Effects of the micro surface texturing in lubricated non-conformal point contacts

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Abstract

This paper presents an experimental study about the effects of micro-textured surfaces on lubricated non-conformal point contacts. Thus, we focus on a regime poorly investigated in literature, where the contact area and the micro-holes have a comparable size. Tribological characterization are performed on three geometrical patterns, which are textured on stainless steel (1.4112) polished surfaces. Experiments are carried out on a Rheometer MCR-301(Ball-on-three plate device), where steel ball slides against the surface of the samples. These samples were tested with two different viscosities of the PAO (Poly-Alpha-Olefin) as a lubricant. Results shows the change in the friction with respect to the sliding velocity under different lubrication regimes due to the stress, void ratio and two different kinematic viscosities of PAO. In particular, we show that, depending on the void ratio, a significant friction reduction or, on the contrary, a deterioration of the frictional performances can affect the boundary and mixed lubrication regimes. This is due to the simultaneous occurrence of two competing effects. One is related to the stress intensity increase, due to the presence of the micro-hole edges on the contact topography, and to the consequent high wear and friction. On the other hand, micro-texture may play a positive role in the friction optimization given the possibility, offered by the micro-holes, to entrap wear debris and, then, to perverse a smoother interface between the contacting pairs.

Keywords: Surface Texturing, femtosecond laser ablation, lubrication, non-conformal, friction.

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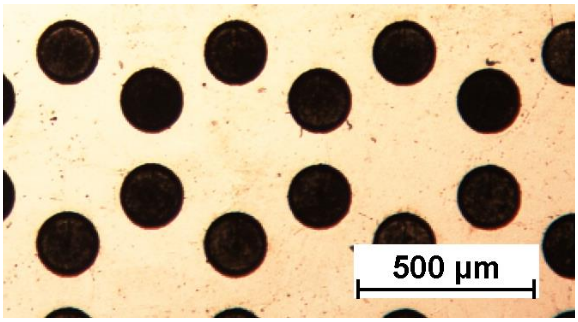
1. Introduction

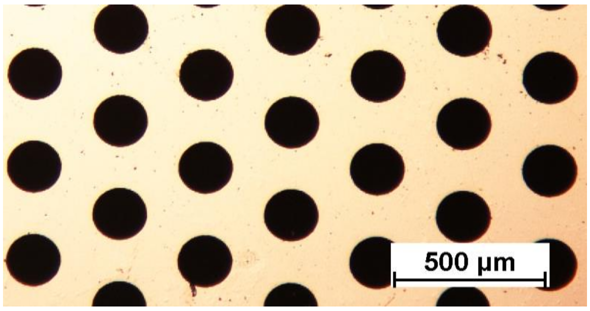
Topography of the surfaces plays a vital role in influencing the tribological properties of the materials and, in particular, the friction behavior of the two-rubbing surfaces during conformal and non-conformal contacts. Different research groups around the globe are trying to understand the complex behavior of the tribological properties, in terms of friction and wear, in order to improve the efficiency and to increase the life time of the mechanical systems or components [1]. In last few decades, surface texturing has shown to be an emerging technique to control the friction and wear. It consists of fabricating a pattern of small dimples or channels upon the surface of the materials in a very controllable way, which causes the change in the surface topography. The research on the effects of surface texturing on friction reduction was started since 1996 by Etsion's group [2]. Over the past 20 years, over 400 papers have been published reporting studies on surface texturing, covering both experimental and theoretical investigations [3].

With regards to the manufacturing procedures, there exist different surface pattering methods to texture tribological surfaces, including vibrorolling [9], reactive ion etching [19]and others (see e.g.[4] for more details). However, Laser Surface Texturing (LST) in particular has emerged in recent years as the best technique of surface engineering, which shows a significant improvement in load capacity, wear resistance, friction coefficient etc. of tribological mechanical components. LST consists of creating an array of high-density micro-dimples on a metal surface by laser ablation and each of these micro- dimples can serve either as a micro-hydrodynamic bearing in cases of full or mixed lubrication, a micro-reservoir for lubricant in cases of starved lubrication conditions, or a micro-trap for wear debris in either lubricated or dry sliding [5,6]. Texturing can be done with different laser systems, but femtosecond laser seems to be more beneficial as compared to the other laser sources. The advantages of using femtosecond laser pulses compared to nanosecond ones reside in the fact, that the ablation process is substantially melting free. Therefore, no burrs create on the edges of the micro-dimples, which could be detrimental to the desired tribological behavior, and no further polishing of the surfaces is required after LST. Furthermore, femtosecond laser ablation allows finely control the depth and the geometry of the dimples with micrometer precision [7]. The benefit arising from micro surface texturing including the micro-cavities or grooves on a flat surface is a combination of several effects, which improves oil supply and reduced abrasion in the sliding contact: surface cavities or grooves can act as oil reservoirs, which transport or retain oil to be released in critical situations. Cavities, grooves and valleys in the surface can disarm wear particles by entrapping them, thereby suppressing abrasion and ploughing friction. When surface irregularities appear at sufficient density, they can improve the wetting of the surface by an oil [8,9], and thereby support the lubricating oil film formation. At higher sliding speed, and with a sufficient supply of oil, individual surface cavities may act as hydrodynamic pressure pockets, which reduce friction, unless the benefit is counteracted by turbulence effects. Recent experimental investigations [19] have shown that, in this regime, also cavitation in the holes can play an important role, by decreasing the viscous losses and, then, the total friction. Finally, we should notice that a drawback of the surface irregularities may occur as abrasive wear of a soft counter surface at high contact pressure [10].

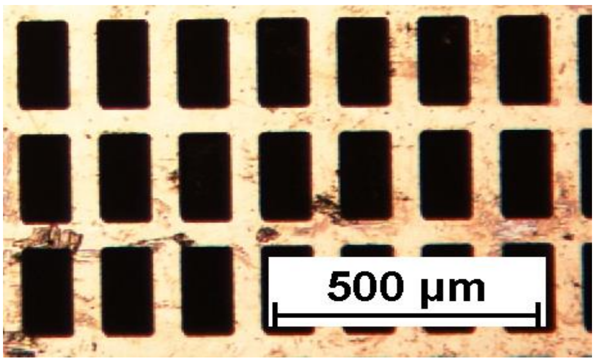
This paper focuses on a topic only partially enlightened in literature: this is the tribological performances of the micro-textured surfaces during non-conformal point contacts under lubricated conditions. Indeed, the largest part of theoretical and experimental analyses have investigated conformal contact conditions, where the contact area is much larger than the pocket size. Here, we wonder what happens, in terms of friction, when the contact region has a width comparable with the hole diameter. Indeed, such conditions are significant in a variety of applications, involving conformal point contacts, like e.g. in ball bearings. Here, different tests are performed to study the tribological effects, which arise due to the contact length or contact pressure (stress) and the void coverage factor. These tests are performed by using a lubricant of two different viscosities from PAO (Poly Alpha Olefin-PAO). We show how, depending on the properties of the texture and, specifically, on its void ratio, the tribological properties may change very differently. This is qualitatively discussed in the paper observing how different and competitive mechanisms occur when a texture pattern is introduced: their interplay may result in an improvement or, conversely, in a deterioration of the friction performaces. Ultimately, the paper shows how, in comparison with conformal contact mechanics, textured interfaces in point contacts may behave very differently, thus demonstrating the necessity of more experimental and theoretical investigations in the field.



Hexagonal microtexturing



Triangular microtexturing



Rectangular microtexturing

Figure 1: Micro-textured geometrical pattern

2. Experimental Setup

2.1 Surface texture manufacturing by Femtosecond laser ablation process (fsLA)

The surface of the samples has been micro-textured with three different geometrical patterns as shown in Figure.1 The micro surface texturing has been performed upon stainless steel (1.4112) samples, having a surface roughness of 0.2 µm. Fabrication has been done by using a scanner interfaced ultrafast fiber CPA laser system (mod. Sci-series from Active Fiber Systems GmbH, shown in Figure 2), delivering 650 fs pulses at a wavelength of 1030 nm, with repetition rate ranging from 50 KHz to 10 MHz, maximum pulse energy of 100 µJ and maximum average power of 50 W. After passing through a beam expander, the laser beam has been guided to the galvo-scanner (Hurryscan from ScanLab GmbH) head, equipped with a 100-mm focal length F-Theta lens. The resulting laser beam spot size on the sample surface was about 25 µm.

Types of textured geometry	Density (%)	Speed (mm/s)	Hatch Type	Track depth (µm)
Hexagonal	27	22	Concentric	6.6
Triangular	29	34	Concentric	6.7
Rectangular	53	50	Crossed, Horizontal and Vertical	7.3

Table 1. summarizes the parameters defined for each texture geometry.

The laser has been operated at 50kHz with an average power between 60 and 70mW. Therefore, laser ablation was performed slightly above the threshold fluence in order to achieve a high level of accuracy and reproducibility of the machined microstructures. For the three different textured geometries, different milling strategies have been used. For both the hexagonal and triangular texturing, the dimples have been generated by moving the laser beam along concentric circles, with a hatch distance of a few micrometers and a speed of 22 mm/s and 34 mm/s, respectively. For the rectangular geometry, crossed horizontal and vertical milling hatches have been performed at 50 mm/s. The desired dimples depth was achieved by finely adjusting the number overlapped loops.

Figure 2: Active Fiber System Laser

2.2. Characterization

The tribological properties of the micro-textured samples were evaluated by different apparatus, including a Rheometer MCR-301, a LEXT OLS4000-Industrial Laser Confocal Microscope, a Leica DM4000 M for Material Analysis, a Fujifilm Pressure Distribution System-FPD 8010E, a CSM confocal Microscope. The MCR-301 was used as a tribometer to perform the friction test under an applied load of 20N at 25°C. As shown in Figure 3, the rig is based on the principle of a ball in contact with three plates, which includes a ball-measuring geometry consisting of a shaft, a ball and a ball fixture [12]. The ball fixture enables the use of balls made of different materials, and their easy replacement. The plate texture at the bottom part is mounted on a special designed spring system allowing motion in all directions of the coordinate system: x, y, z. This flexibility ensures the concentric positioning of the fixture to achieve a uniform force distribution from the ball onto all the three plates. The rotational speed applied to the shaft is producing a sliding speed of the ball with respect to the plates at the contact points. The resulting torque can be correlated with the friction force by employing simple geometric calculations. The normal force of the rheometer is transferred into a normal load acting perpendicular to the bottom plates at the contact points. We have, then, the following relations:

$$F_L = (1/2)\cdot\cos\alpha\cdot F_N , \qquad M = \sin\alpha\cdot F_F\cdot r_{ball}$$

with r_{ball} being the radius of sphere and α the angle of the plates, respectively. The following dimensions have been used: α = 45, r_{ball} = 12.7⁄2 mm = 6.35mm.

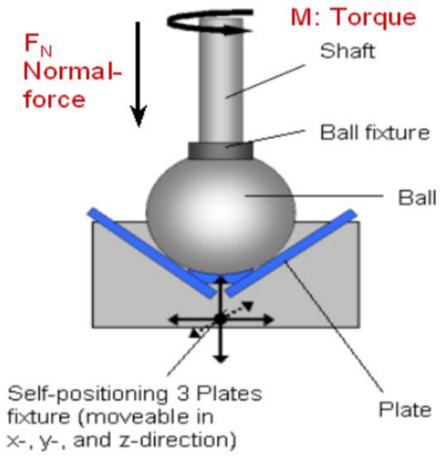


Figure 3: Schematic representation of the ball on three-plates-device

Prior to the friction tests, the tribopairs have been ultrasonically cleaned using isopropanol, followed by rinsing with Petrolether and air dried. Experiments have been performed under pure sliding conditions in a ball (100 Cr6, G-28) on three plate device, by keeping the plates stationary and rotating the ball at a wide range of sliding speeds up to 1.4m/s . Micro-textured samples with a quasi-rectangular geometrical pattern were aligned with their longer axis parallel to the sliding direction of the ball during the alignment test. A fixed quantity of lubricant, i.e. 1µl poly-alpha-olefin (PAO) without additives (base oil: Isoflex Topas L32), was distributed on each plate at the point of the tribo-contact with µ-Pipette during each test and a new ball was used for each test. The measurement process was divided into two stages: the initial stage lasted for about 15 minutes and provided three Stribeck curves, whereas the final stage was performed after a time interval of 1 hour and delivered an additional set of three Stribeck curves. The friction coefficient, µ, was recorded every second during the test. All friction data are averages of the six measurements curves for each type of the micro-texture geometrical pattern.

The morphologies of the surfaces were characterized by using LEXT OLS4000- Industrial Laser Confocal Microscopes 3D and Leica DM4000 M for Material Analysis. Contact pressure measurement was performed with a medium range Fujifilm pressure measurement foil, which gives the point of pressure(stress) varies in a range from 10 to 50 MPa. These foils were installed on the samples tested for the contact pressure measurements.

Table 2: Viscometric Characteristic

Low Viscosity Lubricant (Type 1-Poly-alpha-olefin)	39.5 mm²/s at 20°C
High Viscosity Lubricant (Type 3-Poly-alpha-olefin)	1300 mm²/s at 40°C

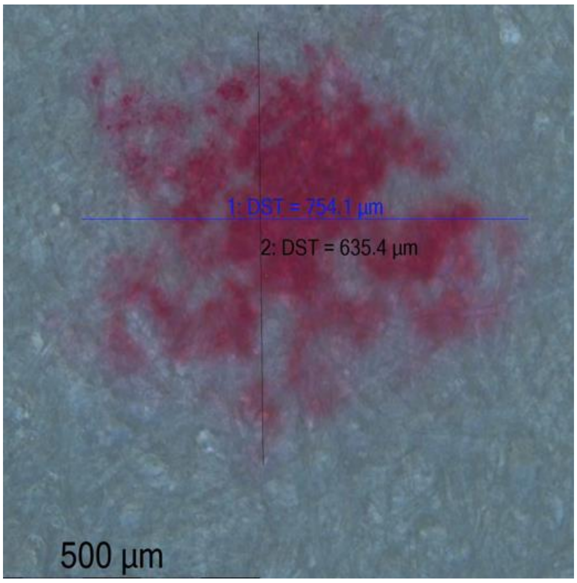
Pressure measurement tests have been carried out under the normal load of 20N, without lubricant in a static condition for 10 minutes. After each test, the area of the contact pressure has been examined by using Leica DM4000 Microscope and Fujifilm Pressure Distribution Mapping system (FPD-8010E).

Finally, the change in the friction behavior due to the temperature change has been studied by using a designed temperature loop for the un-textured sample under an applied load of 20N, with a low viscosity lubricant (PAO). The recorded data have been used for studying the effect of the temperature on the friction coefficient while morphology of surfaces has been examined by LEXT, CSM confocal microscope.

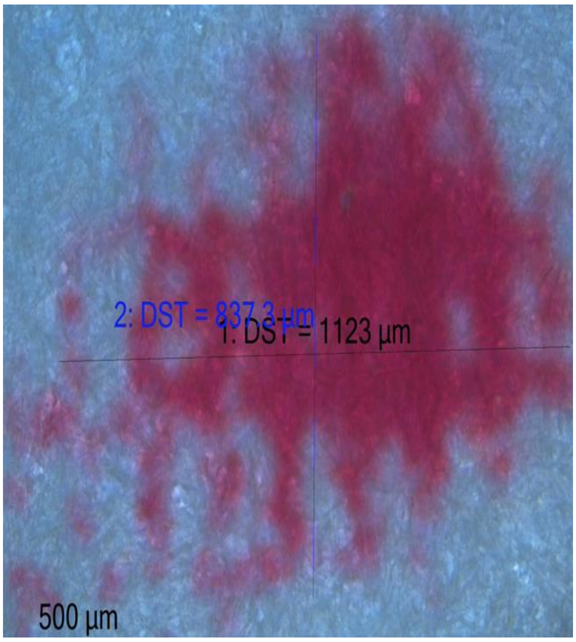
3. Results and Discussion

Preliminary pressure measurement tests have been conducted to visualize the differences, in terms of stress distribution, between the textured and the untextured samples. Indeed, the contact pressure plays a crucial role in determining the wear ratio and, consequently, the friction. The experimental tests have been performed by using Fujifilm medium range pressure measurement foils, placed upon each sample tested under static conditions by using Rheometer 301 under an applied force of 9.84 N on each sample. Given the qualitative features of the technique, the results have an approximate value, but, at the same time, provide significant information on how the surface topography influences the pressure distribution.

In detail, foils have been tested with both textured and untextured samples under the same conditions and later, analysed by using Leica DM4000 microscope: depending on level of the red colour (see Figure 4), by employing the Fujifilm Pressure Distribution Mapping system (FPD-8010E), it is possible to obtain in each point an estimation of the pressure value. In detail, dark red spots shown in Figure 4 indicate the area effected by a high applied pressure (stress), whereas the light red spots represent the contact zone under an area of low pressure or stress.



Polished Sample
Density(P)=25.5MPa)



Textured Sample
Density(P)=12.5MPa

Figure 4: Microscopic Images of contact pressure or stress on fujifilm pressure measurement foils.

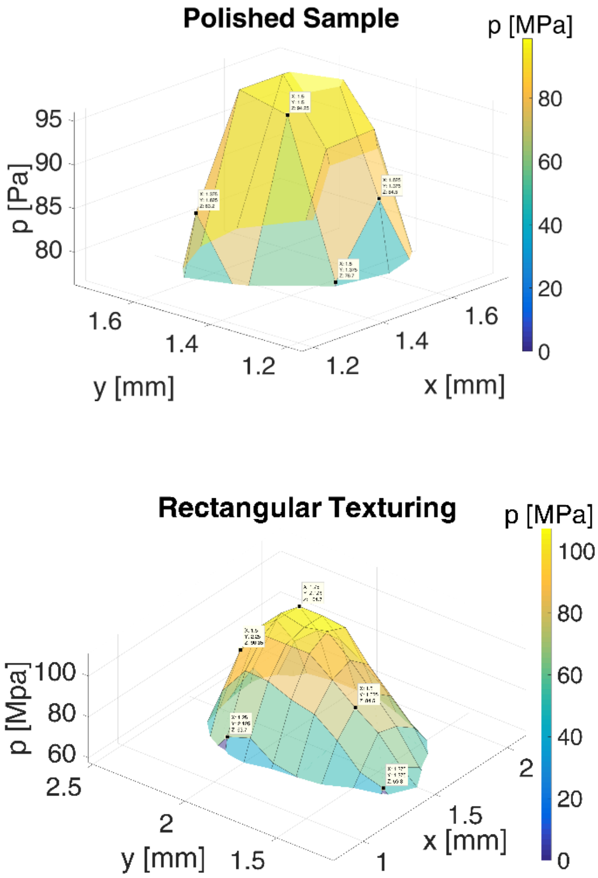


Figure 5: Contact pressure images (FPD-8010E)

In Figure 5, we show the contact pressure distributions in two cases: the first one refers to the untextured samples, whereas the second one is obtained testing the rectangular textured pattern. In spite of the rough estimations offered by the pressure sensitive foils, we observe quite clearly that the micro-texture produces a significant increase of the pressure distribution. This is due to the presence of the micro-holes edges which, ultimately, act as stress intensity factors. Such an effect seems crucial in non-conformal contacts where the contact area is comparable with the pocket size. This is clearly shown in Figure 6, where the worn zone has the same dimensions of the rectangular micro-holes.

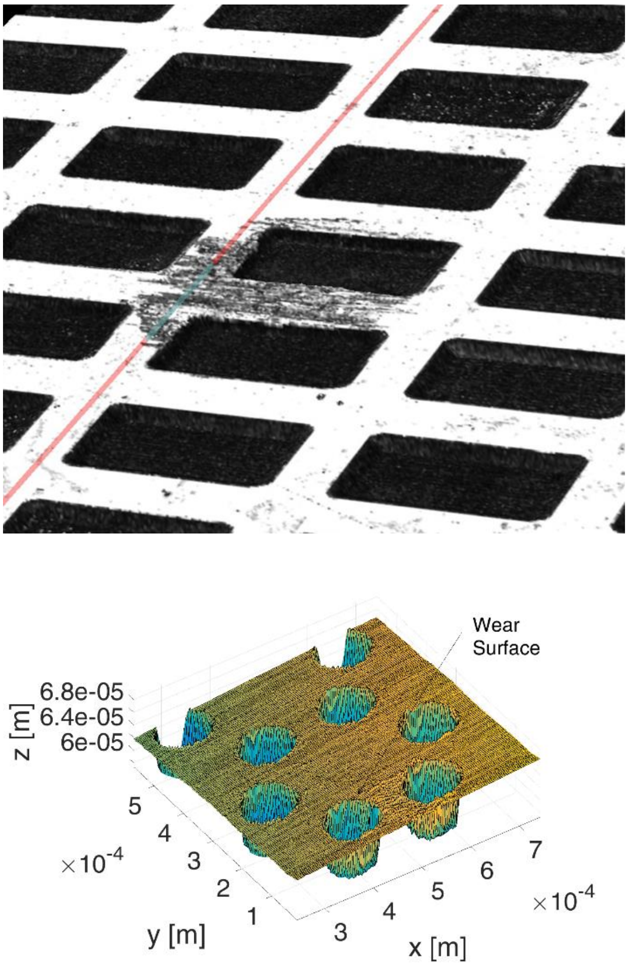


Figure 6: Industrial Laser Confocal Microscope 3D Images(50X) for the rectangular geometry (*on the top*) and CSM Confocal Microscope Images for the hexagonal texturing (*on the bottom*). In both cases, the worn zone is clear.

The higher pressure due to the presence of the micro-texture is a potential evidence of larger wear; this is particular critical in all the regimes where we do not have a fully developed lubrication film and where, as a consequence, the wear ratio tends to be higher. Larger wear would implicate larger friction, and, therefore, the presence of a micro-pattern would seem detrimental in conformal contacts. However, this is not all the story: the presence of micro-holes may play also a positive role. Indeed, in the mixed and boundary regimes, where the wear is larger, the holes may be an opportunity to entrap the debris and, therefore, to contribute to have a smoother interface between the contacting bodies. This may entail the reduction of the interfacial friction. As a matter of fact, in the presence of micro-textured surfaces in point non-conformal contacts, two competitive mechanisms can be expected: on one side, the presence of the holes edges produces an intensification of the stress distribution and, therefore, an increase of the wear ratio; on the other hand, the holes can capture the debris related to the wear process and, therefore, can help in obtaining a smoother interface and, ultimately, a smaller friction force.

All this seems confirmed in Figure 7, where we plot the friction coefficient, μ, as a function of the sliding velocity, u. Each micro-texture geometry has been tested under the same conditions by using a lubricant of two different viscosities (shown in Table. 2). Friction measurements have been taken over a wide sliding range while progressively increasing the speed from 0.0094 m/s to 1.4 m/s. Low viscosity experiments (Type 1) have been performed to see the effect of different textured geometrical pattern in the mixed regimes and high viscosity experiments (Type 3) have been focused upon on the boundary regime and on the transition to hydrodynamic regime. Indeed, in Figure 7a and 7b, we observe that, in comparison with the results of the untextured samples, the hexagonal and the triangular patterns produce a deterioration of the frictional performances, whereas the rectangular pattern shows an improvement in the order of 20%. Such a different behavior can be explained by assuming that the two aforementioned mechanisms intervene differently in two cases. Indeed, for the triangular and the hexagonal lattices, the wear increase related to the change in the topography prevails and determines an increase of the friction force. Conversely, in the case of the rectangular micro-holes, the debris entrapment effect seems to dominate and determines, in the mixed and the boundary lubrication regimes, a reduction of the frictional losses. The very different outcomes may be related to the void ratio: this is greater in the third case, i.e. with the rectangular holes, and seems able to guarantee space enough, for the wear particles, to be captured in the micro-holes.

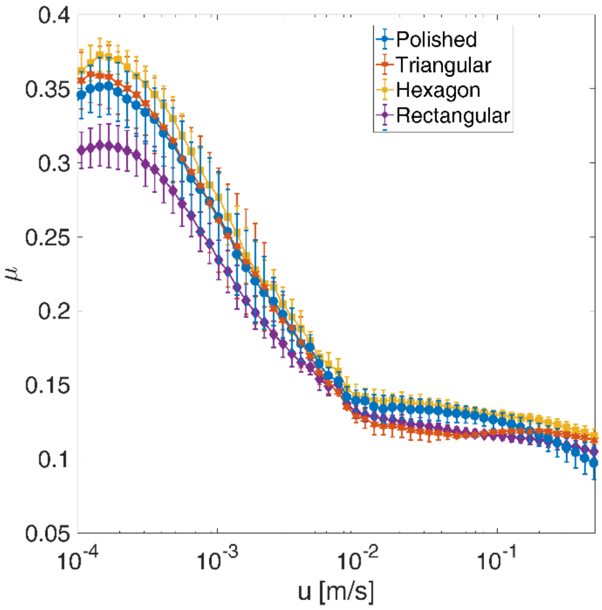


Fig. 7(a)

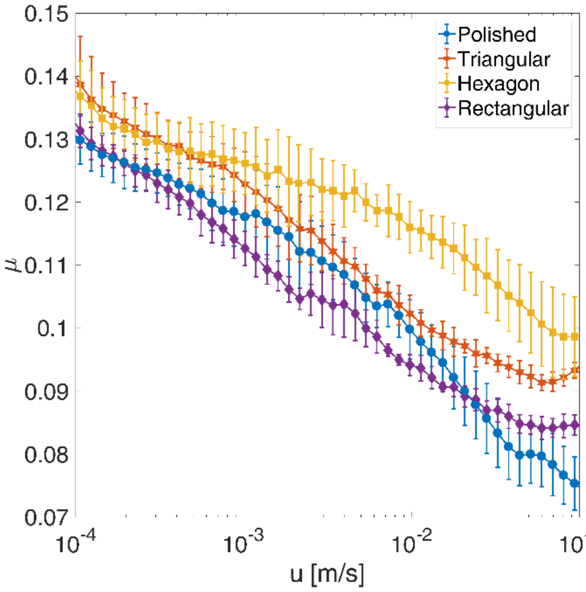


Fig.7(b)

Figure 7: Friction coefficient, μ, vs. sliding velocity, u . Figure 7a and 7b refer respectively to the low viscosity (Type 1) and the high viscosity lubricant (Type 3). For each measure, we report the scatter as an errorbar.

We may conclude that, in the presence of conformal contacts, the presence of a microtextured surface can have different consequences, depending on the effect, which prevails, i.e. the wear increase or the debris entrapment. The latter seems related to an increased void ratio.

4 Conclusions

This paper deals with the study of the micro-textured effects in non-conformal lubricated point contacts. Enormous research efforts have been dedicated to analyze the texture performance in presence of conformal contact mechanics, but a little has been told about what occurs when the contact area has the same size of the textures holes, as in any non-conformal contacts.

In this paper, we focus on this last case and show that introducing a surface texture may have opposed outcomes. Indeed, in comparison with untextured samples. it can bring to a deterioration of the frictional performances, but, on the other hand, can also determine a significant reduction of the frictional losses. This has been related to the occurrence of two different competing mechanisms: one deals with the stress distribution increase provoked by the holes edges, which acts as stress intensity factors, thus increasing the wear ratio and, therefore, the friction losses. The other element is related to the debris particles entrapment, to the creation of a smoother interface and, consequently, to a reduced friction. Depending on the mechanism, which prevails, the texture introduction can worsen or improve the tribological performances. Our tests show that a high void ratio can be useful to enhance the entrapping effect and decrease the friction. Ultimately, the paper points out the necessity to pay more attention to the micro-texture in conformal contacts as a tool to optimize friction.

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