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Research Article

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Femtosecond laser full and partial texturing of steel surfaces to reduce friction in lubricated contact

Abstract: Minimizing mechanical losses and friction in vehicle engines would have a great impact on reducing fuel consumption and exhaust emissions, to the benefit of environmental protection. With this scope, laser surface texturing (LST) with femtosecond pulses is an emerging technology, which consists of creating, by laser ablation, an array of high-density microdimples on the surface of a mechanical device. The microtexture decreases the effective contact area and, in case of lubricated contact, acts as oil reservoir and trap for wear debris, leading to an overall friction reduction. Depending on the lubrication regime and on the texture geometry, several mechanisms may concur to modify friction such as the local reduction of the shear stress, the generation of a hydrodynamic lift between the surfaces or the formation of eddy-like flows at the bottom of the dimple cavities. All these effects have been investigated by fabricating and characterizing several LST surfaces by femtosecond laser ablation with different features: partial/full texture, circular/elliptical dimples, variable diameters, and depths but equivalent areal density. More than 85% of friction reduction has been obtained from the circular dimple geometry, but the elliptical texture allows adjusting the friction coefficient by changing its orientation with respect to the sliding direction.

Keywords: femtosecond laser ablation; laser surface texturing; tribology.

OCIS codes: (320.7090) Ultrafast lasers; (140.3390) Laser materials processing; (240.6700) Surfaces.

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1 Introduction

Reduction in exhaust emissions is a key factor to control environmental pollution and prevent global warming. In the last decade, diverse governments have issued severe regulations to limit exhaust and CO_2 emissions. Road transport has been one of the most affected sectors by these laws. Several technologies have been recently developed to fulfill the new requirements on vehicle emissions. Reducing weight is one of the ways that has been pursued to cut down fuel consumption and, thus CO_2, emissions. Unfortunately, weight saving by substituting conventional materials (most of all steel) with modern lightweight materials increases production costs and will not be sufficient alone to reach the goal. In order for a new technology to spread on a mass scale, it must be economically viable both for the car manufacturers and for the customers. In this direction, fuel economy by optimizing engine efficiency is one of the most important factors, as it affects both customer satisfaction and environmental protection. Automotive engineers are making great efforts to improve combustion and reduce mechanical losses inside vehicle engines. Photonics and, in particular, laser micromachining with ultrashort pulses is one of the key enabling technologies that has been already successfully employed to improve combustion efficiency in a car engine by laser drilling fuel injection nozzles with complex geometries [1].

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It is possible to reduce mechanical losses by reducing friction loss of each component of an engine. In fact, the friction loss in an internal combustion engine is the most important factor in determining the fuel economy and performance of the vehicle utilizing the power of the engine. It has been estimated that friction losses dissipate about 40% of the total energy developed by a typical vehicle engine [2]. Tribology plays an important role in reducing friction, and automotive engineers need now to cooperate with material scientists and tribologists to face this difficult challenge. Besides the choice of a proper lubrication, surface texturing, as a means for enhancing tribological properties of mechanical components, has received a great deal of attention for many years. Laser surface texturing (LST) with femtosecond pulses, in particular, has emerged as a potential new technology to reduce friction in mechanical components [3, 4]. LST consists of creating an array of high-density microdimples on a surface by laser ablation. The macroscopic effect of such a microstructuring is an enhancement of the load capacity, wear resistance, and friction properties of the laser-treated surface [5–8]. It is assumed that the dimples act at the same time as an oil reservoir and as a trap for the wear debris circulating between the sliding surfaces and contributing to friction [5, 8]. Several theoretical models, based on the analytical [9] or numerical solution of Navier-Stokes [10] or Reynolds flow equations [8, 11–13] have been developed to investigate the hydrodynamic bearing effect generated by the surface texture and to analyze its dependence on the textural shapes and orientations [8, 10, 13].

Laser ablation provides high flexibility and precision of the microdimple geometries. The advantages of using femtosecond laser pulses compared to longer ones reside in the fact that no further polishing of the surfaces is required after LST. In fact, laser ablation with nanosecond or longer pulses is often accompanied with resolidified melting and burrs [14] around the microtextured features, which are detrimental to the frictional behavior of the LST surfaces. Working with femtosecond laser pulses and near-threshold fluences allows fast energy deposition, high removal rates, and negligible thermal damage to the material [15] with considerable reduction of surface or subsurface cracks and residual stresses compared to other more expensive or less flexible processes, such as ion beam or chemical etching.

It has been already demonstrated that total texturing of a steel surface with an array of high-density microdimples fabricated by microcasting [10], miniature engraving [8], microphotolithography [16], nanosecond laser [17, 18], or femtosecond laser ablation [3, 19, 20], the latter having the further advantage that does not require any postprocess polishing of the ablated structures, significantly reduces the surface friction in the mixed and hydrodynamic lubrication regimes. The effect of dimple size, depth, and areal density [10, 17–21] as well as the influence of the laser working parameters [22] on the Stribeck curve have been also investigated. In particular, it was found that the depth-to-width ratio of the laser ablated microdimples greatly influences the tribological behavior of the LST surface. Even a degradation of the tribological performance of the LST surface has been registered if the dimple geometry was not optimized, according to the lubrication conditions [19, 20]. Experimental results suggest that the adoption of structural textures of different nature may allow to pointwise differentiate the frictional characteristics of the contact [23]. A very limited number of experimental works have been carried out studying the effect of partial surface texturing [24, 25] or anisotropic textural shapes (elliptical, triangular) [16] on the friction reduction mechanism.

In this work we have fabricated several LST steel surfaces by exploiting the femtosecond laser technology. The surface textures consisted of a square lattice of dimples of different shapes (circular or elliptical), sizes, and depths. The spacing between the dimples was carefully adjusted in order to keep the total area density substantially unchanged. We also produced samples with only half of their surface texturized. The morphology of the LST surfaces has been characterized and their frictional behavior investigated in a wide range of lubrication regimes, aiming to better understand the influence of the dimple geometry on the tribological properties. A further scope of this work was to characterize the tribological response of elliptical or partially texturized surfaces depending on their orientation with respect to the sliding contact direction.

2 Experimental setup and sample preparation

A Sci-series Ultrafast Fiber Laser system from Active Fiber Systems GmbH (Jena, Germany) delivering 650 fs pulses at a wavelength of 1030 nm with repetition rates from 50 kHz up to 10 MHz and maximum pulse energy of 100 μJ was used to fabricate the LST surfaces by laser ablation. The linear polarization of the output beam was converted into circularly polarized light by passing through a quarter-wave plate to prevent anisotropic absorption inside the dimple and improve the ablation quality. A Galilean beam expander with magnification factor of about 3 was set before the 14-mm aperture galvo-scanner (Scanlab AG, Munich, Germany) equipped with an F-Theta lens of

100-mm focal length, to produce a spot diameter of about 12 μm at the waist.

The LST process was performed on truncated 100Cr6 steel spheres from commercial bearings. The truncated spheres (the diameter of the spherical cap was about 4 mm) were polished at a root-mean-square surface roughness of about 20 nm, as measured by an atomic force microscope, before the laser treatment. A laser trepanning technique was employed to ablate circular and elliptical dimple arrays on the sample surfaces. The diameters and depths of the structures were precisely controlled by finely adjusting the laser parameters, and the beam scanning path. We operated the laser at the lowest achievable repetition rate of 50 kHz with variable average power in the range from 40 to 60 mW. The trepanning speed of the laser beam was held constant at 20 mm/s. For a fixed spot size, the control on the dimple diameters was given by increasing the number of concentric circles to be drawn, with a lateral spacing of 6 μm, while the dimple depth was adjusted by varying the number of overlapped loops. For the texture geometry with the smaller diameters, a further sample was produced with only half of its surface texturized (partial texturing). Table 1 summarizes the laser parameters used for each texture geometry.

3 Sample characterization

The morphological characterization of all the LST samples was carried out using a white light confocal microscope by CSM-Instruments (Peseux, Switzerland) with lateral and vertical resolution of, respectively, 1.1 μm and 0.005 μm. Figure 1 shows the confocal microscopy image of a laser microtextured surface with microholes of average diameter d=188 μm and average depth h=7.2 μm. The effect of trepanning leads to a slight conicity of the dimples, probably due to the Gaussian distribution of the laser intensity within the beam spot size, which does not affect the tribological behavior of the surface. It is worth noting that the machined part is completely free from melting and burrs, thanks to the high level of accuracy provided by the ultrashort pulse duration ablation regime together with the near-threshold laser fluence selected for our experiments. Therefore, no further polishing was required after the micromachining.

The tribological characterization of the LST samples was carried out on a High Temperature pin-on-disk Tribometer (mod. THT, CSM Instruments, Peseux, Switzerland). The core of the system is simply constituted by a rotating sample-disk (Aluminum Alloy 6061 sheet with a measured root-mean-square surface roughness of R_a=0.08 μm) in contact with the LST truncated spheres. The contact pair (disk and pin end) was immersed in a lubricant bath, whose temperature was constantly monitored during the tests. The adopted lubricant is a pure mineral oil (Oroil Therm 7 from Orlando Lubrificanti S.r.l., Argenta, Italy), with dynamic viscosity η=0.0516 Pa·s at 50°C.

We have measured the friction coefficient of the laser-textured surfaces and of a flat control surface according to the following test protocol. For each specimen, the measurement was carried out for 10 different values of the sliding velocity *U* of the disk, from 500 mm/s to 10 mm/s, starting from the fastest speed, where the lubrication regime was always of the hydrodynamic type, to the slower value. This practice was adopted to strongly minimize any possible surface wear, which indeed resulted always undetectable. Given the value of the sliding speed, it was kept constant during all the measurements, which were carried out as follows. First, the oil bath was preheated by rotating the disc at the maximum achievable speed of 1.2 m/s, under noncontact conditions, until a constant temperature of about 30°C was reached. Then, a normal load of 1 N was applied to the sphere holder by means of a calibrated weight, and during the first minute, the textured sphere was kept in noncontact conditions at a distance of about 500 μm from the rotating disc. Afterwards, the sphere was brought in contact with the disc, and the friction was measured by the instrument, maintaining stable friction conditions for no less than 120 s. In the final step, the sphere was again lifted up at a distance of 500 μm from the disc and

Table 1 Laser texturing parameters for each different geometry (fixed parameters: repetition rate=50 kHz; translation speed=20 mm/s; pulse duration=650 fs).

Texture geometry	Area density [%]	Average power [mW]	Number of concentric paths[a]	Number of loops
Square lattice of circular dimples (d~41 μm)[b]	0.21	60	3	7
Square lattice of circular dimples (d~188 μm)	0.26	40–50	15	9-12-15-20
Square lattice of elliptical dimples (major axis ~266 μm, minor axis ~128 μm)	0.25	50	10	10

[a] Hatch=6 μm.

[b] Full/partial (half surface) texturing.

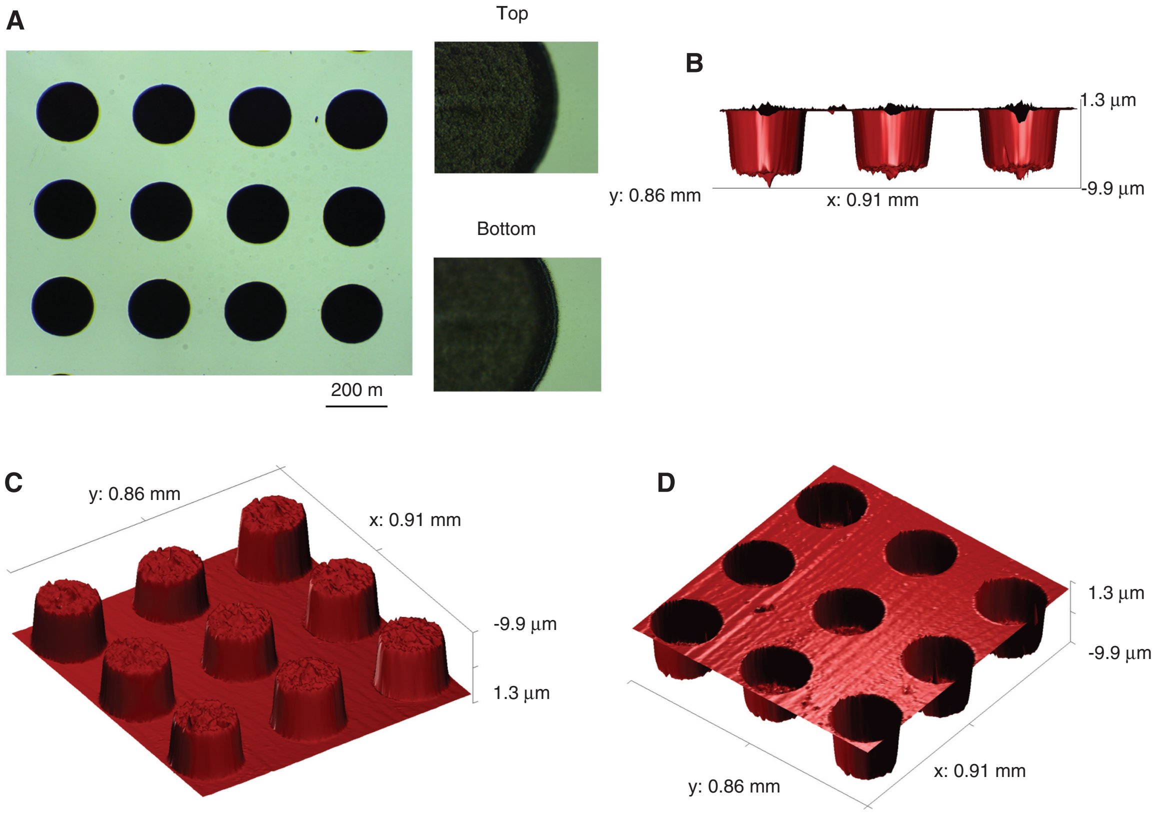

Figure 1 Confocal microscope image of a laser texture with a square lattice of circular dimples with a diameter d=188 μm and a depth h=7.2 μm: (A) top view; 3D reconstruction from the side (B); bottom (C) and top (D).

the hydrodynamic friction, that is, the resistance force due to the action of the oil bath on the holder, was measured. The coefficient of friction μ was derived by subtracting the values obtained during the two measurement steps. Each value of μ plotted on the Stribeck diagram of each specimen was obtained by averaging 10 consecutive measurements. For each set of data, a new contact pair sample and new lubricant were used. All the parts of the apparatus in direct contact with the lubricant have been washed with a copious amount of distilled water, followed by alternating use of isopropanol and acetone. Mobile parts have been also washed in an ultrasonic isopropanol bath.

4 Results and discussion

The friction coefficient values μ have been, first, measured in case of an untextured control surface and plotted as a function of the product of the temperature-corrected oil viscosity η and the sliding velocity U, in order to draw the so-called Stribeck curve. In Figure 2, the results obtained for the control surface are compared with fully (FT) and partially textured samples with circular dimple geometry (effective dimple diameter d=41 μm, depth h~11 μm). Two different sets of data are reported for the partially textured samples according to the orientation of the sample with respect to the sliding direction: microstructured part at the contact inlet (PT) or outlet (PT-R). In all the graphs, the hydrodynamic lubrication regime is clearly recognizable for values of the $\eta \cdot U$ parameter above 0.02 Pa·m. Here, the hydrodynamic pressure completely separates the sliding parts, allowing the formation of full-fluid-film lubrication.

Interestingly, because of the reduced load-carrying capacity of the PT-R surface, the corresponding friction is higher than that for the PT surface. However, even more important is that, if compared to the untextured surface, the partial texturing does not lead to a reduction of friction over the all range of sliding velocities considered in the experiment. The only exception is observed for the case of the PT surface, with a friction coefficient, which is slightly smaller than for the untextured case, only in hydrodynamic lubrication regime. This result is not consistent with previous works [24, 25] and proves that the increased load-carrying capacity of the PT case is not so effective in reducing friction compared to the FT surface, which presents excellent tribological properties with a remarkable reduction of the friction coefficient in the whole range explored, up to 85% than the untextured one

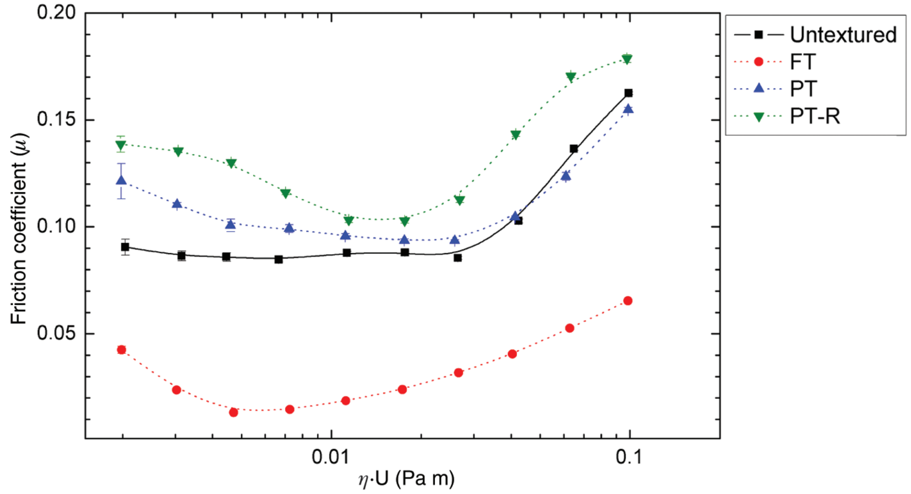

Figure 2 The coefficient of friction μ as a function of $\eta \cdot U$ for a flat control surface (solid black line) compared to a fully (FT) and a partially (50%) textured sample (PT). The LST design is a square lattice of circular microdimples with measured diameters d=40 µm and depths h~11 µm and an area density A[%]~0.21. In the PT curve, the lubricant flows entering by the textured zone while, in the PT-R case, from the opposite side.

(solid line). It can be argued that the friction reduction obtained for a fully textured surface has to be ascribed to a reduction of the shear stress at the microdimple location, where the oil film thickness is increased and equal to the dimple depth [10], rather than to an increase in load-carrying capacity.

Figure 3 shows the tribological behavior of LST surfaces characterized by a square lattice of circular dimples with measured diameters of about 188 µm and different depths ranging from 4.4 µm to 13.8 µm. The most significant friction reduction has been achieved for a dimple depth of 6.8 µm. Remarkably, the friction reduction extends over the entire explored range of sliding velocities, from the mixed lubrication to the hydrodynamic regime. For a shallower depth of 4.4 µm, the friction reduction is less pronounced and mostly confined in the hydrodynamic region. Thus, an optimal value of the dimple depth minimizing friction exists, over which the tribological performance of the LST surfaces gets worse. As shown in Figure 3, already for a depth of 8.4 µm, the advantages of the LST treatments are completely lost, and for deeper holes (h=13.8 µm), the friction coefficient is even significantly higher than the untextured. This result has been already observed for smaller dimple diameters in a previous work

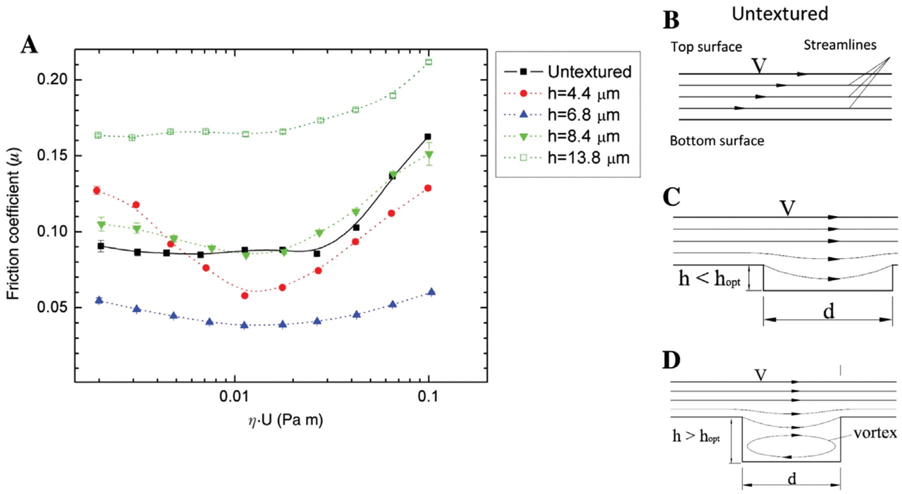

Figure 3 (A) The friction coefficient as a function of $\eta \cdot U$ for LST surfaces with a square lattice of circular microdimples with diameters d~188 µm and different depths h, compared to a flat control surface (solid black line). Fluid dynamics of the lubrication in the case of flat surfaces (B), textured surface with microdimple depths $h<h_{opt}$ (C) and $h>h_{opt}$ (D).

[19, 20]. To explain this unexpected behavior, a couple of arguments can be proposed, which are being tested numerically. The first one is also sketched in the insets of Figure 3. The local motion of the lubricant flowing on an untextured flat surface occurs with streamlines almost parallel to each other with parabolic velocity distribution leading to a wall shear stress, which is inversely proportional to the oil film thickness. If the lubricated surface is textured with an array of shallower dimples, the streamlines will result only as slightly curved and remain almost parallel to each other, but at the microdimple location, the oil film thickness increases due to the hole depth producing a local reduction of the shear stress. Such a reduction occurs on a significant portion of nominal contact area (in our case A[%]=0.26), thus, determining a decrease in the total friction force. Above a certain threshold value h_{opt}, the velocity of the streamlines at the bottom of the hole may experience an inversion causing the formation of eddies, which dissipate part of the energy. The macroscopic effect is an increase in the total friction force, as confirmed by our experiments.

The second possibility is related to the formation of vapor bubbles, i.e., microcavitation, within the microholes. This should explain the strong reduction of friction observed at the interface. However, the increase in friction, observed when the depth of the hole exceeds the optimal value, would imply that microcavitation disappears in such a circumstance. This, even more unexpected behavior, is one of the critical points worthy of being more deeply investigated in a future work.

In Figure 4, the results obtained by changing the dimple geometry from a circular profile to an elliptical silhouette are reported. The total contact area remained substantially unchanged between the two different geometries, with a dimple area density of 26% for the circular profile and 25% for the elliptical one. Similarly to previous results, also for the elliptical geometry, an optimal dimple depth of 6.2 μm was found, which minimizes friction. It is worth noting that this value is very close to the optimal depth found for the circular geometry. The behavior of the surface with elliptical dimples providing the best results in terms of friction reduction has been studied by

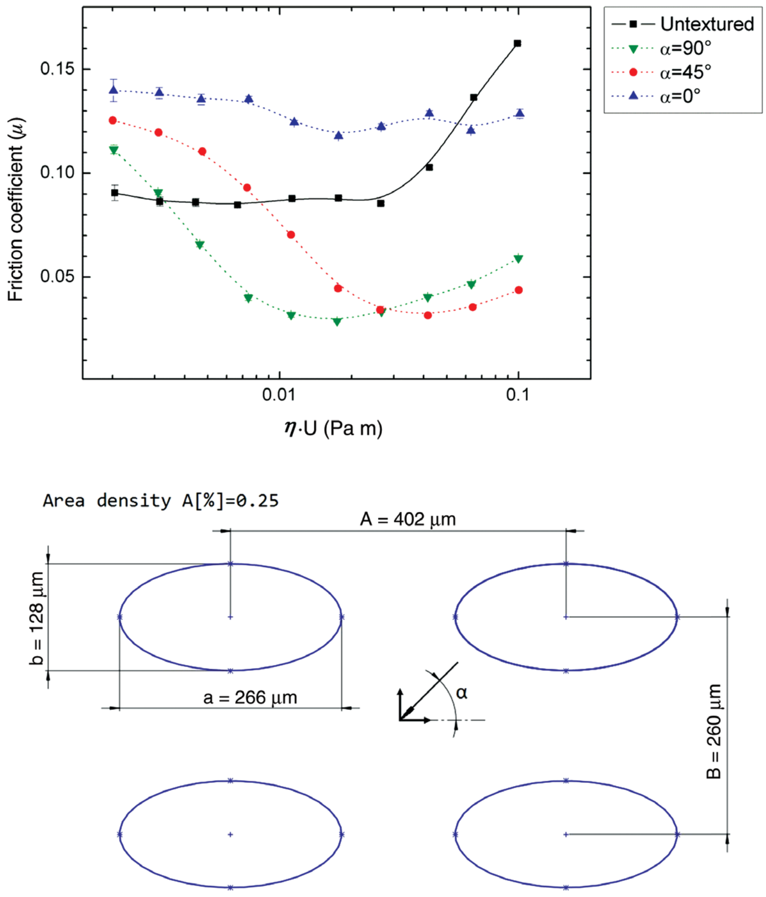

Figure 4 Tribological characterization of a LST sample with dimples of elliptical shape and depth h=6.2 μm, as a function of its angular orientation α with respect to the sliding velocity V.

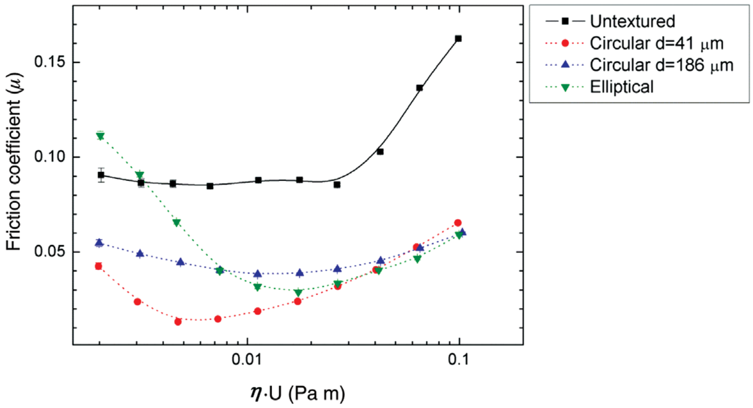

Figure 5 Stribeck diagram of LST samples with different texture geometries (● circular dimples with diameters d=41 μm, depth h~11 μm, areal density A[%]=0.21; ▲ circular dimples d=188 μm, h~6.8 μm, A[%]=0.26; ▼elliptical dimples: major axis a=266 μm, minor axis a=128 μm depth h~6.2 μm, areal density A[%]=0.26) compared to the flat control surface ■.

varying the inclination angle α of the major axis of the ellipses with respect to the sliding velocity direction. For very slow sliding speeds, close to the mixed lubrication regime, the microtextured surfaces exhibit a higher friction coefficient compared to the untextured, regardless of the ellipse orientation. For higher values of the $\eta \cdot U$ parameter, the most pronounced friction reduction was observed when the sliding direction is perpendicular to the major axis (α=90°) of the ellipses. At an inclination of α=45°, the friction reduction is comparable in absolute value, but it shifts toward higher speeds in the hydrodynamic regime, while the mixed lubrication extends over a wider range on the left of the Stribeck diagram. An analogous orientation effect with ellipse dimples perpendicular to the sliding direction showing the most significant friction reduction has been observed in [16]. A theoretical model has been also developed relating this behavior to the load-carrying capacity of the different textures and their orientation [13]. This can be very interesting for real-world applications because, in this case, it would be sufficient to change the orientation of the microstructured surface to adapt to different operating conditions. Indeed, by simply turning the lubricant flow direction, it would be possible to switch between different lubrication regimes. If the major axis of the elliptical texture is oriented along the sliding direction, an increase in the friction coefficient is rather obtained compared to the control surface.

We note that the results shown in Figure 4 suggest that the shape of the microhole may be as important as the area densities of the dimple and suggest that also microcavitation may be one of the key factors in determining friction reduction, as in the case of α=90°, microcavitation is expected to be more pronounced.

Figure 5 shows a comparison of all the best results, in terms of friction reduction, of the different microtexture geometries analyzed in this work. The greater benefit has been obtained for the smaller circular dimples (diameter d=41 μm and depth h~11 μm), although a significant improvement has been also achieved for larger dimples (d=188 μm and depth h=6.8 μm). Remarkably, if one compares the results of the two LST surfaces with circular dimples of different diameters (area density of 0.21 for d=41 μm and 0.26 for d=188 μm, respectively) and the tribological behavior of the elliptical dimple geometry (area density of 0.26) with an orientation perpendicular to the sliding direction, the friction reduction is very similar in the hydrodynamic region. However, employing the elliptical texture geometry reduces the useful range of the hydrodynamic lubrication regime, as the mixed lubrication regime starts at higher values of the $\eta \cdot U$ parameter.

5 Conclusions

We have exploited femtosecond laser ablation to fabricate LST steel samples with a high level of precision and accuracy of the ablated microfeatures. The textures consisted of a square lattice of micro-dimples of different depths, sizes, and shapes. Circular and elliptical profiles have been realized. According to the dimple size, the lattice spacing was adjusted in order to keep the same void ratio. Fully textured surfaces as well as samples with a partial texturing covering only half of their surface have been produced. The tribological behavior of the as-fabricated surfaces has been investigated by measuring their friction coefficient in sliding lubricated contact. The friction measurements have covered about two orders of magnitude of sliding velocity from the mixed lubrication to the hydrodynamic regime. The experimental characterization revealed that:

- up to 85% of friction reduction, compared to the untextured, can be achieved over a wide range of sliding velocities in case of a fully textured surface with a circular dimple geometry (d=41 μm, h~11 μm, A[%]=0.21);
- the partial texturing does not lead to a reduction of friction over the all range of sliding velocities considered in our experiments, except for the hydrodynamic region and only in case of microstructured part at the contact inlet;
- reversing the partially textured sample with respect to the sliding direction (microstructured part at the contact outlet), further enhances friction because of the reduced load-carrying capacity of the LST surface;
- an optimal depth exists, minimizing friction, whose value depends on the dimple diameter. For deeper holes, the friction coefficient of the LST surface may even become higher than the untextured due to the formation of eddy-like flows at the bottom of the dimples, which dissipate part of the energy;
- in the case of elliptical dimples, the ellipses' orientation with respect to the sliding direction strongly influences the tribological behavior. The best result in terms of friction reduction is obtained when the sliding direction is perpendicular to the major axis of the ellipses. By changing the inclination angle, the mixed lubrication regime extends over a wider range on the left of the Stribeck curve, and the hydrodynamic lubrication shifts toward higher speeds. When the ellipses are aligned with the sliding direction, the benefit of friction reduction is almost completely lost.
- an elliptical texture would allow to dynamically adapt the frictional properties of the LST surface by rotating the texture orientation with respect to the sliding direction.

Further experiments are planned to better ascertain the fluid-dynamic mechanism behind the tribological behavior of the partially textured as well as the elliptical dimple geometry LST surfaces.

On-going experiments, which are being carried out in strict collaboration with researchers of Centro Ricerche FIAT, aim to apply this technology to several mechanical components of a commercial car engine. A positive outcome of this research would significantly increase the engine efficiency, thus, resulting in a dramatic reduction of fuel consumption and exhaust emissions not only in road transport but also in several other application fields.

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