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Shear stress characteristics of microtextured surfaces in gap-controlled hydrodynamic lubrication

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ABSTRACT

Microtextured surfaces can reduce friction in lubricated dynamic contact. However, no prior experimental study has explored the dimensionless parameter space of Reynolds number and dimensionless gap, since normal force is easier to control than the fluid film thickness. Here, we develop a custom precision-aligned setup for gap-controlled tribo-rheometry based on a rotational rheometer. The novel experimental setup allows for measurement of full film lubrication of parallel disks down to 20 μm gaps with gap precision ±3 μm, over a range of Reynolds numbers. We show for the first time in gap-controlled conditions that microtextured surfaces reduce friction. The reduction in dimensionless shear stress is nearly independent of velocity for $Re < 10$ which matches computational results in this work.

1. Introduction and background

Surface shape and roughness have a strong influence on fluid film lubrication, influencing the coefficient of friction and load carrying capacity of surfaces in hydrodynamic contact [1,2]. Deterministically-controlled surface shape, known as texturing, has only recently been shown to improve the friction characteristics of parallel sliding surfaces [3,4]. Additional studies have shown that microtextured surfaces can reduce friction compared to flat plates both numerically [5–10] and experimentally [11–19]. Multiple mechanisms have been suggested for this, across the different lubrication regimes. In boundary or mixed lubrication, the contact area of the two surfaces is reduced, thus reducing friction and providing a source for lubricating fluids. It is also possible for microtextured surfaces to produce net hydrodynamic pressure that increases the gap, moving the system from a mixed or boundary regime into a hydrodynamic regime with lower friction. In hydrodynamic lubrication, the larger gap at the location of the microtextures reduces the effective local shear rate and therefore reduces the local viscous shear stress. It is also possible for microtextures to support a gas phase, either by cavitation [2,12] or with super hydrophobic surfaces in a Cassie–Baxter non-wetted state [20–23]. In a non-wetted state, microtextures trap gas pockets, producing a slip boundary condition over the microtextured region and in turn reducing friction. Reduction of friction due to super hydrophobic slip is not our interest here. The present study is concerned with durable materials and conditions where the Cassie–Baxter non-wetted state is not required to be maintained within the microtexture.

Experimentally, friction reduction has been observed by using controlled normal force tribometers with deterministic surface textures. With a pin-on-disk configuration, Ramesh et al. found that optimized microtextures can support a hydrodynamic film with normal pressures of 4.0–8.1 MPa [11]. Qiu and Khonsari used a disk-on-disk configuration and found a reduction in friction compared to flat plates [12]. However, in that study, due to increased wear it appears a hydrodynamic film was not supported for the conditions studied. A limitation of the tribometer method is that the gap between the surfaces or film thickness, H, is not controlled or known. At best, it is inferred. Yet, the Reynolds number $Re_H = \rho UH/\eta$, with density ρ, shear viscosity η, and velocity U, requires knowledge of the film thickness H. Therefore, there has been no systematic experimental study of gap-dependent or Reynolds number dependent friction reduction with hydrodynamic lubrication and microtextured surfaces. This is the focus of our work here.

We have developed a custom precision-aligned setup for gap-controlled triborheometry based on a rotational rheometer (Fig. 1). Our setup is distinct from other rotational [24–29] and linear motion [30–32] rheometer setups for studying tribology and rheology at small gaps. The key component in our rotational rheometer setup is an optically flat, transparent, fixed glass plate that uses a precision-alignment base structure for alignment with respect to the axis of rotation. The component is described in detail elsewhere [33], and has been used for optical access to the fluid sample with standard rheometry measurements [34]. At present, the glass bottom plate allows visual access and high alignment to the instrument axis of rotation but temperature is

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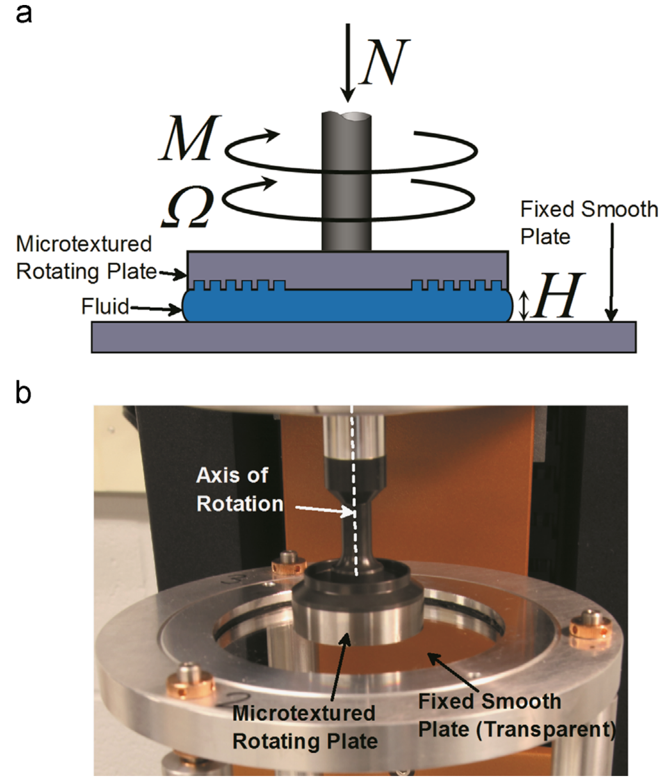

Fig. 1. (a) The experimental setup uses a rotational rheometer where gap height H, angular velocity Ω, torque M and normal force N are measured or controlled. The gap H can be controlled with a step resolution of 0.1 µm. (b) Custom designed and fabricated glass bottom plate with custom plate attached to top plate. Angular alignment α is controlled with the precision-aligned glass bottom plate. Parallelism ≤ 25 nrad is achieved. Radial alignment is controlled by manual application of force with radial alignment tools.

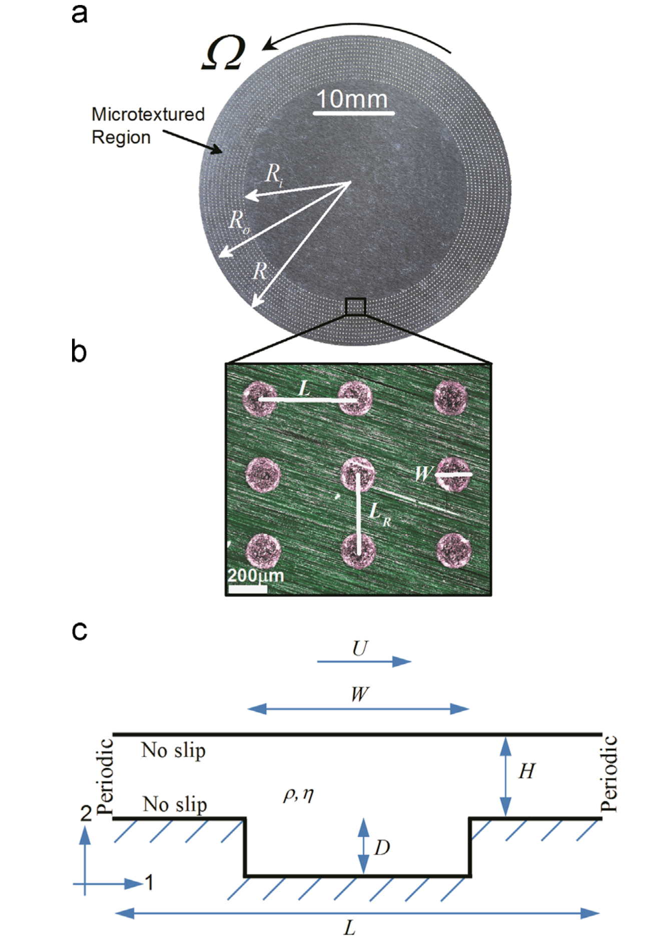

Fig. 2. (a) Microtextured plate (full view) with cylindrical dimple microtextures within the region from $R_i = 14$ mm to $R_o = 19.5$ mm. Total plate radius $R = 20$ *mm*. (b) Microtextures imaged with 3D optical microscopy (focus variation method) have width W, periodic length L, and radial spacing L_R. (c) Seven dimensional variables define the model microtexture with a Newtonian fluid. H is gap height, L is microtexture periodic length, W is microtexture width, D is microtexture depth, U is top plate velocity, ρ is fluid density and η is fluid viscosity.

not controlled. Custom-fabricated disks with microtextures (Fig. 2) are attached to the rotating component. To achieve gap control down to 20 µm, we have minimized planar misalignments and carefully calibrated the gap thickness, H. Flatness of plates is also considered and controlled. The instrument measures torque and normal force at the top geometry. The work here will focus on the torque measurements.

From a gap-control perspective, this work aims to identify the correct dimensionless parameters, develop the experimental capability of a triborheometer with precise alignment and visualization capabilities, and compare computational results and gap-controlled experiments for friction reduction due to fully-wetted microtextured surfaces. (For the present study, friction refers to shear stress independent of normal force since the accurate measurement of normal force is non-trivial due to parallelism effects. As such, normal force measurement is outside the scope of the present work.)

2. Theory and dimensional analysis

In this study, we consider circular microtextures in a deterministic layout with Newtonian fluids in hydrodynamic lubrication (Fig. 2). Seven independent parameters define the design space. With dimensionless groups, this number is reduced to four. This section defines the dimensionless parameter space, validates the choice with numerical simulations, and uses the dimensionless space to summarize related prior work.

The parameterized geometry of a single texture is shown in Fig. 2c. For experiments, this is a cross-section view of a cylindrical texture. For computations, Fig. 2c defines the two-dimensional geometric model. We assume steady-state conditions with incompressible Newtonian fluid, and neglect gravity. Numerically, we solve the two-dimensional mass conservation (continuity) and momentum conservation (Navier–Stokes) equations

$$\underline{\nabla} \cdot \underline{u} = 0 \quad (1)$$

$$\rho(\underline{u} \cdot \underline{\nabla})\underline{u} = -\underline{\nabla} p + \eta \nabla^2 \underline{u} \quad (2)$$

where $\underline{u}$ is velocity, ρ is fluid density, η is Newtonian fluid viscosity and p is pressure. We assume no-slip boundary conditions on the walls with periodic boundary conditions on the inlet and outlet. Cavitation is not considered. We use the second-order upwind scheme for momentum discretization and the coupled scheme for the pressure discretization with a convergence criteria for all residuals of 10^{-7}. The fluid is assumed to be isoviscous and constant density. The energy equation is not considered. FLUENT®, a commercial computational fluid dynamics (CFD) software, is used for all computational results.

2.1. Dimensionless parameters

The two dependent quantities of interest are average normal pressure on the top plate, P, and average shear stress on the top plate, T. For a simple 2D periodic case these measured quantities are