Tribology International 75 (2014) 123–127

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Short Communication

Minimize friction of lubricated laser-microtextured-surfaces by tuning microholes depth

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ARTICLE INFO

Article history:
Received 7 January 2014
Received in revised form
18 March 2014
Accepted 21 March 2014
Available online 4 April 2014

Keywords:
Surface texturing
Laser ablation
Friction
Lubrication

ABSTRACT

We have investigated the friction properties of lubricated laser micro-textured surfaces. The micro-texture consists of a square lattice of micro-holes whose diameter, depth and spacing are controlled during the laser texturing process. All surfaces have the same texture area density, but different diameters and depths of the micro-holes. We measure the coefficient of friction on a range of sliding velocities from the mixed lubrication regime to the hydrodynamic regime. We find that the depth and the diameter of the micro-holes have a huge influence in determining the amount of friction reduction at the interface. Interestingly experiments also show that optimal micro-hole depth values, minimizing the friction in the hydrodynamic regime, are remarkably effective also in the mixed lubrication regime.

1. Introduction

An increasing amount of research is currently devoted to the experimental and theoretical investigation of the effects of surface ordered micro-structuring on the frictional and wear properties of the contact, with particular (growing) attention to laser surface texturing (LST). Indeed, recent technological improvements in LST, which allowed a considerable reduction of surface (and sub-surface) cracks formation and residual stresses (whether relevant), have top-ranked such a micro-manufacturing process in terms of ease and low costly working with respect to other common processes, such as ion beam and etching techniques [6]. This has been obtained by employing ultrafast laser systems with femto- and pico-second pulse duration at frequencies of 100 kHz. As a result, relatively high-aspect-ratio/high-density structures of micro-holes can be successfully fabricated over most common technological material (as steel, silicon carbide, carbon graphite, and many others), where fast energy deposition and negligible heat-affected-zones are guaranteed at such laser material interaction timescales [2]. A decade of experimental (and theoretical) research on micro-structuring lubrication has shed light on the positive effect an artificial surface texturing *may* have on enhancing the load capacity, wear resistance and friction properties of mechanical components [6,7,22] and manufacturing tools [3].

In the case of total texturing, conformal contacts have been investigated in a number of interesting experimental studies. In particular, Kovalchenko et al. [12] firstly reported on the transition from the boundary to the hydrodynamic regime in the case of a texture constituted by a lattice of circular holes, whereas Galda et al. [11] and Vilhena et al. [21] discussed, respectively, the effect of hole shape and laser working parameters on the Stribeck curve. Texturing hydrodynamics has also been investigated in practical cases, e.g. for totally textured rings [16] and partially textured thrust bearings [8,13] and piston rings [9] showing, on the experimental basis, both a remarkable friction reduction due to the micro-dimpled geometry and the existence of optimal texturings for larger load support capabilities. The literature also reports detailed experimental investigations in the case of grooved micro-geometries, see e.g. Refs. [1,15,20,23]. In particular, under lubricated reciprocating sliding motion, Yuan et al. [23] discussed the effect of the groove inclination angle (the angle between the sliding direction and the micro-channel path) on the contact friction. The authors found, as expected, no preferential inclination angle which is able to minimize the friction at the different investigated applied loads. However, friction for the grooved surface resulted usually lower than the corresponding value for

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http://dx.doi.org/10.1016/j.triboint.2014.03.014
0301-679X/

the untextured case, a result not always confirmed in the literature. Recently Adatepe et al. [1] have compared the friction of transverse and longitudinal grooved textures with the untextured case for the journal bearing geometry, showing that the larger friction values were obtained for the transverse grooves over all the Stribeck curve, followed then by the longitudinal texture friction. The latter remarkable result experimentally suggests, together with the recent findings on dimpled texture [12], that the adoption of structural textures of a different nature (i.e. circular/elliptical, or grooved) may allow to (microscopically) pointwise differentiate the frictional characteristics of the contact [19]. The latter practice would correspond to a step-forward in technological applications, such as forming processes, where a tailored friction surface on the tool would contribute to optimize the material flow thus allowing a more efficient die filling. There are, however, still opened issues involving the fundamentals of total-texture lubrication. As an example, whilst it is already well known that, in the hydrodynamic regime, the load support can be maximized (and/or the friction minimized) by optimizing the area density and the hole depth of the surface texture[22], it is not equally clear if the same range of optimal texture characteristics allows to keep (nearly) maximal the load in different operating conditions, e.g. in different lubrication regimes. Indeed, transient loading and unsteady sliding/rolling conditions are quite common in machine as well as technological operations, which may result in the periodic average rupture (boundary regime) and reformation (hydrodynamic regime) of the lubricant film at the contact interface. In such a case, there is no simple argument addressing the suitability of a surface texture, e.g. resulting from the numerical optimization in simplified operating conditions belonging to the hydrodynamic regime, on the whole range of operating conditions.

In the present study we try to elucidate this aspect with a focused tribological campaign for conformal pairs with total dimple-texturing. In particular, we measure Stribeck curves, on a range of sliding velocities spanning about two orders of magnitude, as a function of microhole diameter and depth. The purpose is to ascertain whether the optimal combination of texturing parameters, allowing to minimize the friction in the hydrodynamic regime, can have a similar effect in the boundary and mixed regimes. We employ a microtexture consisting of a square lattice of micro-holes whose diameter, depth and spacing are controlled during the laser texturing process, while keeping constant the texture area density. Our analysis shows that the depth of the microhole, characterizing the optimal choice for minimizing the friction measured in the hydrodynamic regime, is also remarkably effective in minimizing the dissipation over most part of the Stribeck curve.

2. Experimental setup details

Friction measurements were carried out on a CSM High Temperature pin-on-disk Tribometer (THT), see Fig. 1(a). The original contact geometry has been redesigned in order to obtain larger sliding velocities compared to the standard equipment. The core of the system is simply constituted by a rotating sample-disk in contact with a truncated sphere, the latter being cut from a machined bearing 100Cr6 ball, Fig. 1(b). The surface of the truncated sphere was obtained after hot mounting the bearing balls in a thermosetting phenolic resin and removing the spherical cap in excess. In particular, mounted specimens were grinded with SiC papers (in order to remove material and to achieve the specified extension of the contact area) and finally polished with a 1 μm diamond suspension on a synthetic short nap in order to obtain the final finishing state. Subsequently machined bearing balls were laser textured on the polished surface, removed from the mounting

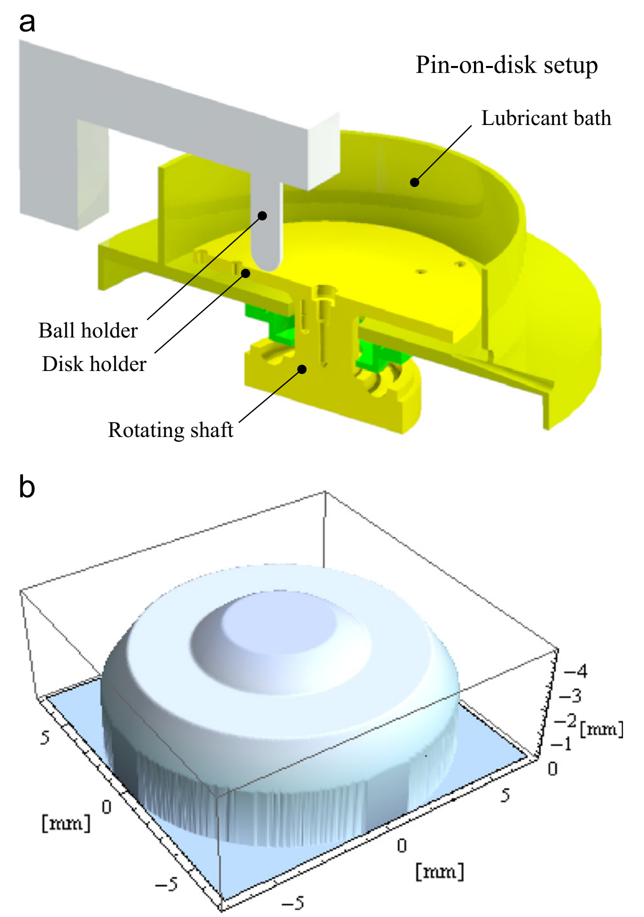

Fig. 1. The experimental setup (schematic) employed to carry out the Stribeck curve measurements (a). The truncated sphere obtained by the 100Cr6 steel ball mounted on the ball holder (b).

resin and assembled in the tribometer pin-holder. Atomic force microscopy acquisition of the final mirror-finished surface reveals roughness characterized by nanometer-sized randomly directed scratches with a root-mean-square value $h_{rms} \approx 20$ nm. The substrate is an aluminium alloy AA6061 sheet with $h_{rms} \approx 0.6$ μm. The contact pair (disk and pin-end) is immersed in a lubricant bath, whose temperature is constantly monitored during the test. The adopted lubricant is a pure mineral oil (Oroil Therm 7 from Orlando Lubrificanti S.r.l.), with dynamic viscosity $\eta = 0.0516$ Pa s at 50 °C. LST technique is employed to texture the surface of the truncated sphere.

The source used for the laser micro-texturing of high-density dimples was a Sci-series Ultrafast Fiber Laser from Active Fiber Systems GmbH, delivering 650 fs pulses at the wavelength of 1030 nm with repetition rates from 50 kHz up to 10 MHz and maximum pulse energy of 100 μJ. The output beam passing through an acousto-optic modulator (AOM) was circularly polarized by a quarter-wave plate (QWP) to prevent anisotropic absorption inside the dimple and improve the ablation quality. Also, a Galilean beam-expander with magnification factor of about 3 was set before the 14-mm aperture galvo-scanner equipped with a F-Theta lens of focal length 100 mm, to produce a spot diameter of about 12 μm at the waist. To study the effect of varying geometries of surface micro-textures on the coefficient of friction, micro-holes of different depths and diameters have been generated by employing a laser trepanning technique. Preliminary micro-texturing experiments allowed to adjust the laser parameters and the beam scanning path optimizing the shape of the drilled dimples and assessing the process reproducibility. In particular, the best strategy to have control on the depth was to vary the speed of