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Varying the geometry of laser surface microtexturing to enhance the frictional behavior of lubricated steel surfaces

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Abstract

We experimentally investigate and theoretically interpret the effect of varying the microstructure geometry introduced by laser surface texturing (LST), on the frictional properties of interacting components. The ability to control the coefficient of friction under lubricated conditions is demonstrated. Particularly, the LST optimization of a regular pattern of microholes on steel allows to reduce friction over the entire range of sliding velocities with respect to the untextured case. Moreover, we measure the Stribeck curves on a range of sliding velocity covering the entire lubrication range, i.e. from the boundary to the hydrodynamic regime under the so called iso-viscous rigid condition. Our measurements show a friction reduction up to 50% in the hydrodynamic regime.

Keywords: laser surface texturing, surface microstructuring, laser ablation, friction, lubrication, smart surfaces

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1. Introduction and motivation

In parallel with the improvement of ultrafast laser micromachining, a significant advancement of the laser surface texturing (LST) technique, based on the high-energy pulse laser ablation, has been observed in the last few years [1].

Particularly, an increasing amount of research is currently pointing out the technological advantages of LST in introducing a regular pattern of structural modifications on the surface of interacting components, with respect to alternative techniques such as wet/dry etching, ion beam lithography, etc.

The surface micro-geometry features are known to significantly affect the local properties of the contact, such as friction, adhesion, and wear [2-3], yielding to a plethora of applications ranging from engineering (e.g. microfluidics, superhydrophobic surface, bio-inspired adhesives, seals and bearings) to life science (e.g. cell adhesion, tissue scaffold, and tactile perception).

In this wider tribology context, LST is being considered a versatile, efficient and cost-effective tool to realize high aspect-ratio/density lattices of microstructures on metallic surfaces and pursue friction control abilities. Indeed, a fast energy transfer process to the material and a negligible heat affected zone are guaranteed by employing ultrafast fiber laser systems with femto- and picoseconds pulse duration. Furthermore, any residual stress, collateral damage and crack formation at the surface (and in the bulk) may be considerably reduced using extremely short laser pulses [4], leading to high quality morphology and defect-free surface texturing.

In this work, we provide an experimental and theoretical research on studying the effect that an artificial surface texturing, introduced by ultrafast laser micromachining, have on enhancing the friction properties of mechanical components under iso-viscous rigid lubrication. Specifically, we measure the coefficient of friction (COF) μ of a textured nominally flat surface, for various micro-geometries, in steady sliding against an untextured nominally flat counter-surface. With respect to our previous work [5], we focused our investigations on studying the influence of micro-dimple depth and diameter on the friction properties. We obtain a remarkable friction reduction over the entire range of lubrication conditions, which is confirmed by a preliminary theoretical analysis. Our findings suggest that the adoption of LST in the introduction of structural textures of different areal-volumetric densities and shapes (i.e. circular, elliptical, grooved) has a key role in controlling the sliding friction.

The proposed technique may be a viable solution to improve all those technological processes, such as forming processes, where a tailored friction surface on the tool would contribute to optimize the material flow thus allowing a more efficient manufacturing technique.

2. Experimental laser ablation apparatus

LST technique is used to microtexture the surface of a spherical cap made of steel. Figure 1a shows the schematic layout of the fabrication setup. The laser beam of a Yb-doped fiber laser system was focused and moved on the target surface using a galvanometric scanning system equipped with a 100 mm focal length F-theta lens (focal spot diameter $\approx$ 20 μm).

Several sets of LST geometries were fabricated to study the effect of micro-texturing densities and laser working parameters on the Stribeck curve. In particular, a representative lattice of circular microholes is shown in Fig. 1b, where the hole radius is $\approx$ 14 μm, the center to center length is $\approx$ 40 μm, and the ablation penetration is $\approx$ 5 μm. No further polishing of the textured surface was performed since the height of bulges, around the rim of the texture border, was comparable with the root-mean-square-height of the residual roughness covering the untextured counter-surface.

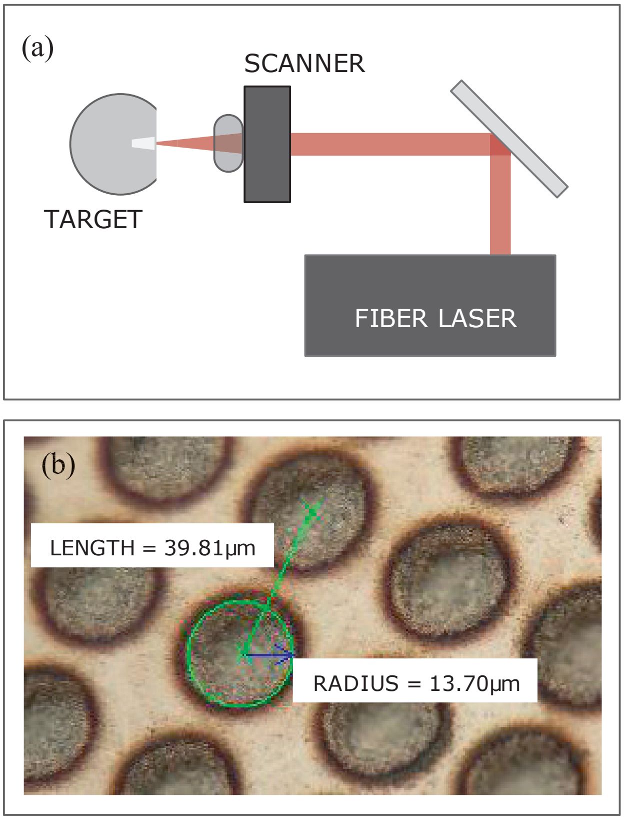

Fig. 1. a) Schematic layout of the experimental setup; b) microscope image of a representative lattice of microholes

3. Results and Discussion

Friction measurements were carried out on a CSM high temperature Tribometer (THT), in condition of pin-on-disk contact. The friction pair is constituted by a steady-rotating untextured disk in contact with the pinned textured spherical cap. The latter is squeezed into contact with a constant normal load during the test. Moreover, the contact pair (disk and pin-end) is immersed in a lubricant bath of pure mineral oil, with a representative dynamical viscosity value of $\eta = 0.052$ Pa s at 50°C. The temperature of the bath is constantly monitored during the test.

Figure 2 shows the comparison of Stribeck curves for the flat control surface (continuous line) and for the structured surfaces with different texture area densities. Remarkably, the COF of the LST surfaces is strongly reduced over the entire range of sliding velocities as a result of the reduced shear stresses at the contact interface. In particular, compared with the flat control surface, a friction reduction ≈ 50% was measured in the hydrodynamic lubrication regime, i.e. for values of $\eta U > 0.01$ N/m.

The experimental evidence agrees with the numerical predictions based on the resolution of the thin film fluid-dynamics [5]. Indeed, we theoretically observe that the introduction of an array of dimples over the surface produces a reduction of the average fluid wall shear stresses as a consequence of two co-operating fluid dynamics mechanism at the interface.

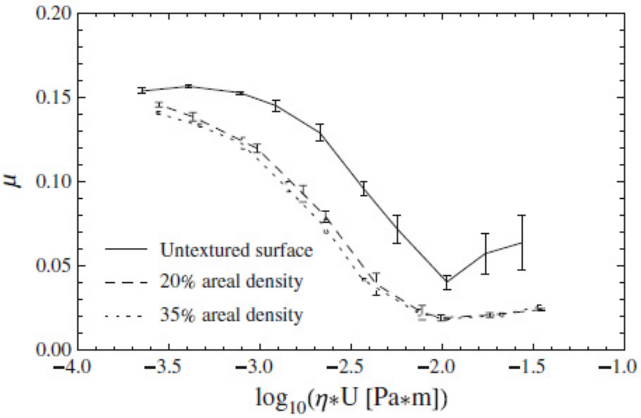

Fig. 2. The coefficient of friction as a function of the product viscosity, η, and sliding velocity, U, in a log-linear diagram, for the flat control surface (solid line, i.e. for the untextured spherical cap) and the microholes array with void density of 20% and 35%, respectively.

In particular, the local wall shear stresses, over the micro-holes, are substantially reduced during sliding due to the combined effect of a reduction of the average shear rates of the fluid, and the occurrence of local cavitation spots in the outlet zone, whose reduced average mixture viscosity determines, consequently, the corresponding reduction of average shear stresses. Moreover, the all fluid overpressure generated at the interface is shown to be basically moderately altered with respect to the untextured case in condition of equal minimum film thickness, allowing for the occurrence of previously discussed friction reduction.

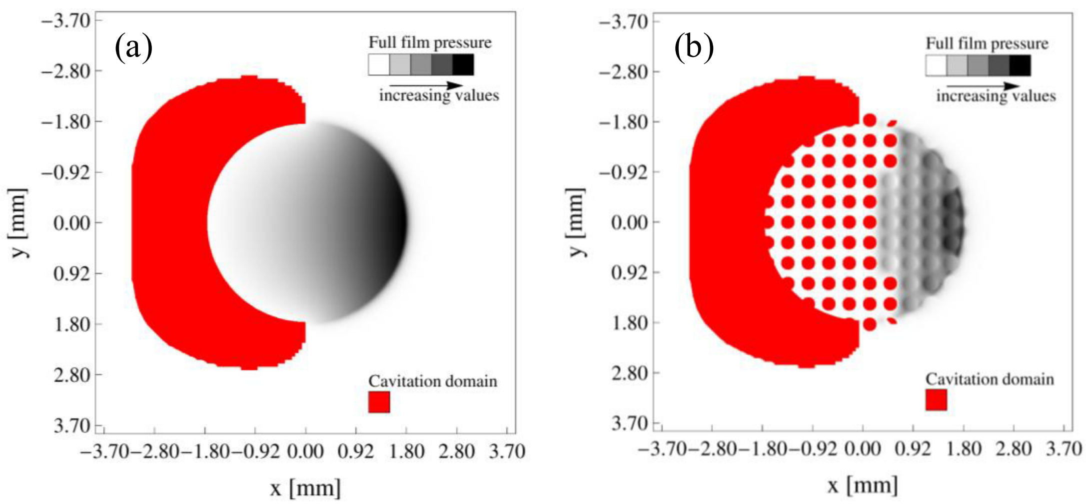

Fig. 3. Fluid pressure field (in gray scale) and cavitation domain (red areas) results in the sliding contact domain, for a) the untextured and b) textured surface.

This is shown in Fig. 3, where we report the fluid pressure field (in gray scale) in the sliding contact domain, for the untextured (Fig. 3a) and textured surface (Fig. 3b), respectively. Red areas correspond to the cavitation regions. Observe that the introduction of micro-texture, in this contact case, allows to extend the cavitation region inside the contact domain (see Fig. 3b), with the consequent proportional reduction of the global wall shear stresses, and therefore of friction. Figure 3 also shows that the average fluid overpressure, occurring in the inlet region (opposite to the cavitation macro-region, see before), is basically unaltered in both cases, resulting in the ability of micro-texturing to preserve the load support ability of the original contact.

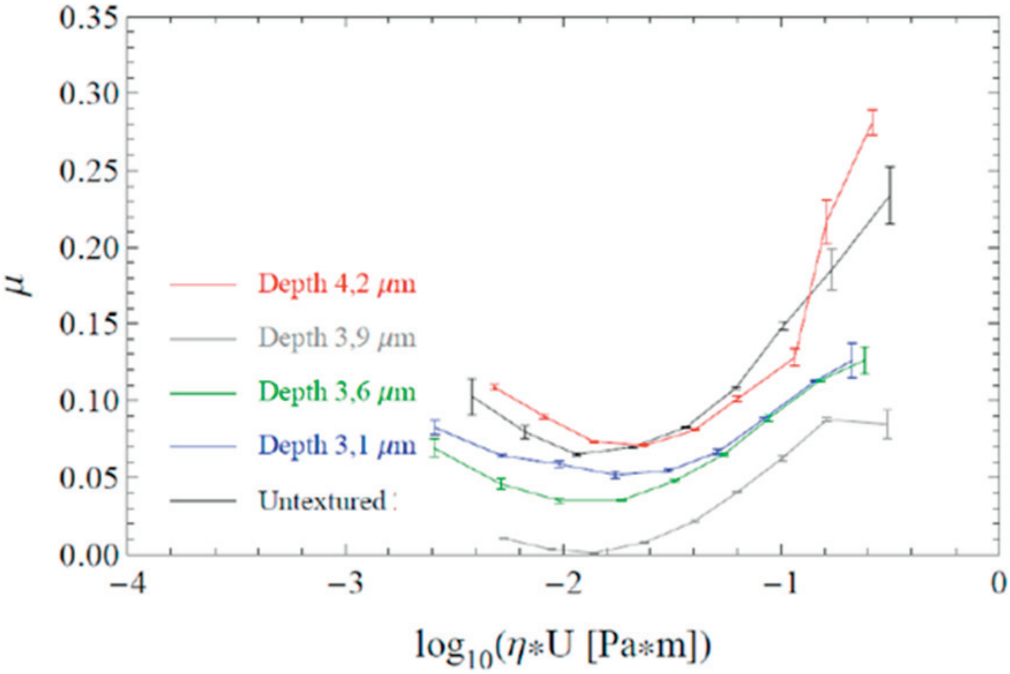

Fig. 4. The coefficient of friction as a function of the product viscosity, η, and sliding velocity, U, in a log-linear diagram, for the untextured spherical cap (i.e. the flat control surface) and the microhole arrays (of external diameter of 100 μm) with various dimple depth, respectively.

Finally, we explored the influence of the dimple depth and diameter on enhancing the friction properties of mechanical components under iso-viscous rigid lubrication. In particular, Fig. 4 shows the comparison of representative Stribeck curves for the flat control surface (see untextured in figure) and for a set of microstructured spherical caps with circular dimples of outer diameter of 100 μm and various ablation penetration depth, ranging from 3.1 μm to 4.2 μm. Here, the COF reduction of the LST surfaces over the entire range of sliding velocities is still experienced, but it is clearly evident the existence of an optimal dimple depth, which causes a dramatic decrease of the coefficient of friction with respect to the untextured cap. Indeed, by further increasing the dimples depth above 4 μm, for this particular geometry, the effect of artificial surface texturing on the COF reduction vanishes. Further studies are ongoing aiming at explaining this phenomenon, probably to be ascribed to cavitations effects inside the micro-dimples.

4. Conclusions

We presented an experimental and theoretical investigation of the effect of regular surface micro-structures on the frictional properties of wet steady-sliding contacts. Accurate micro-geometries have been realized by employing the ultra-short pulse laser ablation technique, which confirms to be a very promising micro-manufacturing process due to the high accuracy and repeatability of the process, and to the negligible impact on the worked sample in terms of heat-affected zone and stress-residuals. We showed that a remarkable sliding friction reduction can be obtained on the all Stribeck curve. The existence of threshold texturing configurations, over which the beneficial tribological effect is reversed, is currently under investigation.

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