Original Article

Friction characterization when combining laser surface texturing and graphite-based lubricants

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\textbf{A B S T R A C T}

The present work analyzes the friction capabilities at room temperature of three types of lubricants (denoted as A, B and C) with a graphite concentration of 5%. To do that, the standard pin-on disc test is deployed to study the variation of the friction coefficient when combining these graphite-based lubricants with surfaces made by grinding and different laser surface textures. These lubricants are characterized by measuring the percent of the chemical elements, the average size of the graphite particles and the kinematic viscosity. The experiments show that the lubricant B combined with a higher density of LST presents the lowest friction coefficient of about 0.24. Additionally, assuming a hydrodynamic regime for the textured surfaces, the fluid dynamics simulations carried out as part of the study showed, in agreement with the experimental measurements, the lowest friction coefficient value for a textured surface with the highest dimple density. This seems to be associated to the combined effect of an increase of the hydrodynamic pressure with a weak vortex formation within the dimples, due to the low distortion of the streamlines which, ultimately, attenuates the friction coefficient between the surfaces.

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1. Introduction

Since the beginning of the 60s, laser technologies have been a hot-topic in the manufacturing field and much research have been published in different areas, such as cut-
and topologies by using different manufacturing technologies, e.g., polishing [10], laser [11,12], burnishing [13,14], among others, have been reported. According to Etsion [15], the Laser Surface Texture (LST) technology is the most used and versatile technique for surface treatment, since it allows create a wide range of textured surfaces with different dimple geometries in a shorted period of time.

Focusing on the laser technology to obtain textured surfaces with micro-dimples distributed along the surface of interest, different surface geometries combined with dimples were studied to determine the influence on the surface damaging, as reported by Sugar et al. [12]. In particular, three type of surface geometries, e.g., flat, parabolic and spherical, were performed to evaluate the quality of the texture in terms of its dimensions, shape and surface damage, observing that it is affected mainly by the metal projections and the class of the textured surface. Additionally, the size and morphology of the dimples have been found to decrease the friction coefficient up to a 15% during a ring test [16]. Furthermore, the initial surface grooves strategy (linear or zigzag) has an influence on the tribological capabilities, as reported by Xing et al. [17] when using a ball-on-disc test on textured surfaces performed with Nd YAG laser on a ceramic material. Consequently, they found that the textured surface with the lowest step size in a zigzag configuration showed the lowest wear rate, due to the small effective contact area which increases the debris entrainment. Similar experiments were carried out by Vlădescu et al. [18], although they utilized a wear equipment with reciprocating movement combined with lubricant. The studied sample presented parallel grooves with different dimensions, steps sizes and perpendicular dispositions to the machine movement. As a result, lowest wear value was achieved when the widest, deepest and biggest step size groove configuration was used. However, they concluded that the volume of the wear was the crucial parameter, as long as the contact area was not exceeded. Furthermore, Dunn et al. [19] stated that the static friction coefficient increases by using a specific LST, combining a pulsing wavelength of a laser fiber of 1064 nm with different frequency strategies. The results showed that the static friction increased almost 4 times compared with that of a non-textured surface. Furthermore, Yang et al. [20] also investigated different textures morphologies where the dimples presented a circle, triangular, square or rectangular shapes, all of them with an equivalent effective volume. These experiments proved that the lowest friction values were found when circular dimples were used. Besides the fluid dynamic simulation exhibited that also the greatest pressure was found for the surface texture with circular dimples. Other studies focused on the density of textured surfaces and the depth of the dimples. For example, Wan et al. [21] analyzed the friction coefficients and the wear capabilities of textured discs with plasma-sprayed Cr and evaluated them with pin-on-disc tests. Geiger et al. [22] analyzed the lifespan of textured punches coated with titanium nitride used to produce parts by cold reverse extrusion. In particular, the laser parameters were adjusted to obtain dimples of 10 μm diameter by 1 μm depth, avoiding in this way the perforation of the layer thickness of 2 μm of TiN. An increase in duration of 183% was found for the punches with a texture density of 20% compared with the base line (same punch without being textured). Besides, Schneider et al. [23] studied circular dimples with a small depth (h < 8 μm), texture densities of 5–30%, velocities between 0.04 and 2 m/s and different geometry patterns of the surface texture. They found that lower friction coefficients are addressed for a density of 10% with a hexagonal pattern distribution when using a temperature of 100°C and polyalpaholefin-base lubricant. Accordingly, computational methods were performed by Scaraggi et al. [24] with the objective to find the geometries and size of the dimples to reduce the vortex in the flow and, subsequently, to decrease the friction forces between surfaces. Bijani et al. [25] performed another simulation study to analyze the film thickness of lubricant in four different dimples geometries (depth of 5 μm), several velocities within 0.15 and 0.75 m/s and textured surface densities between 12 and 40%. They stated that for low velocities, both the volume of the cavity and the thickness of the film increase and, consequently, the friction coefficients decrease.

Following the aforementioned research lines, the present work focuses on the study of the friction behavior while subjecting samples to the pin-on-disc test at room temperature with different surface texture configurations combined with three graphite-based lubricants diluted in water up to 5%. To this end, the surface topographies, chemical composition, particle size and rheological behavior of the lubricants are all characterized. Keeping into consideration the review of Groppe et al. [26], experimental and numerical analyses are carried out to investigate the friction coefficient according to the forging conditions, the lubricant characteristics and the type of surface texture. In this sense, it can be stated which configuration presents better friction capabilities and, consequently, ensures a longer lifespan of the forging tools by reducing the wear and fatigue failure. Finally, a numerical simulation approach with the finite element method is performed qualitatively to validate the experimental results and, also, to define the film thickness and hydrodynamic pressure when studying different LSTs.

2. Methodology

The methodology of this work was divided in four subsections: properties of the graphite-based lubricants, LST characterization, pin-on disk test at room temperature and numerical approach of the lubricant behavior. This section describes the protocols, devices and facilities utilized to investigate the friction capabilities of this kind of lubricants at different LSTs.

2.1. Properties of the graphite-based lubricants

Three different lubricants were used in the present work, i.e., lubricant A, B and C all with a graphite concentration of about 5%. This concentration of graphite is commonly used in warm and hot forging processes in Argentine forging companies that cooperate with INTI. The three lubricants had the graphite suspension in water as a dilute and the density was within the range of 1.10 g/cm³ and 1.20 g/cm³, similar to the value reported in a previous study [27]. In order to characterize the three lubricants and describe their main differences, the analysis encompasses their chemical composition, the
size of the graphite particles and the rheological properties. A scanning electron microscope (FEI model: QUANTA 250 FEG, FEI) was utilized to measure the particle size embedded in the matrix for each lubricant. Also, the rheological properties were assessed with an oscillatory mode rheometer (Anton Paar Physica model: MCR301) for each lubricant to estimate the effective viscosity. Fig. 1 exhibits the viscosity of each lubricant at room temperature of about 5% of graphite diluted in water.

Additionally, a scanning electron microscope (Philips SEM 505, Philips) equipped with the energy-dispersive X-ray spectroscopy module (UTW-Sapphire, model: PV7760/79 ME) was used to study the chemical composition of the three graphite-based lubricants. In particular, a standardless quantification analysis was deployed for the quantitative results for the X-ray spectra. Accordingly, Table 1 quantifies the average grain size and the percent of weight of the chemical composition of each element.

2.2. Laser surface texture characterization

The textured surface was performed by using a fiber laser (Han’s laser model: YLP-H2O) which emits a wavelength of 1064 nm with a maximum average power of 20 W, where the repetition frequency was adjustable from 20 to 200 kHz. The laser beam was focused onto the surface using a 100 mm focusing lens. The topography of the semispherical dimples assessed had 70 μm of diameter and 40 μm of depth with the laser configuration mentioned above. A hexagonal laser texture pattern was used according to a biomimetic concept with the Dung beetle [28]. Besides, three different textured surface densities were carried out: 11%, 31% and 50%, in order to analyze the corresponding friction coefficients in terms of the respective contact effective areas. According to Schneider et al. [23], and Scaraggi et al. [24], common values of textured surface densities are within 5–40%. In this work, we decided to use two intermediate and one extreme values of textured densi-
Table 1 – Percent of the chemical elements and the average size of the graphite embedded.

<table>
<thead>
<tr>
<th>Lubricant</th>
<th>C (%)</th>
<th>O (%)</th>
<th>Na (%)</th>
<th>Al (%)</th>
<th>Si (%)</th>
<th>Graphite size (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lub A</td>
<td>71.94</td>
<td>17.58</td>
<td>2.67</td>
<td>0.20</td>
<td>7.59</td>
<td>10.55 ± 4.21</td>
</tr>
<tr>
<td>Lub B</td>
<td>75.88</td>
<td>15.09</td>
<td>2.15</td>
<td>0.64</td>
<td>6.59</td>
<td>1.93 ± 0.99</td>
</tr>
<tr>
<td>Lub C</td>
<td>78.82</td>
<td>14.29</td>
<td>1.47</td>
<td>0.30</td>
<td>4.76</td>
<td>8.30 ± 4.12</td>
</tr>
</tbody>
</table>

Table 2 – Surface roughness metrics (Rt and Sm) of the specimens tested during the pin-on disc test.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parallel to grinding direction</th>
<th>Perpendicular to grinding direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rt (μm)</td>
<td>5.40 ± 1.76</td>
<td>6.56 ± 0.64</td>
</tr>
<tr>
<td>Sm (μm)</td>
<td>20.60 ± 3.21</td>
<td>17.60 ± 1.34</td>
</tr>
</tbody>
</table>

performed in 9 discs that were previously rectified with a small abrasive tool. The surface textures were assessed in both faces of the disc, so a total of 18 textured surfaces were disposed. The force during the pin-on disc test was recorded with a data logger (Vernier, model LabQuest) with a load range of 50 N. Besides, the rotational plate was connected to a servomotor which allows to vary the rotation speed within the range of 10–1000 rpm. The surface roughness of the specimens was measured with a portable profilometer (Taylor Hobson, model: Surtronic 3+). Table 2 shows the maximum peak-valley surface roughness (Rt) and the mean spacing between profile peaks at the mean line (Sm) of the initial grinded surfaces. The roughness measurements were set with a cut-off and evaluation lengths of 0.8 mm and 4 mm, respectively.

Later, the disc and the pins were allocated in the pin-on disc machine to run the experiment. Subsequently, the diluted graphite-based lubricant was constantly added on the disc verifying the proper dispersion of the lubricant all over the specimen before running the test. The applied load of the tip over the disc was set at 6.5 N and the tangential velocity at the contact region of the tip and disc was 0.2 m/s (~100 rpm). These applied force and the tangential velocity come from previous simulation works to mimic the forging pressure and displacement velocities [29]. The pin-on disc test took about 20 min to ensure that only the stationary scenario of the friction coefficient, found after 10 min, was recorded. Finally, a total of 36 experiments were performed: firstly, 18 experiments were done using the grinded surface (base-line), 3 types of graphite-based lubricants and 6 repetitions per combination. Then, 18 experiments were performed to investigate the friction capabilities of 3 different texture densities and 6 repetitions per configuration using one graphite-based lubricant (the one for which the best performance was achieved from the previous analysis). A schematic illustration of the combination of different graphite-based lubricants and density of textured surfaces investigated in an in-house tribometer (pin-on disc test) manufactured at the INTI-Mechanics Center in Argentina is shown in Fig. 3.

2.4. Numerical approach

To qualitatively assess the influence of the dimple density on the friction coefficient, a 2D numerical simulation of the fluid dynamics response of the lubricant in a film (or channel) mimicking an idealized pin-on disc test was carried out. Cavitation phenomenon was not considered in this approach, due to its complexity and the lack of experimental validation. To this end, the steady-state Navier–Stokes equations of an incompressible laminar flow considering a strain-rate viscosity were solved in the context of the finite element method [30]. Thus, the friction coefficient $\mu$ can be estimated according to the Petroff approach as:

$$\mu = \frac{F_f}{F_s}$$  \hspace{1cm} (1)

where $F_f$ is the tangential viscous force and $F_s$ is the normal pressure force, both per unit length at the upper wall of the channel. These forces can be computed as:

$$F_f = \int_L \frac{\partial u}{\partial y} \, dx$$  \hspace{1cm} (2a)

$$F_s = \int_L p \, dx$$  \hspace{1cm} (2b)

where $\partial u/\partial y$ is the dynamic viscosity, $L$ is the length of the channel wall along the horizontal coordinate $x$, $u(x)$ is the sliding velocity, $p(x)$ is the pressure and $y$ is the vertical coordinate normal to the channel wall (note that for constant $\partial u/\partial y$ and $p$, the classical expression $\mu = \partial u/hp$ is recovered, where $h$ is the film height).

3. Results

The results of the present work are divided in two subsections: experimental measurements and numerical predictions obtained via simulation. Firstly, the friction coefficient is study with the pin-on disc test at room temperature to compare the tribology capabilities of the three graphite-based lubricants and textured surfaces. Later, a numerical approach is carried out to predict the lubricant distribution depending on the lubricant viscosity, shear rate and percentage of surface density.

3.1. Friction coefficient at room temperature

Friction coefficients are studied on the grinded surfaces by using the three lubricants in a pin-on disc test. Accordingly, Fig. 4a shows the trend of the friction coefficients during the duration (20 min) of pin-on disc test for surfaces respectively. While, Fig. 4b present the corresponding box plots of both surfaces tested with the three lubricants at the stationary phase of the pin-on disc test (~10 min).

Lubricant B exhibits the lower friction coefficient of about 0.43, while the friction coefficients for lubricant A and C are close to 0.45. These differences seem to be attributed to the viscosity and grain size of the graphite embedded in the matrix.
of the lubricant, which may affect the cavitation effect and, therefore, change the pressures between surfaces. Lubricant B presents the lowest viscosity and the graphite are about 4.0 times smaller in average than that of the other two lubricants, as we denoted in our previous experiments [31]. The smaller size of the particles of graphite favors the formation of a continuous and effective film thickness at the interfaces [32] and facilitates the filling of the dimples of the textured surfaces, helping to ensure continuity in the lubricant layer between surfaces in starved conditions [25]. Fig. 5 shows SEM images that were taken before and after the pin-on disc to analyze the interaction of the dimples and the graphite embedded in the lubricant.

As a consequence of these filled dimples, the cavitation will be affected and, consequently, the pressure build-up within the dimple will modified the friction coefficient [26]. In order to analyze the lubricant capabilities in different textured surfaces, additional pin-on disc tests were performed using only lubricant B (which showed the lowest friction performance) in three different LST densities of 11%, 31% and 50% and compared with respect to the grinded surface. Consequently, Fig. 6 shows the friction coefficient trends and the associated box plots at the stationary phase.

The LST with higher density presents lower values of friction coefficient, the average values are 0.34, 0.30 and 0.24 for textured surface with densities of 11%, 31% and 50%, respec-
ments performed in the previous sections were carried out with a tangential velocity of 0.2 m/s, which was the best friction scenario based on the Strieber curves. According to the literature [33], for a tangential velocity of 0.2 m/s, axial force of 6.5 N and low viscosity lubricant, the regime of the lubricant for the grinded surface (base-line) is at the frontier between the mixed and hydrodynamic lubrications, which is also called the elasto-hydrodynamic lubrication [31]. Whereas, the textured surface is allocated in the hydrodynamic lubrication for the same aforementioned conditions used during the pin-on-disc tests. As the interest is to investigate the friction coefficient and the film thickness for different LST, as thoroughly studied by Etsion and coworkers [15,34], it is expected that for LST the Strieber curve moves to the left and, consequently, a hydrodynamic lubrication is more likely to be found for the three textured surface conditions. In addition, based on the axial force and the sliding speed configuration used in the present work for a high textured surface density, a hydrodynamic lubrication can be also assumed by looking at the results presented by Kovalchenko et al. [33]. Accordingly, the numerical simulation is performed with a hydrodynamic lubrication regime to describe the film thickness, relative pressure of the lubricant at the dimples and the vortex formation in the center of the dimples. Then, the friction coefficient for textured surfaces with low and high density of dimples will be estimated to validate the experimental results recorded with the pin-on-disc test with a tangential velocity of 0.2 m/s.

3.2. Numerical analysis of lubricant B in two laser textured surfaces (11% and 50%)

Due to the simple assumptions commented in Section 2.4, the numerical simulation carried out in this work is aimed at only comparatively describe the fluid dynamics response of the lubricant in the film between the cases analyzed. In this context, the numerical simulation is focused on the fluid dynamics responses of lubricant B with LST densities of dimples of 11% and 50%, both in a 560 µm film length; see Fig. 8. The dimples are 40 µm depth and have a diameter of 70 µm. The film thickness of case 11% was chosen as 10 µm [20] while the film thickness of case 50% was computed in order to
obtain, as in the pin-on-disc experiment, the same normal pressure force as that of case 11% although the pressure distribution is, as can be appreciated in Fig. 9, different in both cases. Thus, the resulting film thickness of case TSS50% was 15 μm. The strain-rate dependent viscosity was considered according to the relationship shown in Fig. 1. A linear (along the film height) inlet velocity profile was assumed with a sliding velocity of 0.2 m/s. A zero reference pressure value was imposed at the upper outlet corner of the channel. The dimensionless pressure and streamline contours for cases 11% and 50% are plotted in Fig. 8. Although these variables present similar patterns, the normal velocity gradients and consequently the tangential viscous forces differ for both cases due to their different film heights (in these cases, note that the vortex formation does not practically affect the main stream flow along the film). From these results, the ratio between the friction coefficients (computed with Eqs. (1) and (2) from the results of the numerical simulation) of cases 50% and 11% is 0.70, value that agrees well with the corresponding average experimental ratio 0.24/0.34 (see Fig. 6b). Moreover, as expected, the curve corresponding to the grinded case (i.e., texture density of 0%) is linear. The straight line added in Fig. 9 was also obtained under the condition to obtain the same normal pressure force as those of cases 11% and 50% of LST. The resulting film thickness of the grinded case was 8 μm. Once again, the ratio between the friction coefficients of cases 11% of LST and grinded condition is 0.80, value that agrees well with the corresponding average experimental ratio 0.35/0.43 (see Fig. 6b).

The experiments showed that higher LST densities present lower friction coefficient, while the numerical analysis has brought out that the decrease of the friction coefficient can be associated to a higher hydrodynamic pressure and the formation of vortex of lower magnitude in the dimples. The reason of the magnitude attenuation in higher textured surface density is because the dimples are close between each other, which favor a lower distortion of the streamlines and, ultimately, reduces the friction coefficient. The results found in the present work present some differences with the friction results reported in Refs. [23] and [25]. Here, higher densities of textured surfaces (50%) with deeper dimples (40 μm) combined with a graphite-based lubricant have shown better friction capabilities, whereas the aforementioned works stated that this desirable condition is achieved with low densities of textured surfaces (10–12%) with shallow dimples (2–8 μm) combined with a different type of lubricant. Then, four major differences can be identified as responsible for these differences: type of lubricant, depth of dimples, contact pressure (although the initial value is only considered here, the wear of the pin will modify that value) and the temperature of the process. In the present study, our aim was to analyze deeper dimples and graphite-based lubricants, because it is expected to use this LST technology in hot-forging dies and components to enhance their lifespan. In short, as a smaller friction coefficient was found for LSTs of high density with respect to a grinded surface, this can be attributed to several aspects: firstly, a larger number of dimples induce a larger film thickness, as reported by Tala-Ighil et al. [6] and Cong and Konshari [7], but also it could also be related to a lower distortion of the streamline due to the proximity of the dimples leading, subsequently, to a less intense vortex formation.

4. Conclusions

The present work successfully evaluates the friction characterization of three different graphite-based lubricants diluted in water up to 5% concentration at room temperature on various types of textured surfaces. Therefore, the following aspects can be summarized from this research work:

- The laser texturing was performed in a material surface with a maximum height of the roughness profile of 5.98 ± 1.76 μm. A decrease of the friction coefficient up to 0.24 (a decrease of 41.6% with respect to the grinded surface) was found when higher density of textured surface is combined with lubricant B (graphite size of 1.93 ± 0.99 μm and an effective viscosity of 25 mPa.s for the tested conditions).
- The low viscosity, the size of the graphite embedded in the lubricant and the density of the LST have been crucial parameters to affect the friction coefficient. Smaller size of the particles of graphite facilitates the filling of the dimples of the textured surfaces, helping to ensure continuity in the lubricant layer between surfaces in starved conditions. Besides, the higher filled dimples with graphite
particles seems to affect the cavitation effect increasing the pressure build-up and, consequently, decrease the friction coefficient.

- Thanks to the experiments we have identified the lubrication regime for our operating conditions that was found to behave in the hydrodynamic lubrication regime for the textured surfaces. The numerical simulation exhibits that a higher LST density has validated the decrease of the friction coefficient found in the experimental trials. This is attributed to the formation of vortex in the dimples, where lower magnitudes of vortices are found when the dimples are close between each other (higher textured surface density scenario) and, consequently, a lower distortion of the streamlines that reduces the friction coefficient.

In future work, this kind of textured surfaces will be implemented in a forging matrix to study the wear evolution compared with a non-treated surface lubricated at warm and hot forging processes. The combination of graphite-based lubricants and textured surfaces with deep dimples have showed a significant decrease of the friction coefficients as the textured surface density increases. This application presents a huge potential in forging matrices and components, since deep dimples are required to avoid that the textured surface disappear in the first forging blow. In this sense, lifespan and friction coefficient can be analyzed in a real industry scenario with complex geometries.

**Conflict of interest**

I would like to mention that there are no other author's professional and/or financial affiliations that may have biased this research work.

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