel textured sliding contact. The predictions show that well-chosen slip on textured zone can considerably improve the sliding contact behaviour and largely justify future numerical analysis.

INTRODUCTION

The general purpose of lubrication in lubricated sliding contact is to minimize friction, wear, and heating of machine components which move relative to each other. The main factor is the understanding of lubricant film formation and its effect on load support and friction. Control of the boundary condition will allow a degree of control over the hydrodynamic pressure in confined systems and be important in a lubricated bearing. One of the developed treatments to eliminate high friction is the development of new materials or design of surfaces and interfaces with hydrophobic behaviour [1, 2]. Non-wetting (hydrophobicity) is a critical surface property for materials or devices in micro/macro-applications. The hydrophobicity of a surface is generally presented in terms of a slip length, which quantifies the extent to which the fluid elements near the wall are affected by corrugation of the surface energy [3].

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A number of excellent works have evinced the presence of fluid-solid interfacial slip on a hydrophobic surface [4-6]. It has been demonstrated that the fluid-solid interfacial slip velocity on a hydrophobic surface results in a significant friction reduction [4, 5]. For most hydrophilic surfaces, however, no-slip occurs. In a lubricated sliding contact, one is able to enhance, in a controlled way, a hydrophobic/hydrophilic behaviour of the surfaces. If one surface is hydrophobic (slip) and the other is hydrophilic (no-slip), the sliding velocity or displacement between the surfaces is accommodated by shear at the hydrophobic surface (the lubricant is kept in the contact by the hydrophilic surface). In this way, high liquid friction of the surfaces is reduced.

The great challenge for a hydrophobic surface from the perspective of a numerical simulation is choosing a model for the fluid-solid interfacial slip. This is because the hydrodynamic behaviour of lubricated contacts is mainly governed by the boundary conditions of the lubricant that provide lubrication. The Navier-slip boundary condition is the most widely used boundary condition to describe fluid-solid interfacial slip with methods based on the solution of the continuum equations. Recently, the use of fluid-solid interfacial slip in bearing has become popular with respect to lubrication, since this type of surface enhancement would give the better tribological performance. Several researchers such as [7-9] have explored the behaviour of the sliding contact using fluid-solid interfacial slip with respect to load support. The results of all these investigations show the existence of a lifting force (load support) even there is no wedge effect (two parallel sliding surfaces) using such the fluid-solid interfacial slip.

Another attractive technique to reduce the friction and improve the load support is by patterning or texturing the lubricated surface. Friction reduction was obtained with the employment of different patterns in the form of micro-textures on the surface by laser surface texturing (LST). Theoretical analysis of such textured surface system generally has been carried out using Reynolds equation. However, with the increase of engineering problems in complex geometries for which Reynolds equation is unsuited and increasing availability of user-friendly, commercial CFD codes based on the Navier-Stokes equations, the application of CFD simulation is quite effective.

However, most investigations dealing with textured surfaces were conducted by assuming the surface as hydrophilic property, that is, no fluid-solid interface surface boundary condition. Very few researchers appear to have considered the interplay of the surface texture and fluid-solid interface slip on lubrication performance, for example, Aurelian et al. [7], Rao et al. [8], Muchammad et al. [9], and Susilowati et al. [10] for recent publication. Even though major progress has been made in the lubrication of textured slippage surfaces, the majority of work is still based on the Reynolds equation, which means that in their model, the inertia-less approach was employed. Therefore, to complement the previous findings by clarifying the interaction of fluid-solid interface slip with surface texture, it is necessary to give a distinct analysis based on the CFD approach on the lubrication property of hydrophobic textured surfaces.

In general, based on literature survey the surface texturing combined with the fluid-solid interfacial slip is an effective means of controlling lubrication performance in lubricated sliding contact. It is interesting to check whether a different arrangement of the fluid-solid interfacial slip applied on textured contact has a significant effect on the tribological performance. Thus, in the present study in order to further explore the advantage of the existence of the fluid-solid interface slip, in the following computations, the predicted performance simultaneously will be evaluated. In some case, such performance will be compared with the performance of an optimum operating smooth (without textured) sliding contact. The hydrodynamic performance in terms of load support, friction force, and friction coefficient is estimated using CFD (Computational fluid dynamic). An user-defined-function (UDF), to model a fluid-solid interfacial slip in the FLUENT® package, is developed to simulate the effect of a hydrophobic surface in a deterministic way. In this study, the square shape is adopted in textured bearing because in real application it is easier to manufacture. In addition, based on the point of view of load support generation, the square shape is quite effective [10].

NUMERICAL MODEL

Governing Equations of Continuum Mechanics

The Navier–Stokes equations are solved over the domain using a finite-volume method with the commercial CFD software package FLUENT®. The equations are applied with constant density and viscosity, without body force. The equations are steady and solved in the *x*- and *z*-direction only. With these properties, the Navier–Stokes and the continuity equations can be expressed, respectively,

$$\rho(\mathbf{u} \bullet \nabla)\mathbf{u} = -\nabla p + \eta \nabla^2 \mathbf{u} \tag{1}$$

$$\nabla \cdot \mathbf{u} = 0 \tag{2}$$

Fluid-solid Interfacial Slip Modeling

With the availability of hydrophobic coating materials and the use of sliding surfaces in very narrow-gap situations and, the classical (no-slip) boundary condition can be broken down. When fluid slips along a fluid-solid interface, the slip length β according to Navier-slip theory is generally used to address the relation between slip velocity and surface shear rate, that is,

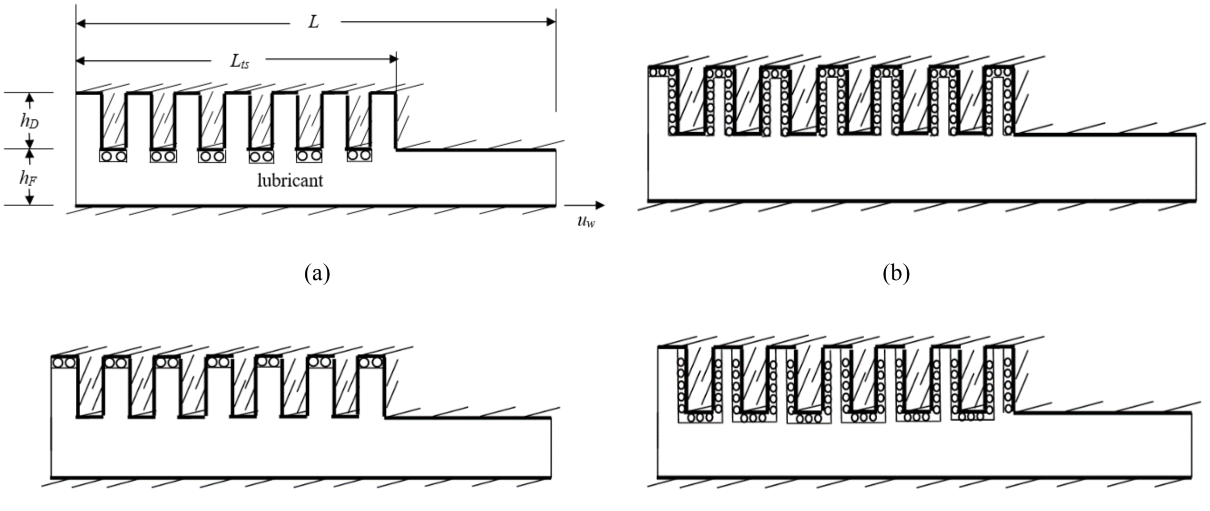
$$u_s = \beta \left.\frac{\partial u}{\partial z}\right|_{\text{surface}} \tag{3}$$

where u_s indicates the streamwise slip velocity at the hydrophobic surface, β denotes the slip length and $\left.\partial u / \partial z\right|_{\text{surface}}$ is the surface shear rate.

CFD MODEL

To analyze the effect of fluid-solid interfacial slip of a hydrophobic surface on lubrication, the simulation is performed for a value of the slip length proportional to the slip length in the experimental work of Choo, et al. [11]. Hence, a slip length of $20\text{x}10^{-6}$ m is considered. In the analysis of a textured parallel sliding surface, a textured cell is characterized by three non-dimensional parameters: the texture density α (defined as the ratio between the dimple length l_d and the texture cell length l_c), relative dimple depth K (defined as the ratio between the dimple depth h_d and the land film thickness h_f), and the texture aspect ratio λ (defined as the ratio between the dimple length l_d and the dimple depth h_d). It is assumed that h_f is set equal to h_o.

In real application, a fluid-solid interfacial slip pattern can be obtained by treating the surface with a hydrophobic chemical treatment. This can be accomplished by techniques such as film or molecule deposition, solution coating or self-assembly of hydrophobic layers. In this section, four arrangements of fluid-solid interface slip, applied to create four hydrophobic textured configurations (see Fig. 1), are proposed and compared with each other. In the present work, the texture parameters of the surface with T^+ (where $T^+ = L_{ts} / L$) of 0.55 and λ of 5 are used.



(a) (b)

(c) (d)

FIGURE 1. Four configurations of square shape textured sliding contacts: (a) “bottom slip”, (b) top-multiple slip (c) “top slip”, (d) “bottom-multiple slip”

Boundary Conditions

In the present study, the boundary condition of fluid-solid interface slip at a hydrophobic surface is permissible to occur in a deterministic way in a textured edge for the momentum equations. The main assumption of the CFD model presented here is the sole existence of full hydrodynamic lubrication (i.e. no-contact between the surfaces is permitted). At the inlet and outlet of the domain, the pressure was set to atmospheric and a zero velocity gradient in the direction normal to sliding was assumed. This can also be thought of a fully developed flow approximation. The simulated parameters used in the present research is reflected in Table 1.

A Newtonian laminar flow model was assumed for the solution. All the cases in this study will be regarded as isothermal and therefore the energy conservation equation is not included. The control volume-based technique was employed to numerically solve the Navier-Stokes equation. The second order upwind scheme was applied for momentum discretization, and the SIMPLE procedure was used for pressure-velocity coupling in the calculations. All calculations have been performed with double-precision and the iterative error has been reduced to machine accuracy. Therefore, the numerical uncertainty is mainly due to the discretization error.

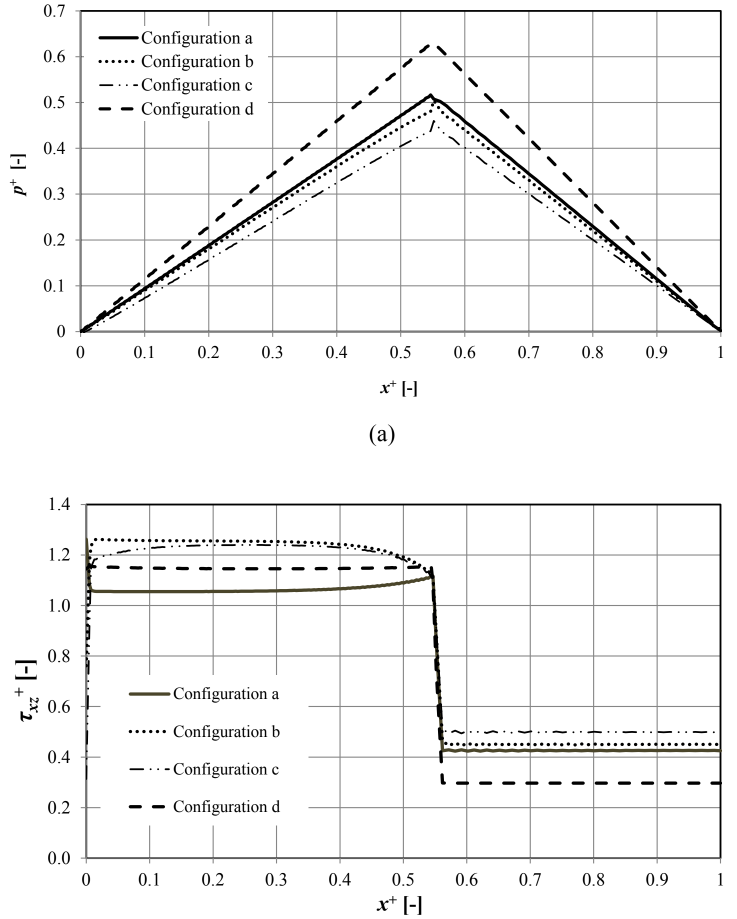
TABLE 1. Simulated parameters

Parameter	Data setting	Unit
Slip length β	20×10^{-6}	m
Non-dimensional hydrophobic textured region $T+$	0 – 1	[-]
Texture density α	0.7	[-]
Relative dimple depth K	1	[-]

RESULTS AND DISCUSSIONS

The load support, the viscous friction force, and the friction coefficient are a good measure of the effectiveness of the square shape textured contact. Load support of a lubrication film can be achieved by the integration of the positive pressure on the stationary surface, and the friction force can be obtained by integrating the shear stress on the top surface of the lubrication film. In the present work, the friction coefficient is defined as the ratio of the friction force per unit length to the load support per unit length.

Figure 2 depicts the non-dimensional hydrodynamic pressure distribution and wall shear stress, respectively for different configurations of the hydrophobic textured pattern. The results suggest that for the same textured region and texture cell aspect ratio, a surface with "bottom-multiple slip" (i.e. configuration *d*) generates a larger non-dimensional hydrodynamic pressure profile compared to the others. In relation to the surface shear stress distribution, as shown in Fig. 2 (b), the results show that the variation of shear stress distribution for all configurations is not significant. However, configuration *d* gives a lower non-dimensional shear stress distribution especially in the untextured region compared to other configuration. It means that configuration *d* generates a lower friction force, and thus a lower friction coefficient. Figure 2 (b) also reflect that all shear stress curves do not very much. It indicates that the friction force is not that sensitive to the arrangement of artificial fluid-solid interfacial slip. However, for the untextured part of the sliding contact ($x^+ > 0.6$ where $x^+ = x / L$), configuration *d* gives lower values, and as a result, the friction force is reduced. Obviously, this trend can also be observed in Fig. 3. The predicted friction force ratio f^+ / f^+_{ns} (where $f^+ = fh_o / (u_w \eta L)$ and subscript *ns* refers to no-slip) ranges from 1.01 to 1.10, which means that compared to the optimum classical contact, no significant change in friction force is obtained using surface texturing no matter how the fluid-solid interfacial slip is applied.



(a)

(b)

FIGURE 2. Hydrophobic textured surface: (a) Non-dimensional hydrodynamic pressure distribution, p^+, and (b) non-dimensional surface shear stress, τ_{xz}^+ (where $\tau_{xz}^+ = \tau_{xz} h_o / (u_w \eta)$), for several configurations. All curves are calculated for the optimum texturing parameters $T^+ = 0.55$ and $\lambda = 5$.

In order to shows the true benefits of the textured pattern considering the fluid-solid interfacial slip over the optimum classical contact for all configurations, the performance ratio (non-dimensional load support, friction force, and friction coeffient) is summarized in Fig. 3. It should be noted that for classical (untextured) sliding contact, the optimal performance of lubrication is achieved when the slope incline ratio (i.e. the ratio of inlet over the outlet) is 2.3 [12].

Based on Fig. 3, it is clear that for all configurations considered with respect to hydrophobic textured surfaces presented here, a significant enhancement of the load support can be generated compared to optimum classical contact (i.e. no-slip and $h^* = 2.2$). For example, an improvement in load support with 97% is obtained when configuration *d* is employed, and an improvement with 38% (lowest value) when configuration *c* is used. It indicates that combining texturing with hydrophobic coating inducing fluid-solid interface slip wherever the arrangement of boundary slippage application are put, is beneficial with respect to the lubrication performance. However, a well-chosen slippage within the texture cell is important for an optimal improvement. However, compared to optimum traditional contact, due to the high load support, a hydrophobic textured surface results in a lower friction coefficient. This, because of the presence of boundary slippage effect on the texture cells, has a more dominant force if compared to a hydrophilic textured surface, and thus results in an increase of the load support.

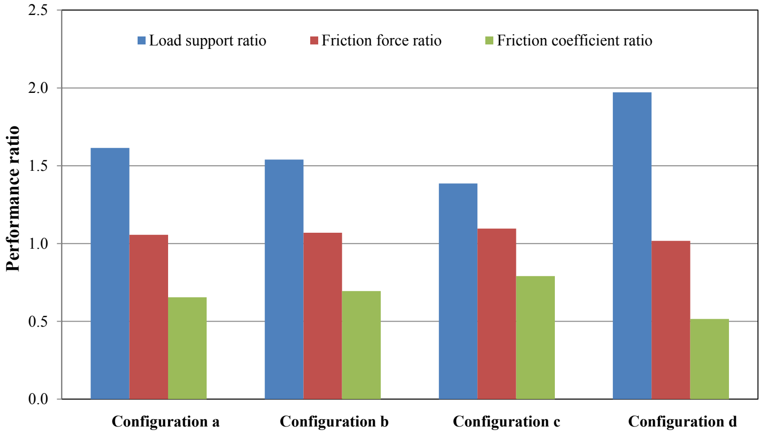


FIGURE 3. Effect of the placement of fluid-solid interfacial slip of the textured surface on the lubrication performance ratio.

CONCLUSION

In the present study, the connection between the surface texturing and the fluid-solid interfacial slip (hydrophobicity) dealing with the effect of the placement of slip of textured contact was discussed with respect to the load support, friction force, and friction coefficient. The finite volume method was employed to solve the lubrication problem. Based on the simulation results, it was highlighted that a well-chosen slip arrangement within the textured surface is important for an optimal improvement in the parallel textured sliding contact. Indeed, an effective hydrophobic textured surface, as indicated in this paper, can be utilized as a guideline for the fabrication of modified sliding surfaces. The interesting outcome of this study is that the results can be considered as a good evaluation tool for the tribological performance of the surface "fluid-solid interfacial slip" concept.

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