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Numerical and experimental investigation of texture shape and position in the macroscopic contact

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ABSTRACT

In this work, the influence of operating conditions on the shape parameters of surface texture is investigated by means of both numerical and experimental investigations. The analysed texture consists of micro-dimples obtained through laser surface texturing on a pin-on-disc configuration. From the numerical point of view, particular attention is paid to the faithful representation of the 2D surface of the experimental set-up and to modelling cavitation phenomena through a mass conserving algorithm. As results, the dimple depth shows a higher relevance than diameter in determining the optimal texture shape (both in terms of friction reduction and load carrying capacity). Moreover, the dimple depth, corresponding to the minimal friction, is found to scale with the square root of the Sommerfeld number in agreement with the experimental results. Finally, it is found that a numerical approach with the present hydrodynamic model cannot account for friction reduction obtained experimentally with different orientation of the texture.

1. Introduction

Using textured surfaces is a widely spread stratagem in nature in order to improve specific performance in the interaction between surfaces and their surrounding environment [1]. Taking inspiration from this fact, a huge interest has emerged in the last decades on the applications of such surfaces for tribological purposes [2]. The great potential of such engineered surfaces was tested in the early works of Hamilton [3], Anno [4] and subsequently with experimental and numerical investigations by Etsion's group for various kinds of industrial applications such as parallel sliders [5], mechanical seals [6] and piston rings [7,8].

Among the unlimited ways to realize surface textures, non-communicating textures like grooves and dimples have drawn most of the attention, thanks to the great improvement of Laser Surface Texturing techniques (LST) [2,9]. In the struggle to identify the condition under which dimpled surfaces bring actual benefits, the following main mechanisms have been detected. In the boundary lubrication regime, dimples can reduce static friction mainly thanks to a contact area reduction [10]. In mixed lubrication, dimpled surfaces can better entrap debris, hence reducing the wear by minimizing the third-body abrasion [11,12]. Their ability to act as a lubricant reservoir improves the contact wettability under starved lubrication [13]. Moreover, dimples can shift the transition from the mixed lubrication regime to the hydrodynamic one to lower velocities [14]. Finally, regarding the hydrodynamic regime, dimples are responsible for a pressure build-up which consequently leads to a reduction of the tangential stress through a thickening of the fluid film and thus to a reduction of the overall friction coefficient.

From the numerical point of view, the underlying mechanisms of the above mentioned effects have been extensively studied over the last years for various applications. In case of low convergence bearings, dimples are deemed to be effective thanks to the hydrodynamic lift which results from the asymmetrical pressure distribution when cavitation [15] occurs. The physical mechanism behind this pressure build-up has been explained by Fowell et al. as an "inlet suction" effect due to the reduced pressure in the dimples [16]. More generally for other kind of geometries, the effects introduced by dimples can be interpreted in terms of density changes or by considering the coupling with thermodynamics [17]. Non-linear effects also play a role in generating a non-symmetrical pressure distribution, which may lead to beneficial as well as detrimental effects, as found in many works [18–20]. For more complex geometries, an explanation of the pressure build-up has been provided by Cupillard et al. by analysing how energy is transferred from the moving wall to the fluid and converted into pressure at the beginning of the texture [21].

The difficulty in the thorough comprehension of the physics behind

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textured surfaces is complicated by the large variety of texture design parameters such as texture location, pattern and density, as well as details of the texture shape (*e.g.* dimple depth and diameter). In order to cast light on the design and optimization of dimples many studies adopted a systematic approach in describing the influence of each of the above mentioned design parameters on the overall performance of typical industrial applications. Different texture shapes are analysed by Adjemount et al. [22], who show that cylindrical and spherical dimples have the most positive influence. The role of partial texturing is investigated, among others, by Fillon's group, showing that a partial texturing can lead to an increase in load carrying capacity if compared to a fully textured case [23,24]. In respect to texture density, a disagreement existed originally between numerical and experimental analysis, since most of numerical works [25] overestimated the experimentally determined optimal value found between 10% and 20% [26]. An explanation to this discrepancy is proposed by Wang et al. [27] by considering the influence of roughness and contact mechanics.

Among the above mentioned design parameters, the diameter and the depth of dimples have risen the biggest interest in the research community. Numerical analysis revealed the importance of texture depth on texture performances [28,29]. In particular, Ramesh et al. [30] and Fowell et al. [31] present a direct correlation between dimple depth and gap height for a 2D geometry and point out that the optimal depth increases with higher viscosity. A systematic experimental investigation of this trends is carried out by Braun et al. [14] with a pin-on-disk set-up. In this work, different dimple diameters ranging from 15 μm to 800 μm are considered at constant texture density and depth-to-diameter ratio. The results, based on various sliding velocities and viscosities, indicate that the Stribeck curve of the optimal texture scales with the Hersey number $\frac{\mu\Omega}{W}$, where μ is the viscosity of the lubricant, Ω the rotational speed and W the average contact pressure. With respect to the influence of the texture pattern and the optimal orientation angle on friction reduction, experimental and numerical studies come to different conclusions [26,32].

In this work we intend to deepen the physical understanding of the experimental results from Braun et al. [14] by numerically investigating the same geometry of the experiments. The numerical approach allows to analyse the scaling of optimal dimple parameters with respect to the operating conditions; particularly viscosity, velocity and gap height. At first we focus on the numerical and experimental investigation of the sensitivity of the load carrying capacity with respect to the position of the dimple on the macro-geometry. After this prior analysis an exhaustive parametric study of a 2D textured surface as extension of the 1D works of Fowell and Rahmani [31,33,34] is performed. Lastly, we discuss the effects of the texture orientation based on a comparison of numerical and experimental results.

2. Numerical approach

Among the different effects that textures have on tribological performance we consider from the numerical point of view only those which are related to the hydrodynamic regime; an approach taken in the vast majority of literature on this topic [2]. In contrast to some previous studies with 1D textures [31,34,35], a realistic 2D surface, which corresponds to the one employed in the corresponding experiments, is considered for the numerical parameter studies in the present work. In order to enable such a parametric study at reasonable computational cost, particular attention is paid to an efficient numerical implementation.

2.1. Governing equation

We model the shear flow of a Newtonian lubricant between two sliding walls through the incompressible Reynolds equation. The employed equation considers also cavitation phenomena through a mass conserving algorithm as presented by Woloszynski et al. in Ref. [36].

$$\nabla\cdot\left(h^3\nabla p - 6\mu\vec{V}h(1-\theta)\right) = 0 \tag{1}$$

where $h(x,z)$ describes the gap height distribution, μ is the dynamic viscosity, $\vec{V} = \{U, W\}$ is the upper wall velocity. The cavity fraction θ is defined through a reference density ρ_{ref} as follows:

$$\theta = 1 - \frac{\rho}{\rho_{ref}}. \tag{2}$$

The pressure p and the cavity fraction θ satisfy the complementarity constrain $(p - p_{cav})\theta = 0$, in which the relative pressure $p - p_{cav}$ and the cavity fraction θ are always positive. The cavitation pressure is kept at a realistic constant value of $P_{cav} = 80000Pa$, in order to keep the investigated parameter space in a reasonable dimension. The flow is considered isoviscous and isothermal.

As shown in Ref. [36] and subsequently also in Ref. [37], equation (1) can be directly coupled with the complementarity constrain in a non-linear unconstrained system, whose solution requires only few steps of the Newton-Raphson scheme, making this algorithm tremendously faster than other traditional approaches based on constrained solution of the Reynolds equation (such as, for example, the $p-\theta$ algorithm by Elrod and Adams [38]). For the present work, the non-linear unconstrained system is iteratively solved until the residuum on pressure and cavity fraction drops below 10^{-6}.

The Reynolds equation is discretized with a finite volume method, which is based on its weak formulation [39], allowing to increase the solution precision in the presence of high geometry discontinuities like in the considered set-up. Moreover, the finite volume method is a good compromise between computational performance and easiness of implementation [18], the achieved convergence for one of the test cases is presented in Table 1.

2.2. Geometry description

The geometry of the untextured pin is extracted from the experimental set-up based on optical profiler measurements of the employed pellets. It should be noted that the experimental campaigns (see section 3) employed two different pin geometries which are both considered numerically. The 3D numerical representation of the first pin (A) is shown in Fig. 1 for a case in which a computer generated partial texture is imposed on the surface topography of the untextured pin. In the experiments, the pellets are textured with LST resulting in very similar shapes as the dimples that are considered numerically [14,26]. The surface of the pin is not perfectly flat, but presents a perceptible curvature which is shown through a magnification in Fig. 2 which corresponds to a cut through the computational domain at $z = 0$. This curvature is the main cause for the creation of a pressure distribution along the gap which is perturbed by the presence of the texture. We define the reference gap height H in the centre of the pin surface where the distance between the two surfaces has its minimum. The second pin (B) is also cylindrical, but its surface is much flatter ($< 0.1\ \mu m$) than the one of pin A. The average profile of pin B is shown through a further magnification in Fig. 2.

A constant ambient pressure $p|_{\partial A} = p_{amb}$ is prescribed at the domain

Table 1
Convergence of the Reynolds solver with respect to the normal and tangential force. The results corresponds to the textured pin geometry A with a dimple diameter $D = 40\mu m$.

number of cells in each direction	normal force $[N]$	tangential force $[N]$
65	1178.379057	5.029480
129	1188.524679	5.037692
257	1193.755952	5.045461
513	1196.401560	5.049900
1025	1197.470182	5.051418
2049	1198.008821	5.052289
4097	1198.288155	5.052802