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On the effect of viscosity wedge in micro-textured parallel surfaces

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ABSTRACT

A computational model for predicting the performance of micro-textured parallel surfaces with provision for viscosity wedge effect is developed. The model is based on the simultaneous solutions to the Stokes equation and the energy equation in the fluid film. The governing equations are solved using the finite element method combined with the Streamline Upwind Petrov Galerkin *method (SUPG) and* Uzawa solution algorithm. Results are presented to gain insight into the role of viscosity wedge on the pressure distribution and the load-carrying capacity (LCC) of the textured surfaces. The influence of the Reynolds number and the texture size on the LCC are also investigated and discussed.

1. Introduction

Surface texturing has emerged as a viable technique for improving the performance of many vital tribological components such as mechanical seals, piston rings, bearings, cutting tools and the like. According to the literature, surface textures offer different beneficial mechanisms ranging from the formation of micro-bearings, creation of oil reservoirs and capability to capture debris [1]. It is thus not surprising that rich volumes of recent research reports have been devoted to both theoretical and experimental works to gain better insight into the texture's lubrication mechanisms in different regimes [2–4], performance analyses [5–7], and shape-optimization techniques [8,9]. Sudeep et al. [10], for example, have contributed a review article on the application of surface textures in the concentrated contacts and Gropper et al. [11] published a survey paper on the hydrodynamic lubrication of textured surfaces along with a summary of the current status of research and the development of this promising technology.

Reviews of the literature reveal that, insofar as performance prediction of surface textures is concerned, the treatment of the Reynolds equation is the most popular approach due to the simplicity of the governing equation and availability of many computational solution algorithms [12,13]. The majority of published papers consider the cavitation effect within each dimpled-shaped texture as the main source for generation of additional load-carrying capacity (LCC).

According to the work of Dobrica and Fillon [14] on the simulation of surface textures, in analyzing lubrication problems involving high Reynolds number (*Re*), it is necessary to resort directly to the Navier-Stokes equations particularly when one deals with large texture depth-to-diameter ratios where the fluid inertia and recirculation effects within the textures have a dominant influence on the pressure distribution. In their multiscale model of surface textures, De Kraker et al. [15] also emphasized the effect of microcavitation and convective inertia. They pointed out that when the nominal film thickness is sufficiently smaller than the texture depth, the microcavitation is the dominant flow effect and the Reynolds equation is valid. When the nominal film height is on the same order or larger than the texture's depth, the convective inertia becomes important and limits the applicability of the conventional Reynolds equation.

Another important factor that substantially influences the tribological performance of surface textures is thermal effects. Jeong and Park [16] investigated the effect of dimple size on the performance of textured parallel surfaces in relative sliding motion by developing a thermo-hydrodynamic lubrication model based on the Navier-Stokes equations coupled with the energy equation. They found that the strong vortex in the dimples greatly increases the film temperature. Papadopoulos et al. [17,18] studied the thermal effect of 3D sector-pad thrust bearings with rectangular dimples and showed that the thermal effect decreases the LCC especially at high speeds. Other researchers such as Dobrica et al. [19] and Guzek et al. [20] also arrived at similar conclusions on the ground that fluid viscosity decreases with increasing temperature. Nevertheless, there are reports that point to the positive contribution of thermal effects. For example, Cupillard et al. [21,22] showed that in the case of a textured slider bearing, the thermal effect was responsible for increasing LCC when the textures are positioned near the inlet of bearings.

One of the mechanisms responsible for generating LCC in parallel surfaces is known as the viscosity wedge effect. In one of the earliest report on this subject, Cameron [23] provided an explanation of

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Nomenclature

Br	Brinkman number, $\mu_0 u_0^2/(k_f\, t_i)$
c_p	Fluid special heat
d, D	Dimensional and dimensionless texture width, $D=d/l$
Eu	Euler number, $p_0/(\rho u_0^2)$
h	Gap thickness
h_g, H_g	Dimensional and dimensionless texture depth, $H_g=h_g/h$
k_f	The thermal conductivity of the fluid
l	The slider length
p, P	Dimensional and dimensionless pressure, $P=p/p_0$
p_0	Inlet and outlet pressure
Pe	Peclect number, $Pe=\rho c_p u_0 h/k_f$
Re	Reynolds number, $Re=\rho u_0 h/\mu_0$
t, T	Dimensional and dimensionless temperature, $T=t/t_i$
t_0, t_i	Reference temperature and inlet temperature
u, U	Dimensional and dimensionless velocity in x direction, $U=u/u_0$
u_0	The slider velocity
w, W	Dimensional and dimensionless velocity in z direction, $W=w/u_0$
x, X, z, Z	Dimensional and dimensionless coordinate, $X=x/l$, $Z=z/h$
β	Viscosity-temperature coefficient
μ, $\overline{\mu}$	Dimensional and dimensionless dynamic viscosity, $\overline{\mu} = \mu/\mu_0$
μ_0	Reference viscosity
ρ	Fluid density

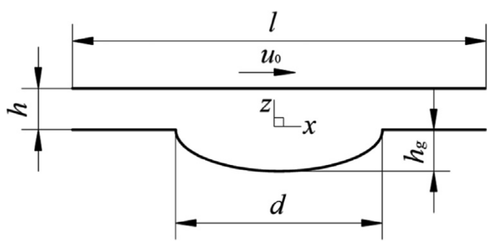

Fig. 1. Geometrical model.

viscosity wedge effect and pointed out that the variation in the fluid viscosity accounts for the development of LCC even in thrust bearings with parallel surfaces. He also stated that the viscosity wedge effect can be positive or negative according to the surface temperature difference (STD) along the entrainment velocity [24]. Yang [25] numerically studied the viscosity wedge effect under the different temperature boundary conditions. He pointed out that the viscosity wedge is more important as an LCC mechanism compared to that of the density wedge. In a recent study, Cui et al. [26] numerically analyzed the thermal behavior of lubricated surfaces and found that the film temperature gradient (FTG) from thermal wedge effect is another important factor to generate LCC.

Viewed from the available literature, few works have been done on the study of the thermal effect for the textured sliding parallel surfaces, which may play a significant role in the hydrodynamic effect. In this article, we propose that viscosity wedge effect can offer a mechanism for generating LCC in textured parallel surfaces in relative sliding motion. To investigate, a computational model based on coupled solution of the Stokes equations and the energy equation is developed, and the effect of viscosity wedge on the pressure distribution and the LCC are analyzed. Series of results are presented to quantify the effect of viscosity variation, the Reynolds number, the fluid recirculation within the dimpled-shaped texture, and to examine the effect of its dimensions (depth and diameter) on the generation of LCC.

2. Theoretical models

2.1. Geometrical model

In order to closely examine the flow behavior and the LCC of textures, we focus our attention on only one dimple, as shown in Fig. 1. The upper surface represents the slider whose width is infinite and the length is l. Suppose that the slider's surface is smooth and that it moves at a constant velocity u_0 along the x axis in the Cartesian coordinate system shown in Fig. 1. The bottom surface is also smooth and stationary. It is separated from the upper surface by a gap h. The center of the bottom surface contains a single dimple whose bottom profile has a semi-elliptical shape. The diameter of the texture is d and the maximum depth is h_g, respectively, being the major axis length and minor semi-axis length. The center of the ellipse is coincident with the origin of the Cartesian coordinate system. The fluid is filled in the gap and in the texture.

2.2. Mathematical model

Assuming creeping flow of an incompressible fluid, the convective acceleration terms in the Navier-Stokes equations are neglected. We note that the assumption of incompressibility restricts the problem to neglecting the density wedge effect because the results presented by Cui et al. show that the density wedge can yield very high fluid temperature when temperature-viscosity coefficient is too small [26]. The fluid pressure between the parallel surfaces, p, the velocity distribution of the fluid film, can be derived from the following Stokes equations.

$$\frac{\partial p}{\partial x} = \frac{\partial}{\partial x}\left(\mu(t)\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial z}\left(\mu(t)\frac{\partial u}{\partial z}\right) \tag{1a}$$

$$\frac{\partial p}{\partial z} = \frac{\partial}{\partial x}\left(\mu(t)\frac{\partial w}{\partial x}\right) + \frac{\partial}{\partial z}\left(\mu(t)\frac{\partial w}{\partial z}\right) \tag{1b}$$

where u and w are the fluid velocity along x- and z-direction in the Cartesian coordinate system. μ is the dynamic viscosity of the fluid film, which is the following function of the fluid temperature, t.

$$\mu(t) = \mu_0 e^{-\beta(t-t_0)} \tag{2}$$

where μ_0 is the fluid dynamic viscosity at the reference temperature t_0 and β is the so-called temperature-viscosity coefficient.

Because the slider is moving with respect to the fixed bottom surface, the fluid is sheared and this will generate heat via viscous dissipation that raises the lubricant temperature. The following generalized energy equation describes the temperature variation in the fluid.

$$\rho c_p\left(u\frac{\partial t}{\partial x} + w\frac{\partial t}{\partial z}\right) = k\left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial z^2}\right) + \left[2\mu\left(\frac{\partial u}{\partial x}\right)^2 + 2\mu\left(\frac{\partial w}{\partial z}\right)^2 + \mu\left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right)^2\right] \tag{3}$$

where ρ, c_p and k are the density, the specific heat and the thermal conductivity of the fluid, respectively. The terms in the square brackets are the viscous dissipation terms.

To simplify the computation, the following dimensionless expressions are used.

$$X = \frac{x}{l},\ Z = \frac{z}{h},\ P = \frac{p}{p_0},\ U = \frac{u}{u_0},\ W = \frac{w}{u_0},\ \overline{\mu} = \frac{\mu}{\mu_0},\ T = \frac{t}{t_i} \tag{4}$$

where t_i is the ambient temperature.