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Asymmetric surface textures decrease friction with Newtonian fluids in full film lubricated sliding contact

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ABSTRACT

Surface texturing can decrease friction in lubricated sliding contact. The majority of existing experimental work has focused on symmetric-depth-profile surface textures. This experimental work examines asymmetric-depth-profile surface textures using gap-controlled experiments with Newtonian fluids on a custom tribo-rheometer setup. Measurements of normal force and shear load are reported as a function of texture geometry, gap height, and bi-directional sliding velocity. This work shows that, in the absence of cavitation, surface texture depth symmetry must be broken to produce normal forces (through viscous effects) for gap-based Reynolds Number up to $\mathrm{Re}_h = \frac{\rho V h}{\eta} = 1.21$. Asymmetric surface textures reduce shear stress and generate normal load, and therefore decrease the effective friction coefficient, which we observe to be smallest for the shallowest texture angle tested, $\beta = 5.3°$.

1. Introduction and background

Surface texturing can be used to reduce the friction in lubricated sliding contact [1,2]. A key focus of applying surface textures has been in lubricating piston rings in internal combustion engines [3] where frictional losses account for up to 50% of the overall mechanical losses of the engine [3–5]. Surface textures can decrease the apparent area of contact in boundary lubrication, act as reservoirs that retain lubricant during startup [6,4], increase the film thickness and increase hydrodynamic pressure to further separate the surfaces [7], and decrease the local shear stress [8], all of which contribute to friction reduction.

Previous experimental studies primarily examine *symmetric* surface textures; although there are some exceptions as will be discussed. By symmetric, we mean fore-aft symmetry in the direction of motion of texture shape as viewed either (A) normal to the surface (top profile view) e.g. circular or elliptical, or (B) cross section view (depth profile), e.g. square or pyramidal, or (C) both. Examples of the different types of symmetry are shown in Fig. 1. Whereas (A) and (B) are defined by a line reflection symmetry, either spanwise or normal to the surface, respectively, (C) the combination of both symmetries results in fore-aft reflection symmetry about a mirror plane defined by the spanwise and normal directions.

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The majority of the previous experimental and numerical work examined symmetric top profile surface textures with a constant depth profile ((C) above) [9,7,10,11,4,3,12]. Johnston et al. [8] showed that the addition of such symmetric surface textures would lower the effective resistance of the lubricant to shearing. Qiu and Khonsari [13] tested circular and elliptical top profile textures with a constant depth in a thrust-bearing-like setup and showed that the textures reduced friction from the flat plate reference. Marian et al. [14] examined square top profile textures with a constant depth profile and showed that using the textures would increase the load carrying capacity.

Experimental and numerical work has also been performed examining asymmetric top profile textures with a constant texture depth [15,16]. Shen and Khonsari [17] used a sequential quadratic programming method to determine an optimal top profile shape with a constant depth for producing normal forces due to cavitation under unidirectional and bidirectional sliding. Costa and Hutchings [18] showed that chevron type surface textures increase the film thickness. Vladescu et al. [5] showed that surface textures can decrease friction in the boundary lubrication regime.

Symmetric top profiles with asymmetric depth profiles have not been studied as much as the previously mentioned surface textures. Shen and Khonsari [19] examined experimentally and numerically surface textures with a circular top profile and a linearly varying bottom profile under cavitation conditions, and showed that normal forces could be generated with asymmetric textures, but the normal forces were *smaller* than with a constant depth circular texture. However, Han et al. [10] and Nanbu et al.

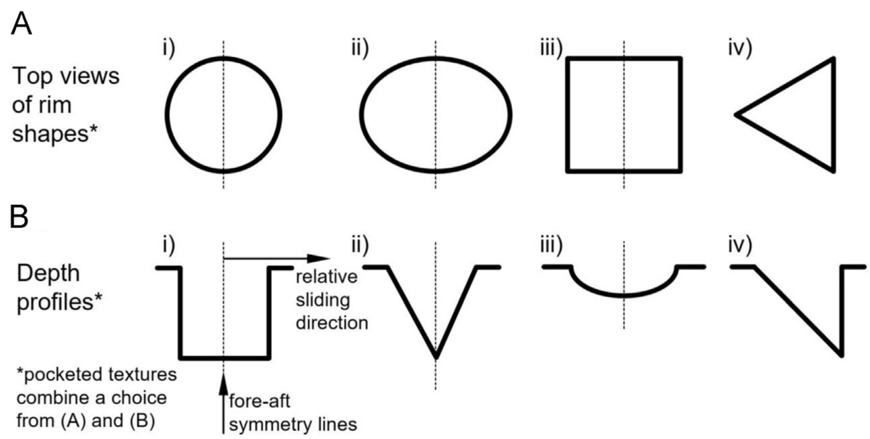

Fig. 1. Symmetry and asymmetry categories for surface textures, considering fore-aft symmetry in the direction of relative motion. (A) Top view and (B) depth profile. (A) Top view examples, (i)–(iii) symmetric circle, ellipse, and square; (iv) asymmetric equilateral triangle. (B) Depth profile examples, (i)–(iii) symmetry with constant, pyramidal, and elliptical depth profiles; (iv) asymmetric depth profile with linear slope. Our work here studies approximately circular top view (A.i) with asymmetric linearly sloped depth profiles (B.iv) (c.f. Figs. 2–3).

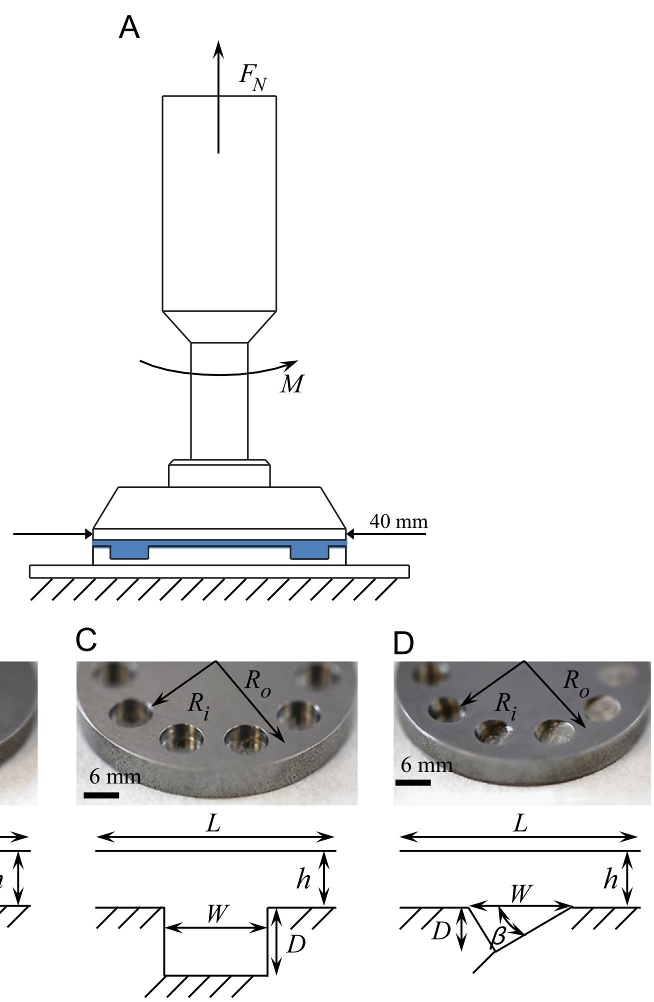

Fig. 2. Experimental setup on a gap-controlled tribo-rheometer configuration with matched diameter parallel disks. The drawing in (A) is to scale with the gap between the flat and textured surface set to 1 mm. In the experiments, the textured plate is stationary while the top plate rotates in both directions. F_N is the measured normal force and M is the measured torque. (A) The top moving geometry and the primary measured quantities. (B)–(D) Photographs and centerline depth profile schematics for the three types of surfaces tested. (B) Flat plate, (C) symmetric texture, and (D) asymmetric texture with $\beta = 21.7°$.

[20] also numerically examined linearly varying bottom profile textures, and they showed that normal forces generated with asymmetric textures can be *larger* than forces generated with symmetric textures.

The work in this paper experimentally examines the effects of different surface texture depth profiles on decreasing friction through the reduction of apparent viscosity and the production of normal forces. Gap-controlled experiments are performed on a