Texture Orientation Effect on the Performance of Parallel Sliding Contact in the Presence of Fluid-Solid Interfacial Slip

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Abstract

In recent years, it is observed that introduction of specific textures on a sliding surface improves the tribological properties. A lot of research is carrying out on the specific features of surface textures like size, shape, distribution and orientation. The present paper aims to study the effect of triangular texture orientation on the performance parameters like load support, end flow and friction parameter of parallel sliding contact by varying critical threshold shear stress. The fluid-solid interfacial slip is provided on the stationary surface on which surface textures are produced. The two-component slip length model is used to include slip velocity terms in the pressure governing equations. The obtained modified Reynolds equation is solved by finite difference method using Gauss-Seidel iterative scheme. The results indicated that consideration of fluid-slip improves the performance parameters; however, texture orientation has small / negligible effect on load support and friction parameter when fluid / solid interfacial slip is considered.

Keywords: Fluid-solid interfacial slip, Orientation, Parallel sliding contact, Triangular texture.

1 Introduction

One of the basic assumption in classical Reynolds equation is no-slip condition at the fluid-solid interface. This assumption may be suitable for macroscopic level but there is an uncertainty in the micro / nano level of work. Because recent studies in molecular dynamics simulation [1, 2] and experimental [3 - 6] depicts the presence of fluid-solid interfacial slip. Spikes and Granick [7] noticed that even Newtonian fluids can slip against the smooth walls through their experiments, following which, a new equation is modelled called as two-component slip model. The results obtained by this model is in good agreement with the experimental results. Using numerical technique, Salant and Fortier [8] analyzed the performance of slider bearing by considering an engineered slip / no-slip surface on one of the solid

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surface. They assumed, slip occurs when shear stress exceeds critical shear stress and the rise of slip follows a Navier relation. The authors observed a significant increase in load support and decrease in frictional coefficient for an appropriate slip surface pattern. The location and size of the slip on sleeve surface significantly affects the performance of journal bearing [9].

In recent times, a lot of research is carrying out related to the effect of surface textures on the tribological performance characteristics. For a simple thrust slider application, Siripuram et al. [10] utilized numerical techniques to explore the effect of basic asperity properties comprised of shape, size, concavity and orientation on the lubrication characteristics. They found that friction coefficient is largely independent of asperity shape and orientation but very sensitive to asperity area fraction (size) and the leakage is dependent on asperity shape, concavity, orientation and size. Most of the work in literature is observed on dimple shapes due to ease of manufacturing.

From the literature it has been observed that surface texturing and fluid-solid interfacial slip provides a positive effect on the tribological performance characteristics. Therefore, current research is heading towards the combined effect of both surface textures and fluid-solid interfacial slip. Aurelian et al. [11] studied the combined effect of partial texturing and slip / no-slip configuration. It has been observed that power loss is reduced in this configuration as compared to simple partial texturing condition. Syed and Sarangi [12] numerically studied the combined effects of the texture shape and fluid-solid interfacial slip on the lubrication performance of parallel sliding contacts. They observed that depending on shape and size of texture, considering fluid-solid interfacial slip may increase or decrease the tribological performance characteristics as compared to conventional textured surface. In the present work, effect of triangular texture orientation on the tribological performance of parallel sliding contact is studied while considering fluid-solid interfacial slip.

2 Theory

In parallel sliding contacts, the textures are assumed to be provided on stationary surface while moving surface is considered to be smooth. An imaginary unit cell is assumed on the stationary surface in such a way that each texture is at the centre of unit cell. For the numerical analysis, a single unit cell is taken by considering appropriate boundary conditions. When the positive textures are considered on the stationary surface, the clearance / film thickness between the two sliding surfaces is

Dimensional Non-dimensional

$$h = \begin{cases} C - h_g & \text{above the protrusion} \\ C & \text{elsewhere} \end{cases} \qquad \bar{h} = \begin{cases} 1 - \bar{H} & \text{above the protrusion} \\ 1 & \text{elsewhere} \end{cases}$$

The momentum equations along with continuity equation is used to obtain modified Reynolds equation. The slip is provided on the grooved surface and no-slip condition is considered on the top surface of texture. The two-component slip length model is used to calculate the slip-velocity terms presented in the modified Reynolds equation. In two-component slip length model, fluid-slip occurs when shear stress of the fluid-surface interaction reaches critical threshold shear stress and in those areas where surface has been treated to allow it. After that with any additional shear stress, slip rises according to the constant slip length coefficient *b*. The detailed analysis can be studied in [12] and the non-dimensional modified Reynolds equation and slip velocity terms are

$$\frac{\partial}{\partial \bar{x}}\left(\bar{h}^3\frac{\partial \bar{p}}{\partial \bar{x}}\right)+k^2\frac{\partial}{\partial \bar{z}}\left(\bar{h}^3\frac{\partial \bar{p}}{\partial \bar{z}}\right)=6\frac{\partial \bar{h}}{\partial \bar{x}}+6\frac{\partial\left(\bar{U}_S\bar{h}\right)}{\partial \bar{x}}+6\frac{\partial\left(\bar{W}_S\bar{h}\right)}{\partial \bar{z}} \tag{1}$$

$$\bar{U}_S=\frac{\left[1-\frac{\bar{h}^2}{2}\frac{\partial \bar{p}}{\partial \bar{x}}-\mathrm{sgn}\left(U_S\right)\left|\bar{\tau}_{CO}\right|\bar{h}\right]}{\left[1+\bar{h}/\bar{A}\right]} \tag{2}$$

$$\bar{W}_S=\frac{\left[-\frac{\bar{h}^2}{2}\frac{\partial \bar{p}}{\partial \bar{z}}-\mathrm{sgn}(W_S)\left|\bar{\tau}_{CO}\right|\bar{h}\right]}{\left[1+\bar{h}/\bar{A}\right]} \tag{3}$$

where, sgn( ) is known as a signum function whose value is +1 when the slip speed is in positive direction and -1 when the slip speed is in negative direction. The fluid-slip exists only when $U_S > 0$, $W_S > 0$, $U_S < 0$ and $W_S < 0$.

2.1 Boundary Condition

Due to surface texture interaction in *x*-direction, a periodicity condition is considered while an ambient pressure condition is used in *z*-direction. The non-dimensional form of boundary conditions are

$$\bar{p}(\bar{x},\bar{z}=0)=0,\ \bar{p}(\bar{x},\bar{z}=1)=0 \tag{4}$$

$$\bar{p}(\bar{x}=0,\bar{z})=\bar{p}(\bar{x}=1,\bar{z});\quad \frac{\partial \bar{p}}{\partial \bar{x}}(\bar{x}=0,\bar{z})=\frac{\partial \bar{p}}{\partial \bar{x}}(\bar{x}=1,\bar{z}) \tag{5}$$

At the cavitation boundary, Swift-Stieber condition is used which implies that the pressure at each node and the pressure gradient with respect to direction normal to the boundary is zero i.e.

$$\bar{p}=0 \text{ and } \frac{\partial \bar{p}}{\partial \bar{x}}=0 \quad \text{when } \bar{p}<0 \tag{6}$$

2.2 Numerical Solution

The modified Reynolds equation Eq.(1) along with Eqs. (2) & (3) are solved using finite difference method by satisfying boundary and cavitation conditions Eqs (4) - (6). A Gauss-Siedel iterative scheme is employed to solve the set of algebraic equations obtained by finite difference method. Once the pressure at each node is calculated, load support, end flow and friction parameter are calculated using the known pressure values. The equations of these parameters are (non-dimensional):

$$\bar{W}=\int_0^1\int_0^1 \bar{p}\,d\bar{x}\,d\bar{z} \tag{7}$$

$$\bar{Q}=\begin{cases}\int_0^1\left(-\frac{k\bar{h}^3}{12}\frac{\partial\bar{p}}{\partial\bar{z}}+\frac{\bar{W}_S\bar{h}}{2}\right)d\bar{x} & \text{slip zone}\\ \int_0^1\left(-\frac{k\bar{h}^3}{12}\frac{\partial\bar{p}}{\partial\bar{z}}\right)d\bar{x} & \text{no-slip zone}\end{cases} \tag{8}$$

$$\bar{f}\,(\text{frictional parameter})=\frac{\bar{F}}{\bar{W}} \tag{9}$$

where, $\bar{F}$ is friction force,

$$\bar{F}=\begin{cases}\int_0^1\int_0^1\left(+\frac{\bar{h}}{2}\frac{\partial\bar{p}}{\partial\bar{x}}+\frac{1}{\bar{h}}-\frac{\bar{U}_S}{\bar{h}}\right)d\bar{x}d\bar{z} & \text{slip zone}\\ \int_0^1\int_0^1\left(+\frac{\bar{h}}{2}\frac{\partial\bar{p}}{\partial\bar{x}}+\frac{1}{\bar{h}}\right)d\bar{x}d\bar{z} & \text{no-slip zone}\end{cases} \tag{10}$$

3 Results and Discussion

The present analysis is carried out on a triangular type of surface texture because it shows better tribological performance as compared to other texture shapes [13]. The texture orientation angles considered in the present work is shown in the Fig. 1. Syed and Sarangi [12] explained that lower values of aspect ratio and texture height ratio exhibit better tribological performance when fluid-solid interfacial slip is considered. Moreover, non-dimensional slip length coefficient ($\bar{A}$) should be greater than or equal to 10. Therefore, present work considers an aspect ratio ($\bar{a}$), texture height ratio ($\bar{H}$) and non-dimensional slip length coefficient ($\bar{A}$) are 0.2, 0.1 and 100 respectively.

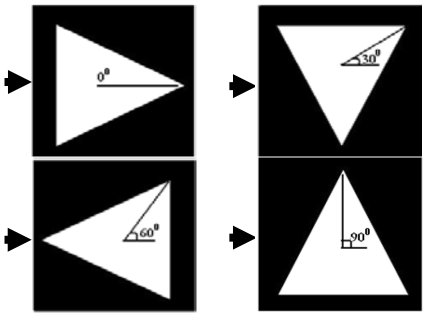

Fig.1 Orientation angles of triangular texture. Arrow mark indicates the fluid flow direction

The developed numerical code is validated with previously available result. The present model is reduced to a model described by Salant and Fortier [8] i.e. a plane slider with engineered slip surface of rectangular shape at the inlet section, and the comparison of result is shown in the Fig. 2, where good agreement is achieved.

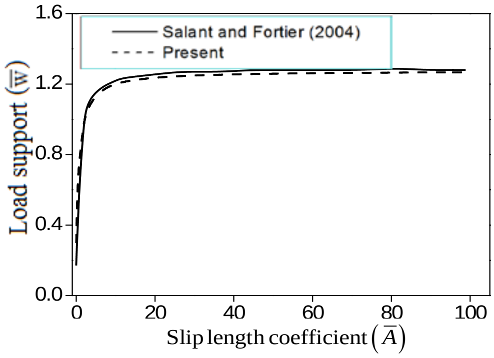

Fig.2 Comparison of load support with previously available result

The variable parameter considered in the present analysis is critical threshold shear stress ($\overline{\tau}_c$). Figure 3 shows the effect of texture orientation on load support by varying critical threshold shear stress. Considering slip at the grooved surface shows a larger load support as compared to conventional condition i.e. no-slip. The load support increases up to $\overline{\tau}_c \leq 0.25$, and then decreases as $\overline{\tau}_c$ increases.

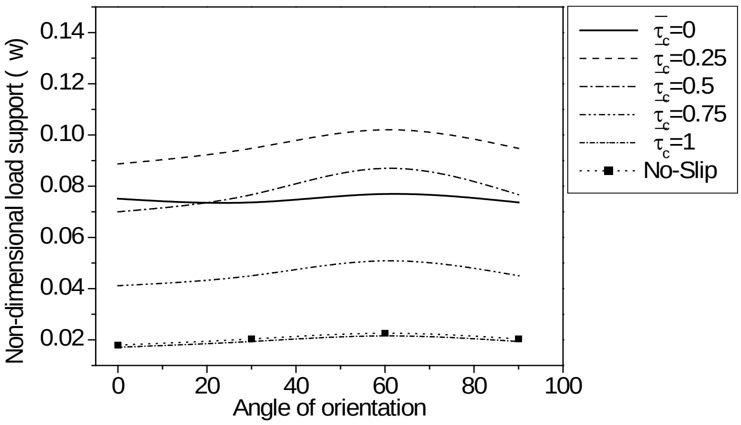

Fig. 3 Effect of texture orientation on load support for different critical threshold shear stress values

It can be observed from the Fig. 3, for higher values $\overline{\tau}_c \geq 1$, load support converges to the conventional value. At 60^0 triangular orientation, load support shows a slightly higher value as compared to other orientations because at that angle the texture offers more resistance to the flow leading to higher pressure development which enhances the load support.

Effect of orientation angles on end flow by varying $\overline{\tau}_c$ for a particular value of $\overline{A} = 100$ is shown in the Fig. 4. For lower values of $\overline{\tau}_c$, texture orientation shows significant effect on end flow.

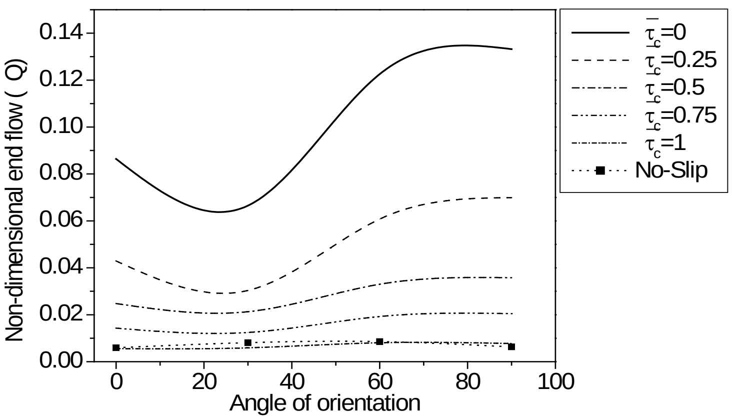

Fig.4 Effect of texture orientation on load support for different critical threshold shear stress values

Figure 4 shows that end flow decreases with increasing $\overline{\tau}_c$ values and finally the end flow value converges to the conventional case when $\overline{\tau}_c \geq 1$. Higher values of end flow is observed at an angle of orientation of 90^0 which is suitable for sealing applications. Effect of texture orientation on friction parameter for different values of $\overline{\tau}_c$ is shown in the Fig. 5.

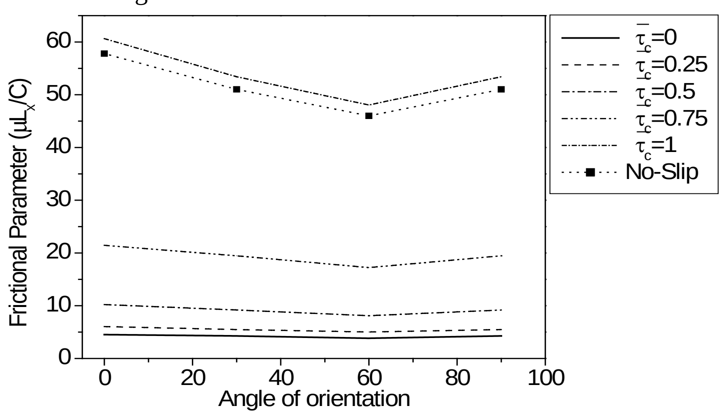

Fig. 5 Effect of texture orientation on friction parameter for different critical threshold shear stress values

A drastic reduction in the values of friction parameter is observed when fluid-solid interfacial slip is considered. However, for a lower values of $\overline{\tau}_c$ there is a negligible effect of texture orientation on the friction parameter. For the higher values of $\overline{\tau}_c$, the value of friction parameter converges to the solution of conventional case. Moreover, texture orientation shows significant effect in these conditions.

4 Conclusions

The present work aims to study the effect of triangular texture orientation on the tribological performance of parallel sliding contact by varying critical threshold shear stress while considering fluid-solid interfacial slip at the grooves of the stationary surface. From the results, it has been concluded that lower values of critical threshold shear stress shows significant effect on the performance parameters. Texture orientation has significant effect on end flow parameter especially at lower values of critical threshold shear stress. However, texture orientation has small / negligible effect on load support and friction parameter when fluid / solid interfacial slip is considered.

Notations

b = constant slip length
C = maximum clearance between the surfaces
F = friction force
h = film thickness of the lubricant
h_g = height of the protrusion
L_X = length of the unit cell in x-direction
L_Z = length of the unit cell in z-direction
p = pressure in the lubricant film
Q = end flow in z-direction
u, v, w = velocity components in the x, y and z directions, respectively
U = maximum velocity in x-z plane
U_S = slip velocity in x-direction
W = load support
W_S = slip velocity in z-direction
η = dynamic viscosity of the lubricant
τ_c = critical threshold shear stress of fluid

Non-dimensional parameters

$\bar{a}$ = aspect ratio $\left(\text{area of textured surface}/\text{area of unit cell}\right)$
$\bar{A}$ = slip length coefficient $\left(b/C\right)$
$\mu L_x/C$ = friction parameter
$\bar{F}$ = friction force $\left(FC/\eta UL_X L_Z\right)$
$\bar{h}$ = film thickness $\left(h/C\right)$
$\bar{H}$ = texture height ratio $\left(h_g/C\right)$
k = ratio of the imaginary cell lengths (L_X/L_Z)
$\bar{p}$ = pressure $\left(pC^2/\eta UL_X\right)$
$\bar{Q}$ = end flow $\left(Q/UCL_X\right)$
$\bar{U}_S$ = slip velocity in x-direction $\left(U_S/U\right)$
$\bar{W}$ = load support $\left(WC^2/\eta UL^2_X L_Z\right)$
$\bar{W}_S$ = slip velocity in z-direction $\left(W_S/U\right)$
$\bar{x}$ = x-coordinate $\left(x/L_X\right)$

$\overline{y}$ = y-coordinate $\left(y/C\right)$

$\overline{z}$ = z-coordinate $\left(z/L_Z\right)$

$\overline{\tau}_c$ = critical shear stress $\left(\tau_C C/\eta U\right)$

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