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Tribological Analysis of Laser-Textured WC-Co Against Ti6Al4V Under Dry and Lubricated Conditions for Different Sliding Times

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Abstract: Machining titanium alloys, particularly Ti6Al4V, pose significant challenges in manufacturing engineering. The combination of high strength and low thermal conductivity makes Ti6Al4V a particularly difficult material to machine. One of these difficulties is the rapid wear and short tool life of cutting tools, which substantially increases manufacturing costs. To address this issue, the texturing of cutting tools, especially using laser-based techniques, has garnered significant attention due to its potential to enhance the tribological performance of textured surfaces. In this paper, by means of a groove design applied to a tungsten carbide (WC) disc by laser surface texturing (LST), its behavior and wear have been evaluated after subjecting it to tribological pin-on-flat tests by confronting it with Ti6Al4V pins with different reciprocating times (250 s, 500 s, 750 s and 1000 s) in lubricated and dry conditions. In addition, these same tests have been replicated without textures for comparison. Through conducting this research, we expect to gain new insights into texturing processes and their influence on friction and sliding behavior under lubricated conditions. Additionally, the study aims to evaluate how lubricant retention capacity varies to reduce friction and wear across different testing durations. The results show better behavior with textures, reaching a higher rate of volume loss in the titanium pins. The main conclusions obtained after these tests are that textures offer a better performance in tests up to 800 s. In addition, after this time, the lubricant begins to lose its properties, becoming an abrasive paste.

Keywords: WC-Co; laser texturing; lubricant; reciprocating; wear

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1. Introduction

Ti6Al4V, renowned for its exceptional strength, lightweight nature, and superior resistance to corrosion, is among the most extensively utilized titanium alloys. These characteristics make it a preferred choice in aerospace, medical, and advanced engineering applications, particularly in scenarios requiring a high strength-to-weight ratio and excellent fatigue resistance.

The machining of titanium alloys, such as Ti6Al4V, presents a significant challenge in manufacturing engineering due to the properties and characteristics of these materials. Also, their high strength, low thermal conductivity, and high chemical reactivity make the machining process difficult. The main challenge in forming these materials is the high wear and short life cycle of cutting tools, which leads to increased manufacturing costs and compromises the surface quality of the fabricated parts. These operations require cutting tools with superior hardness, high thermal conductivity, and a high Young's modulus [1]. Commonly used materials for such tools include tungsten carbides, both coated and uncoated, predominantly tungsten carbide (WC-Co) with cobalt compositions ranging from 6% to 12% [2].

During machining, the cutting tool applies high compressive pressures, inducing a shearing mechanism that produces serrated chips (see Figure 1). These chips flow over the rake face of the cutting tool, causing intense friction and generating additional heat beyond that produced during the shearing process. Due to the low thermal conductivity of Ti6Al4V, it is estimated that up to 80% of the generated heat is transferred to the cutting tool [3].

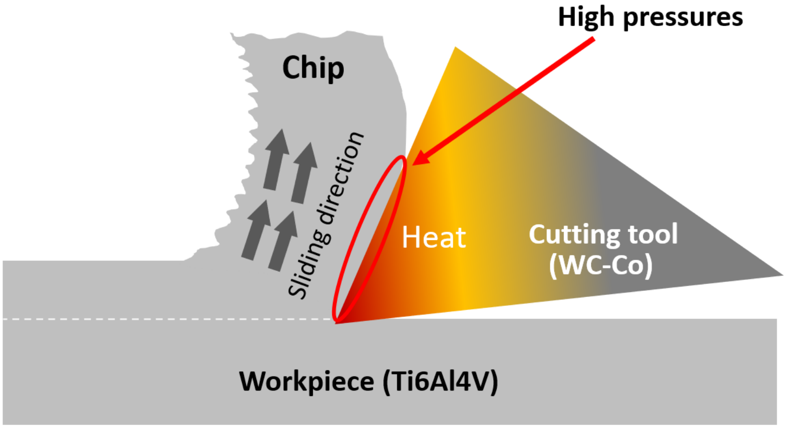

Figure 1. High compressive pressure during machining.

Tool life is a critical factor in the machining of titanium alloys due to these challenges posed by elevated cutting temperatures, intense dynamic loads, and substantial mechanical pressures [4]. Various approaches have been devised to enhance the efficiency of manufacturing processes based on machining operations. Specifically, these include the development of novel cutting tool materials and designs, the optimization of cutting parameters tailored to the tools in use, and the implementation of advanced cooling techniques [5].

The performance of machining Ti6Al4V has improved over time by using chip-breaker geometries on the rake face of cutting-tools, which reduce contact length and decrease contact area [6].

Another method commonly used for machining titanium alloys is the application of coatings. Coated tungsten carbide tools (WC or WC/Co) use a special surface treatment that consists of manufacturing wear resistant coatings by physical vapor deposition PVD or chemical vapor deposition CVD methods [7]. These exhibit superior performance compared to their uncoated counterparts, offering reduced tool wear, smoother machined surfaces, extended tool life, and lower friction [2]. The application of cutting fluids (coolants and lubricants) is also widely employed, primarily to dissipate heat and minimize friction. But one of the most recent techniques, which is also more sustainable, is the use of cryogenic cooling [8].

A sustainable technique that has recently been utilized for machining titanium alloys is the application of laser-induced micro-textures. These textures are applied to the rake face of the cutting tool [9]. Surface texturing refers to the process of altering the surface of a cutting tool through the selective removal of material to generate structures of varying scales and geometries, such as dots, grooves, or dimples.

At present, the laser surface treatment of materials is widely utilized and represents one of the most advanced and effective technologies [10–13]. The properties of laser radiation allow for a range of precise technological operations on various materials, offering efficiency and accuracy that significantly surpass traditional methods. Laser treatment is distinguished by its non-contact nature, selectivity, and the potential for full automation [7]. Furthermore, they are established as a sustainable alternative to the excessive use of cutting fluids, serving as an optimal complement to sustainable lubrication and cooling techniques, such as micro-lubrication or Minimum Quantity Lubrication (MQL). However, this technique is still the subject of research at the industrial level, paving the way for tribological research on textured cutting tools and their tribological characterization, as well as facilitating the generation of surface texturing through the development and use of parameterized systems.

Several investigations demonstrate that texturing the tool on its rake face results in a reduction in the contact area and adhesion. Moreover, it ensures adequate lubrication compared to non-textured cutting tools [14]. According to [15], textured cutting tools significantly reduced cutting temperature, flank wear, rake wear, and surface roughness by as much as 21%, 37%, 15%, and 13%, respectively [15], when compared to non-textured tools under MQL conditions. The integration of MQL with textured cutting tools led to a considerable reduction in surface roughness by ensuring a continuous coolant flow through the micro-grooves, thereby promoting a more consistent cutting process. Also, textured cutting tools can modify chip flow behavior, transforming it from a segmented pattern to a more uniform and stable flow, similar to laminar chip flow, by minimizing friction at the tool–chip interface [16,17].

For the Ti6Al4V alloy, textured cutting tools have demonstrated a decrease in cutting force (up to 30%) and power consumption (up to 20%) during machining under lubricated conditions, attributed to the previously mentioned reduction in the chip–tool contact area [18].

Tribological testing across varying reciprocating times demonstrates that the benefits of surface textures are sustained during short-to-medium durations but may diminish with prolonged operation. This reduction in performance is attributed to the gradual degradation of the textured features due to wear and mechanical deformation. These findings underscore the necessity for optimizing the texture geometry and distribution to balance initial performance with long-term durability.

Therefore, laser surface texturing (LST) has emerged as a transformative technique for enhancing the tribological properties of tungsten carbide (WC) substrates, particularly under conditions involving reciprocating motion. By introducing micro- and nano-scale textures, LST effectively reduces friction and wear through mechanisms such as improved lubrication retention and reduced contact area. These textures, often in the form of dimples or grooves, enable the development of hydrodynamic lubrication, especially under dynamic operational conditions, significantly enhancing the tribological response [19].

This work examines the effects of groove spacings textures on the tribological behavior of the Ti6Al4V/WC-Co pair. Laser surface texturing is used to create specific topographies and sliding tribological tests with four different reciprocating time values (250 s, 500 s, 750 s and 1000 s) are performed and compared with non-textured surfaces. These experiments were conducted in dry and under lubricated conditions.

The present study hypothesizes that surface texturing and the combined effect of lubrication significantly influence tribological performance in a reciprocating sliding system. By varying sliding times, the interaction between WC surfaces and Ti6Al4V pins is expected to exhibit distinct wear and friction behaviors. It is anticipated that texturing will enhance lubricant retention, reducing wear rates and friction coefficients, particularly under longer reciprocating cycles. This hypothesis aims to establish a correlation between surface modifications, lubrication mechanisms, and their combined impact on the tribological outcomes.

2. Materials and Methods

A specific experimental methodology was designed and developed to investigate the influence of texture design on the wear behavior of laser-treated WC-Co substrates under increasing sliding durations. This methodology integrates precise laser-texturing processes to create controlled surface patterns, followed by a systematic evaluation of wear performance using standardized tribological testing setups. Key parameters, including sliding duration, lubrication conditions, and texture geometry, were carefully varied to ensure a comprehensive analysis of their effects on wear mechanisms. The approach was tailored to isolate the impact of surface texturing while maintaining consistent material and environmental conditions throughout the study.

2.1. Material

The tribological pair employed in this study consisted of a tungsten carbide as disk and titanium Ti6Al4V alloy as pins, both from the manufacturer Kendu (Kendu, Segura, Spain). This configuration has been designed this way because it best simulates the behavior of Ti6Al4V chips as they flow along the rake face of the WC-Co tool. Additionally, in accordance with the setup of "pin-on-flat" tests, the disc with the test surface facing upward and the pin made of Ti6Al4V in this case with its test surface facing downward, replicates the positioning of both components during the machining operation. Additionally, this approach allows for texturing a larger surface area on the WC-Co.

Flat WC-Co specimens, with 2 mm in thickness, were extracted from a cylindrical cutting-tool shank with a diameter of 32 mm. Ti6Al4V samples, whose composition is detailed in Table 1, were prepared from a 4 mm diameter bar, with an initial length set at 10 mm. To prevent the introduction of residual stress or microstructural alterations, the specimens were cut using an ONA AF25 (ONA Electroerosion, Vizcaya, Spain) Wire Electro-Discharge Machining (WEDM). Each specimen was polished using a Struers TegraSystem metallographic machine (Struers, Copenhague, Denmark) to ensure a surface roughness not exceeding Ra $\leq$ 0.1 µm and Rz $\leq$ 0.2 µm.

Table 1. Ti6Al4V composition (wt%).

Al	V	Fe	C	O	N	H	Ti
6.26	3.91	0.18	0.011	<0.10	<0.10	<0.10	Rest

2.2. Laser Texturing Parameters

WC-Co specimens were textured using a femtosecond infrared laser LS-MARKPRO SC-IR 21002 (Lasing, Madrid, Spain) with a pulse duration of 354 fs, a spot diameter of 25 µm and a wavelength of λ = 1030 nm. A circular internal area with a diameter of 28 mm was etched and subsequently filled with parallel lines spaced 0.1 mm apart. These parallel lines textures or grooves show good performance, as studies such as the one conducted by Hu et al. [20] analyzed how continuous grooved textures can provide effective channels for lubricant distribution, potentially improving load carrying capacity and reducing friction under certain conditions. The study suggested that grooved textures may be more effective in applications where continuous lubricant flow is essential. Additionally, another specimen was left untextured. The textured specimen was subjected to this with an orientation of 90° with respect to the sliding direction. The laser parameters used in this study were those that allow us to obtain grooves with a depth of 15 µm, and width of 45 µm (Table 2), from previous tests in which different combinations of frequency and power were employed.

Table 2. Laser parameters.

Laser power	50 W
Frequency	2 MHz
Scanning speed	200 mm/s
Pulse energy	25 µJ
Energy density	5.09 J/cm^2

To ensure that the laser treatment has not induced thermal treatment on the textured surface, microhardness has been evaluated in irradiated areas, comparing it with the nominal value of the non-textured surface. In this way, Vickers microhardness tests have been carried out on untextured and textured surfaces. The measurements were performed with a Shimadzu HMV microhardness measuring instrument (Shimadzu Scientific Instruments, Kyoto, Japan). For the textured surface, measurements were taken at the top of the grooves (see Figure 2), since the distance between grooves was very small (0.1 mm) and the geometry of the probe was in contact with the grooves.

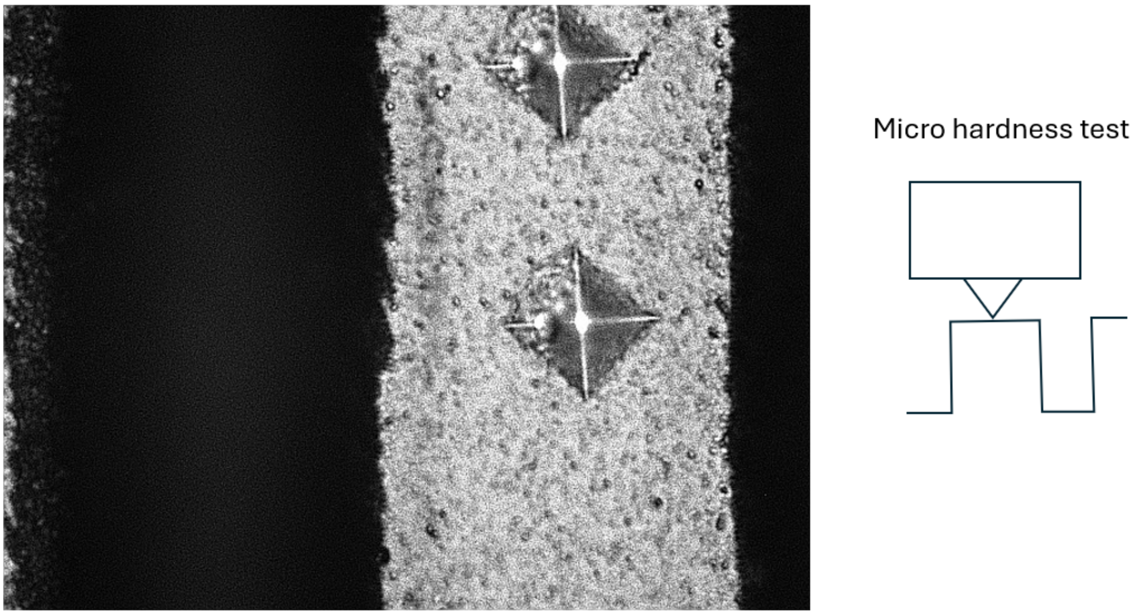

Figure 2. Microhardness test on textured surface at the top of the grooves.

For the non-textured surface, a hardness of 1685 HV0.5 ± 9.19 was obtained. On the other hand, a hardness of 1683 HV0.5 ± 7.12 was obtained for the textured surface. Then, it can be ensured that no thermal treatment has been applied.

2.3. Tribology Tests

Due to its similarity to the machining process geometry, where a constant chip section slides over the rake face of the cutting tools, the type of tribological test employed was pin-on-flat reciprocating. The equipment used for this was an MFT-5000 multi-function tribometer (Rtec Instruments, San Jose, CA, USA), using WC-Co as surface tested and Ti6Al4V as pins. For this case, linear wear tests have been carried out, applying a constant force and frequency, using the sliding time as a variable.

To perform each test, the Z-axis is lowered until the normal load is reached; then, the movement of the platform carrying the disk begins, while the pin is static. The load cell is synchronized with the Z-axis to keep the load constant during the entire time the pin is sliding.

For the wear tests, a linear stroke of 10 mm and a frequency of 10 Hz were applied to both the textured and non-textured specimens, resulting in four test durations for each: 250 s, 500 s, 750 s, and 1000 s (Figure 3). These sliding parameters were selected based on our own previous studies, some of which have been published as dissertation works. After performing different tests and trials for other experiments being carried out by the research group, some of which have been published as dissertation work, it has been observed that with them high-quality textures are obtained with the femtosecond laser. The selected time intervals were chosen because tool manufacturers generally guarantee a service life of 15 min (900 s). For this purpose, three repeated experiments were carried out for each test. This approach enables testing under conditions that closely resemble real-world industrial scenarios, starting with shorter test durations. In all cases, a normal load of 50 N was applied. The normal load (FN) and the coefficient of friction (CoF) were monitored and recorded during the tests at an acquisition rate of 1000 Hz, with data averaging every 10 samples.

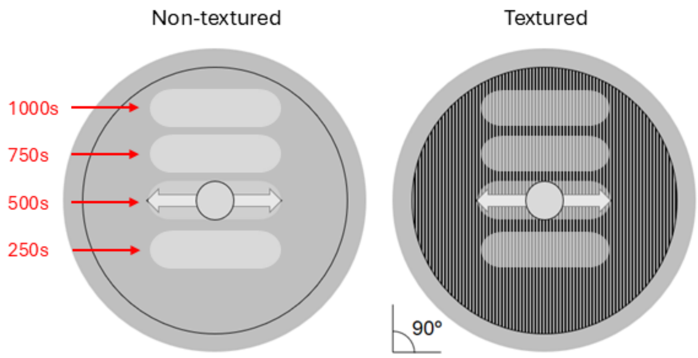

Figure 3. Tested surfaces (non-textured and textured with an orientation of 90°) with 250 s, 500 s, 750 s, and 1000 s reciprocating cycle.

These parameters were assessed in both dry and lubricated environments. For the lubricated tests, performed under a boundary lubrication regime, 0.5 mL of Accu-Lube LB-5000 was applied prior to testing. This quantity of lubricant has been chosen because these are drop tests and not tests with a constant flow of lubricant. The environmental impact of the current machining processes forces more and more researchers to use MQL systems or directly dry systems in an approach to so-called "Green Machining" or eco-efficient machining, an aspect of great relevance in a society that is becoming increasingly concerned about the need for the rational use of resources and the protection of the environment. This micro-lubricant used, derived from natural oils, is specifically designed for light to medium-duty machining of non-ferrous materials and is commonly employed in the aerospace industry for processing Ti6Al4V components.

2.4. Wear Analysis

The wear morphology of the samples was initially inspected using a stereoscopic optical microscope (SOM) model S9i (Leica, Wetzlar, Germany). For a more in-depth analysis of the wear tracks on WC-10%Co specimens, a focus variation microscope (FVM), specifically the Alicona Infinite Focus G5+ (Bruker, Billerica, MA, USA), was employed. Additionally, the 3D surface reconstruction and evaluation were carried out using MountainsMap v7.4 software (Digital Surf, Besançon, France). These analyses were conducted on the surfaces of the specimens where wear tests were performed using the tribometer.

3. Results and Discussion

This section details the findings from the experimental methodology, where variations in texture orientation and lubrication conditions were systematically analyzed. The study emphasizes the evolution of the Coefficient of Friction (CoF), alongside the examination of wear morphology and the quantitative assessment of wear and friction within the WC-Co/Ti6Al4V contact pair. Furthermore, the predominant wear mechanisms occurring during the frictional interaction between WC-Co and Ti6Al4V were identified and thoroughly characterized.

3.1. Laser Texturing

The laser irradiation process produced linear topographies characterized by parallel tracks. This approach enabled the creation of high-resolution surface features free from burrs. The resulting grooves exhibited a depth of 13 µm and a width of 90 µm, measured using the previously detailed FVM technique with an uncertainty of 0.5 µm, as illustrated in Figure 4, where the type of tribological test (pin-on-flat) is also shown, as well as the most relevant data of the topographies examined.

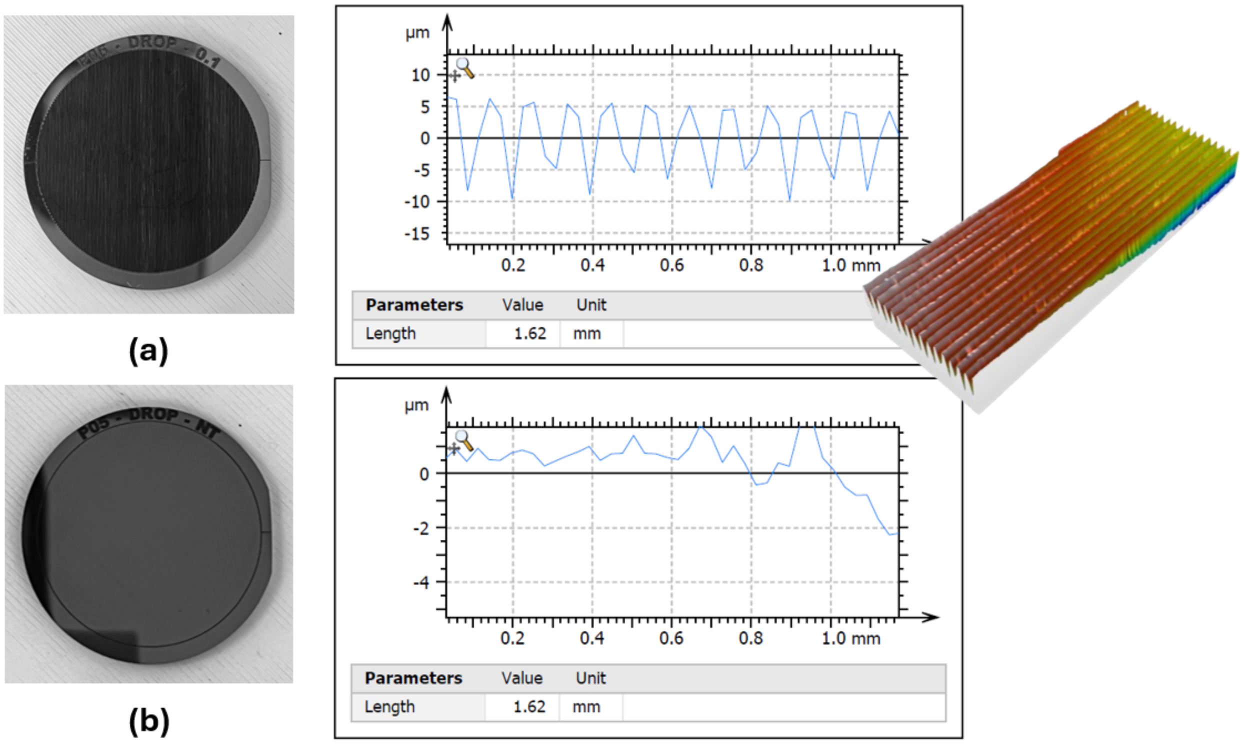

Figure 4. WC-Co substrates: (**a**) 90° texture and (**b**) non-texture and surface topography of textured specimen.

It has been of special interest to perform this measurement study due to the behavior that textures show. Several investigations, including the study conducted by Vázquez-Martínez et al. [21], have assessed the performance of surface texturing in enhancing lubricant retention. This study concluded that laser texturing significantly enhances the lubricant retention capabilities of tungsten carbide–cobalt (WC-Co) surfaces. By employing tailored laser parameters, the process altered the surface microgeometry, creating distinct roughness patterns that enhanced the surfaces' lubricating performance. This improvement in lubricant retention resulted in reduced tool wear and preserved the machined parts' surface quality at standards similar to those of untextured tools. The profile graphs have shown interesting results, enabling comparative analysis across varying test durations.

3.2. Influence of Reciprocating Time on the Coefficient of Friction

In this regard, the introduction of surface textures leads to more uniform sliding paths compared to tests conducted on untreated surfaces. In all scenarios, more pronounced wear effects are observed in the central regions of the sliding tracks, where sliding speed remains unaffected by acceleration or deceleration. Furthermore, in the tests of 250 s, 500 s, and 750 s, under dry contact conditions (Figure 5), the directional changes in the pin result in more severe wear impacts on the tracks, particularly in the lateral sections, where uneven wear is evident in non-textured specimens. These changes in direction introduce local fluctuations in the frictional force. These fluctuations result from variations in sliding velocity and changes in adhesion and deformation mechanisms at the contact interface. These transient variations can lead to uneven dissipation of energy along the surface, potentially causing localized wear patterns. Studies such as the one conducted by Lefranc et al. [22] provide a basis for understanding these tribological phenomena in similar materials.

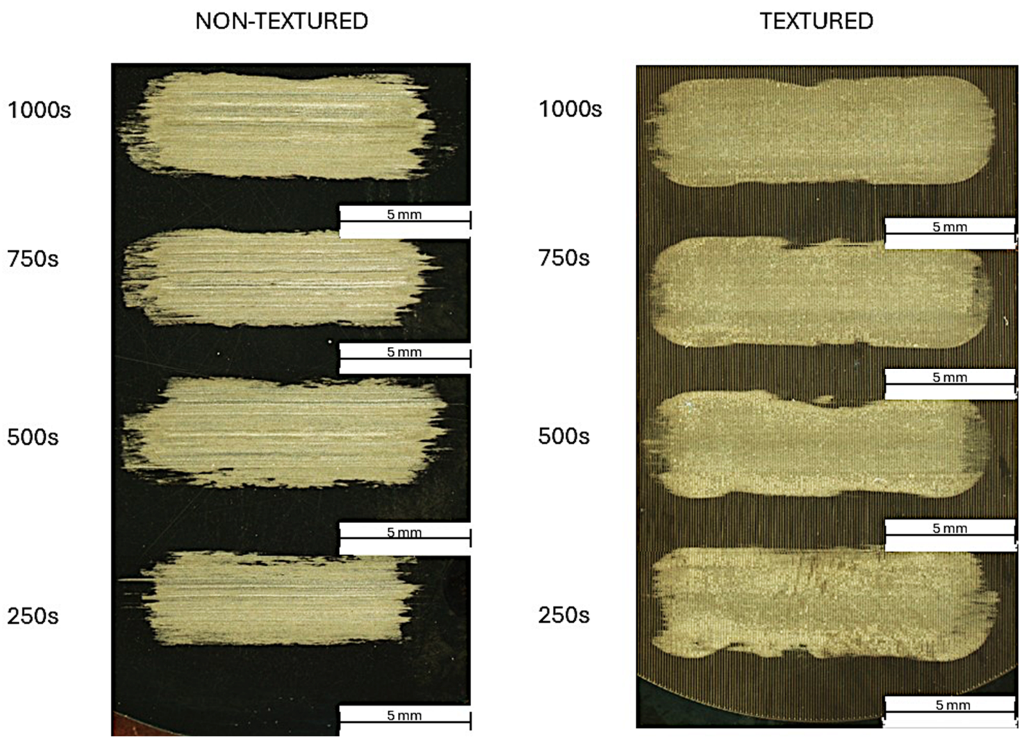

Figure 5. Comparison of textured and non-textured samples tested under dry conditions with test durations of 250 s, 500 s, 750 s, and 1000 s.

Furthermore, the introduction of lubricants during friction and sliding enhances the contact interface between the tribological components, primarily due to the formation of a lubricant film at the interface. This phenomenon alters the wear tracks, leading to sharper definition and greater uniformity along the edges, clearly exposing regions with a higher concentration of affected material, as observed in the non-textured samples (Figure 6). Additionally, for tests lasting 1000 s with textured samples, significant wear was observed. This trend is reflected in the Time vs. Coefficient of Friction (CoF) graph (Figure 7d), where a sharp increase in the CoF is noticeable beyond 800 s. These findings will be further discussed in the following section.

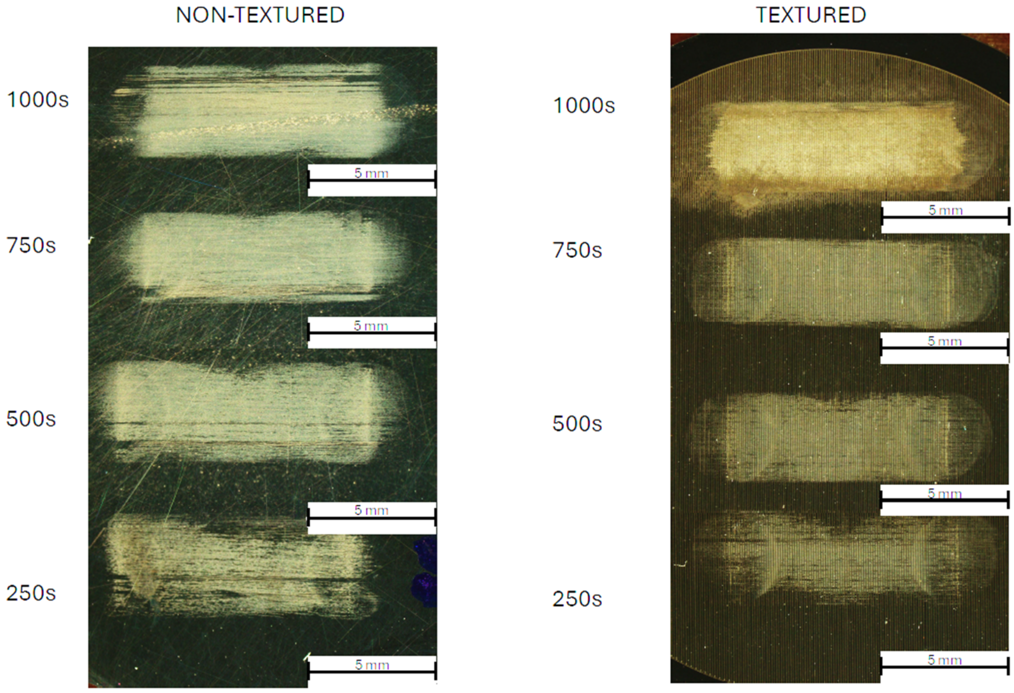

Figure 6. Comparison of textured and non-textured samples tested under lubricated conditions with test durations of 250 s, 500 s, 750 s, and 1000 s.

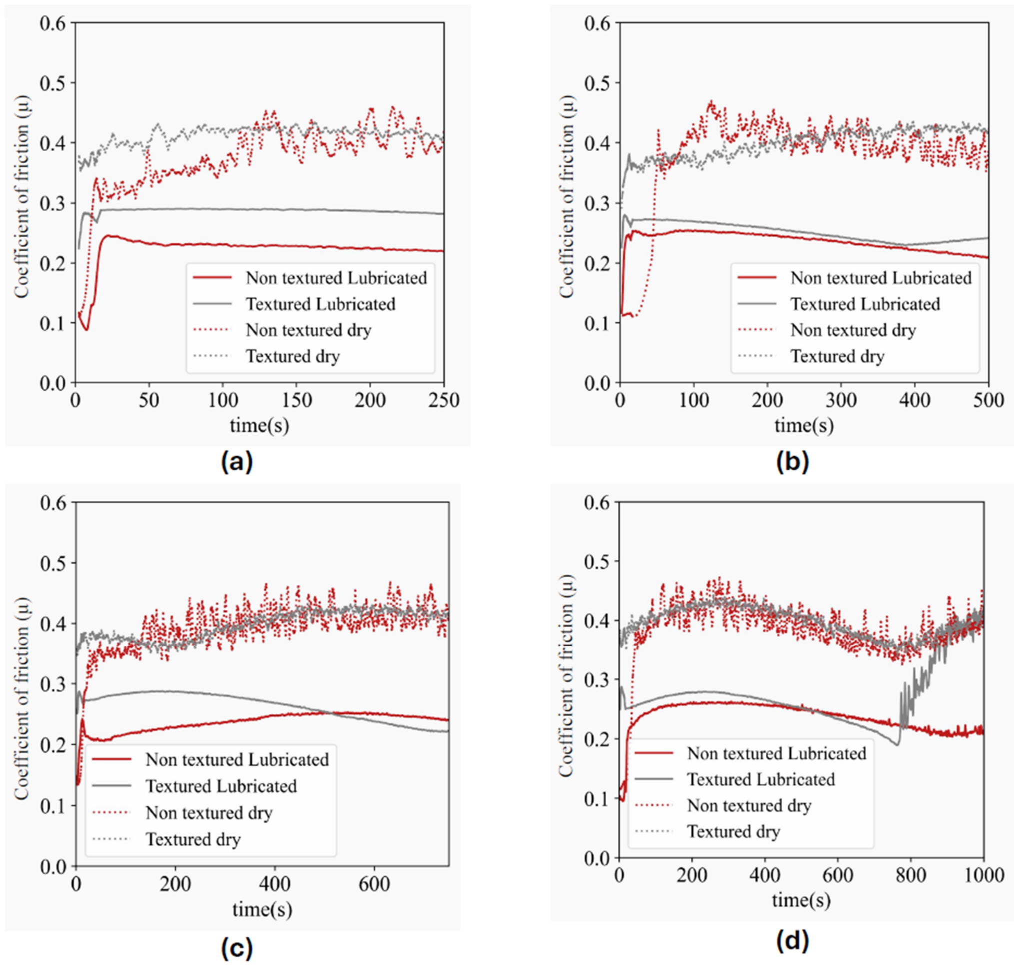

Figure 7. Comparison of the coefficient of friction for textured and non-textured samples under dry and lubricated conditions at test durations: (**a**) 250 s, (**b**) 500 s, (**c**) 750 s, and (**d**) 1000 s.

When comparing dry and lubricated conditions on the same scale (Figure 7), the advantageous effect of lubrication becomes evident, resulting in an average reduction in the CoF during the stable regime by 25.0% for the 250 s tests on the non-textured sample, 23.08% for the 500 s tests, 21.43% for the 750 s tests, and 20.0% for the 1000 s tests, compared to their dry counterparts.

The 1000 s tests (16 min and 40 s) have been of particular interest since many tool manufacturers specify a tool life of approximately 15 min. In some cases, the zone of high risk of flank wear begins at 250 s and above. That is why the tests have been started taking this time as the initial one. This has indeed been verified in the lubricated tests. On the disc, it was observed that the lubricant lost its properties after approximately 800 s, transforming into an abrasive paste, which further accelerated wear, ultimately resulting in friction coefficients like those observed in dry tests (Figure 6). This phenomenon can also be seen in Figure 7 on the textured disc after 1000 s of testing.

As Özel et al. [23] explains, the lubricant is deposited in the grooves of the texture, which act as distribution channels and improve the tribological behavior of the sample. However, as has been observed, when the lubricant reaches a point in the test after such a long duration (from 800 s), it loses properties, has weakened textures, and has transforms into the abrasive paste that we commented on.

The variation in the reciprocating test duration for the textured sample reveals a significant modification in its tribological behavior compared to the non-textured sample. Furthermore, under dry test conditions, the textured sample exhibits a substantially higher variation in tribological performance (Figure 8).

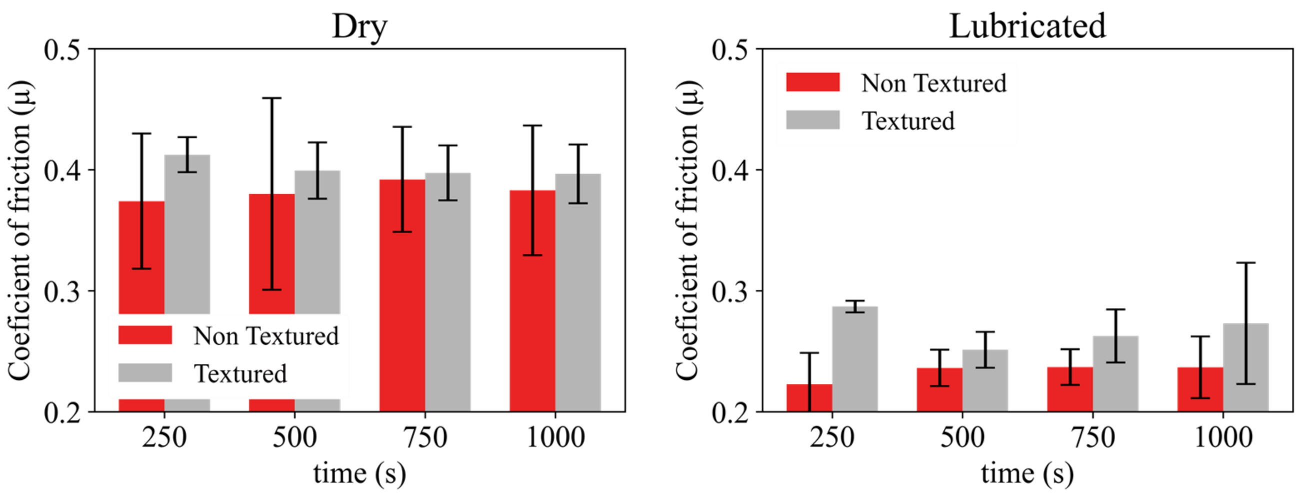

Figure 8. Coefficient of friction as a function of test duration for textured and non-textured samples in lubricated and dry conditions.

3.3. Wear Quantification

Figure 9 presents two bar charts comparing mass loss (measured in grams) of a material under two experimental conditions: dry and lubricated. Both charts examine the performance of textured and non-textured tools over varying time intervals (250, 500, 750, and 1000 s).

The x-axis represents the testing duration in seconds, while the y-axis quantifies the mass loss. In dry conditions, non-textured tools (depicted by red bars) exhibit lower mass loss compared to textured tools (gray bars) across all time intervals. Conversely, in lubricated conditions, textured tools display higher mass loss than non-textured tools, particularly during longer durations (750 and 1000 s).

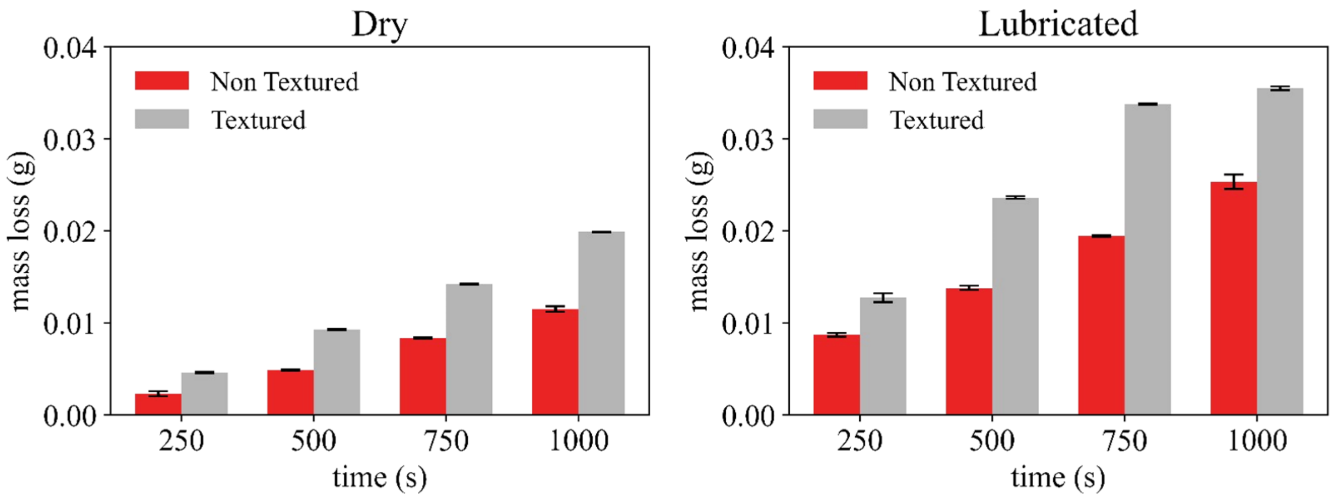

Figure 9. Mass loss of the pins between the textured and non-textured samples in lubricated and dry conditions.

Overall, the mass loss increases progressively with time in both conditions. The disparity between textured and non-textured tools is more pronounced under lubricated conditions, especially at extended time intervals. The consistent color coding (red for non-textured and gray for textured) and the uniform y-axis scale between the charts enhance the clarity of the comparison. This visual data effectively highlight the contrasting effects of texturing and lubrication on material wear over time.

The figure compares the mass loss of textured and non-textured samples under dry and lubricated conditions over time. In the dry condition, at 250 s, the mass loss of the textured sample is approximately 0.007 g, while the non-textured sample loses around 0.005 g, resulting in a 40% greater mass loss for the textured sample. This wear mechanism is strongly influenced by factors such as the effect of surface textures on the pin. Groove-shaped textures create an uneven friction surface. However, they result in greater stability in the friction coefficients, particularly in dry tests, without significant fluctuations in variability, as observed in non-textured samples. This can lead to increased pin wear, making the textured sample more effective than the non-textured one. Studies such as the one carried out by Fouathiya et al. [24] further assert that this wear mechanism induced by surface textures is attributed to their effect during continuous sliding against another surface and how they facilitate the wear of the counter material. As time progresses, the trend continues: at 500 s, the textured sample shows a mass loss of about 0.01 g compared to 0.007 g for the non-textured one, corresponding to a 43% increase. By 750 s, the difference becomes more pronounced, with the textured surface exhibiting 80% higher mass loss (0.018 g compared to 0.01 g). Finally, at 1000 s, the textured sample loses around 0.02 g, whereas the non-textured sample loses approximately 0.013 g, reflecting a 54% increase in mass loss for the textured sample. This indicates that, under dry conditions, pins which have been tested under textured surfaces consistently experience higher wear, with the percentage difference increasing with time. This is because, as discussed by Kang et al. [25], the groove-like textures generate micro-cuts and facilitate the wear of titanium, thus optimizing its machining.

In the lubricated condition, a similar trend is observed, but the differences in mass loss between the textured and non-textured samples are even more significant. At 250 s, the textured sample loses about 0.012 g, compared to 0.009 g for the non-textured one, which is a 33% higher mass loss. At 500 s, the difference widens, as the pin tested on the textured sample loses about 0.022 g, while the non-textured loses 0.014 g, corresponding to a 57% increase. At 750 s, the mass loss of the texturized sample reaches 0.035 g, while the non-texturized one loses approximately 0.02 g, corresponding to a 75% higher mass loss. Finally, at 1000 s, the textured surface shows a mass loss of approximately 0.038 g, compared to 0.027 g for the non-textured sample, an increase of 41%. The latter is due to the fact that the time generally recommended by manufacturers for cutting tools has been exceeded. However, it has also been observed that the lubricant has deteriorated much more than in the rest of the tests (see Figure 10), red arrows indicate points where the deteriorated lubricant, which has turned into an abrasive paste, is located). The lubricant has lost its properties and has been transformed into an abrasive paste that further accelerates wear. This is due to the 90° texture's ability to retain lubricant and trap abrasive particles detached during sliding. These particles mix with the lubricant, and over a prolonged period, they eventually form an abrasive paste, leading to a loss of the lubricant's properties.

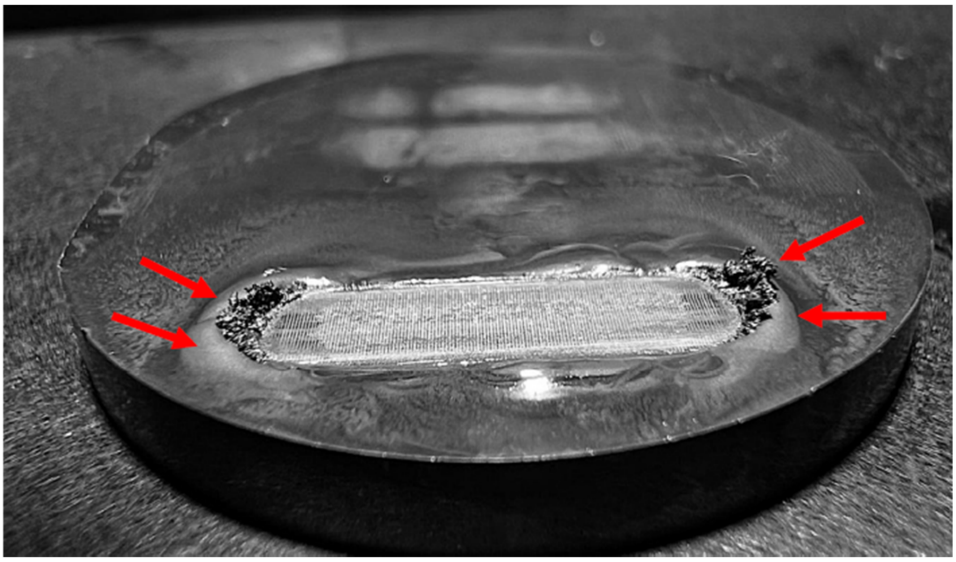

Figure 10. Mixture of wear debris and lubricant at the ends of the sliding track in 1000 s test with texture.

In general, under both dry and lubricated conditions, pins tested on textured samples show consistently higher mass loss compared to non-textured samples, suggesting that surface texturing leads to increased wear. This effect is more pronounced in lubricated conditions, where the differences reach up to 75% at certain time intervals. The higher wear observed on textured surfaces could be attributed to increased contact interaction, debris retention and micro-cutting effects during the sliding process, which are not sufficiently mitigated even in the presence of lubrication. This same phenomenon was commented by Suárez-Bustamante et al. [26] in their study where the influence of surface textures on the performance of plain bearings was analyzed.

The wear analysis of the dry test (Figure 11) reveals that the predominant wear mechanism on the pin is abrasive, but there is also debris adhesion. Abrasion deteriorates the surface quality, facilitating the adhesion mechanism. Wear tracks appear in the sliding direction, and the debris volume increases. The primary wear effects on the pins are concentrated in their center, mainly due to the test configuration, where inertia during trajectory changes generates a rounding effect on the contact face, trapping debris in this region.

In the 750 and 1000 s test pins which were tested with texture, higher wear, and loss of material was observed than those tested without textures. Additionally, higher adhesion was also observed in these pins. The 1000 s (16 min and 40 s) tests have been of special interest since many tool manufacturers specify a tool life of approximately 15 min. In fact, this has been verified in dry tests [27].

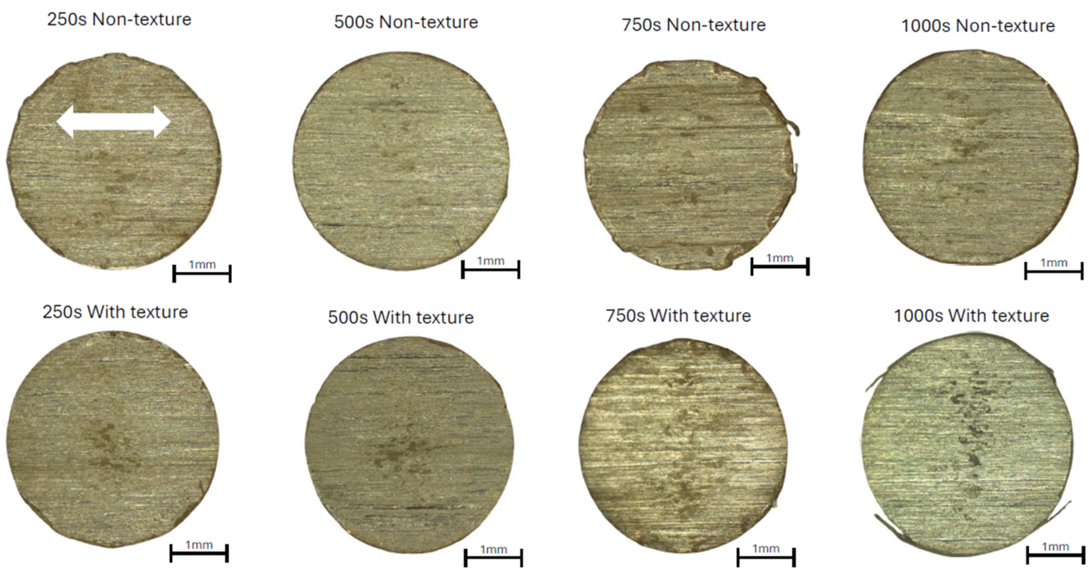

Figure 11. Wear effects on pins (Ti6Al4V) for dry tests.

Under lubricated conditions, the dominant wear mechanism is abrasion, characterized by wear tracks aligned with the sliding direction. A notable reduction in debris adhesion was observed during these tests, as no residual debris was detected in any of the trials conducted (Figure 12). This behavior is primarily attributed to the lubricant, which functions as a conductive medium, effectively facilitating the removal of wear debris. However, on the pin that was tested with texture and with a duration of 1000 s, more adhesion was observed compared to the others. This is due to the behavior of the lubricant after a longer test time. This has deteriorated and facilitated more wear. Figures 11 and 12 pins are oriented as illustrated in the upper indicative drawing of the figure.

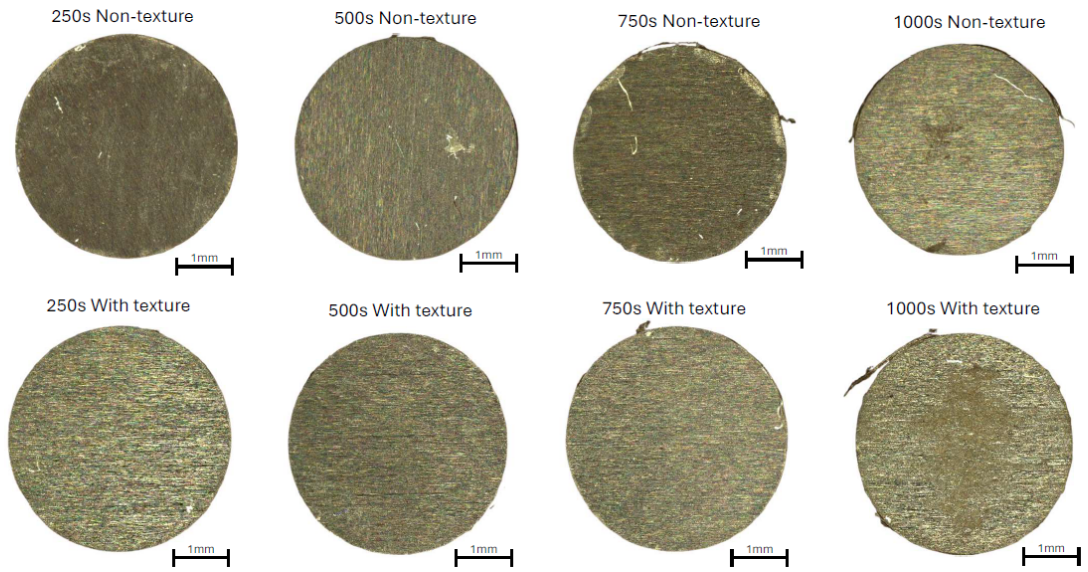

Figure 12. Wear effects on pins (Ti6Al4V) for lubricated tests.

As described, the lubricated test with a duration of 1000 s has been of particular interest since, at 800 s, a change in the noise generated by friction between the WC disc and the pin was detected, which, as previously shown, corresponds to a significant increase in the coefficient of friction. This can be observed in Figure 13, where the image darkens, and the area with adhesion appears lighter.

Figure 13. Details of wear in the pin with 1000 s, tested with texture sample and under lubricated conditions.

Similar behaviors were observed by Saketi et al. [28], where Ti6Al4V components were turned using carbide tools under dry conditions, and it was noted that this adhesion of work material (Ti6Al4V) also occurred on the rake face of the tool, along with significant crater wear.

This same phenomenon of adhesion on the peeling and crater wear face was discussed by Olander et al. [29] where a comparison was made with different cutting parameters (speed, feed and cutting length). It could be observed that at low cutting speeds lower tool wear was obtained. This could be the basis for future tests using different frequencies on the tribometer.

This difference in the behavior of textured disks under lubricated conditions is clearly observed in the images obtained through variable focus microscopy and subsequently processed using MountainsMap software (see Figure 14) for the 750 s and 1000 s tests, where a profile graph for each case has also been extracted.

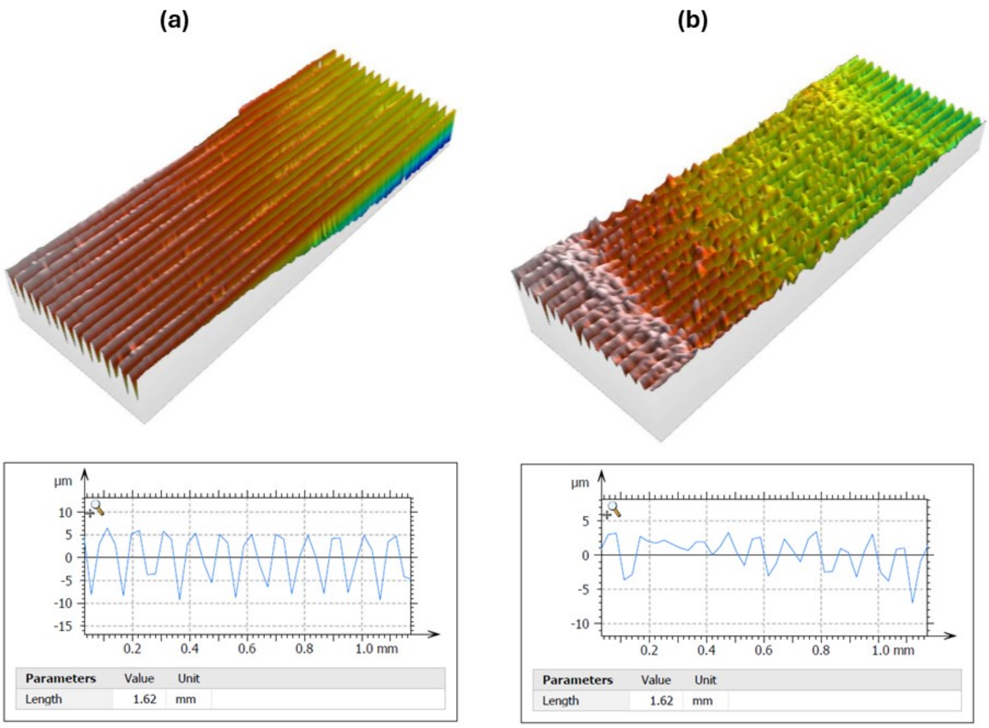

Figure 14. Comparison of the textured footprint under lubricated conditions at (**a**) 750 s and (**b**) 1000 s.

The comparison between the two textured surfaces under lubricated conditions reveals significant differences in behavior with increasing test duration. In Figure 14a, corresponding to the 750 s test, the surface texture displays a regular and well-defined pattern of ridges and valleys, with minimal signs of wear or deformation. The grooves remain consistent and prominent, maintaining a uniform profile across the analyzed surface.

Conversely, in Figure 14b, which represents the 1000 s test, the surface shows significant deterioration. The ridges appear less pronounced, with increased roughness and irregularities indicative of progressive wear. This degradation is also evident in the surface profile, where a reduction in the amplitude and uniformity of peaks and valleys can be observed compared to the previous test duration.

When examining the profile graph, it becomes clear that the texture, in comparison to Figure 14a, is considerably more deteriorated, particularly in the ridge peaks and valleys, with some valleys having disappeared entirely. As noted by Sristi et al. [14] in their research, these valleys or grooves act as channels for lubricant distribution, thereby aiding in better temperature dissipation across the surface.

However, in this case, as previously mentioned, the lubricant in this test has lost its properties and has behaved as an abrasive paste, effectively blunting the texture and impairing temperature dissipation. Consequently, higher friction coefficients and greater wear have been observed on the disk's contact area.

The topographic images also reveal a higher concentration of protrusions in the 1000 s wear track compared to the 750 s track. The underlying cause of this phenomenon is the onset of adhesion, as explained by Maressa et al. [30], which further facilitates wear and leads to higher friction coefficients during the test, particularly after reaching 800 s of duration.

4. Conclusions

The effects of time cycles (250 s, 500 s, 750 s and 1000 s) on the tribological behavior of the Ti6Al4V/WC-Co pair were investigated in terms of friction coefficient and wear, under both dry and lubricated conditions. The sliding wear processes, as well as their effects on WC-Co surfaces and Ti6Al4V pins, were characterized. The main conclusions are outlined below.

1. With tests lasting longer than 750 s, major changes are observed in the behavior of both the pin and the sample, both in lubricated and dry conditions. It is observed that at durations longer than 750 s, the lubricant begins to lose properties and therefore effectiveness, becoming just another agent that facilitates the wear of the textures and therefore worsens the test conditions.
2. After this first point, it has been observed that once the lubricant loses its properties and becomes denser, it is deposited in the channels, generating greater wear and turning the test conditions into a dry test.
3. The pin's volume loss graphs show once again that laser texturing improves the material removal, thus improving the machining process and showing good results.
4. The importance of the influence of reciprocating times. At shorter reciprocating durations (e.g., 500–750 s), surface textures enable a more efficient distribution of contact, minimizing initial adhesion and delaying the accumulation of severe wear. However, with longer durations (e.g., 1000 s), significant deterioration is observed on the textured surfaces due to progressive wear, as well as the accumulation of abrasive particles that alter the initial properties of the texture.

As the main conclusion, the texturing of WC disks for pin-on-flat tests proves to be a promising technique for mitigating wear and enhancing tribological performance in interactions with Ti6Al4V. However, the effectiveness of the textures is highly influenced by the reciprocating time, emphasizing the need for careful selection of design parameters for industrial and scientific applications.

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References

1. Gandreddi, J.P.; Kromanis, A.; Lungevics, J.; Jost, E. Overview of Machinability of Titanium Alloy (Ti6Al4V) and Selection of Machining Parameters. *Latv. J. Phys. Tech. Sci.* **2023**, *60*, 52–66. [CrossRef]
2. Hourmand, M.; Sarhan, A.A.D.; Sayuti, M.; Hamdi, M. A Comprehensive Review on Machining of Titanium Alloys. *Arab. J. Sci. Eng.* **2021**, *46*, 7087–7123. [CrossRef]
3. Uçak, N.; Aslantas, K.; Çiçek, A. Experimental Evaluation of Tool Wear and Surface Roughness under Different Conditions in High-Speed Turning of Ti6Al4V Alloy. *J. Mater. Manuf.* **2023**, *2*, 1–10. [CrossRef]
4. Ezugwu, E.O.; Wang, Z.M. Titanium Alloys and Their Machinability—A Review. *J. Mater. Process Technol.* **1997**, *68*, 262–274. [CrossRef]
5. Imbrogno, S.; Sartori, S.; Bordin, A.; Bruschi, S.; Umbrello, D. Machining Simulation of Ti6Al4V under Dry and Cryogenic Conditions. *Procedia CIRP* **2017**, *58*, 475–480. [CrossRef]
6. Di, W.; Chen, S. Study on the Influence of Chip Break Groove Front Angle on the Performance of Cutting Ti6Al4V. In Proceedings of the ICIIBMS 2023—8th International Conference on Intelligent Informatics and Biomedical Sciences, Okinawa, Japan, 23–25 November 2023; pp. 357–360. [CrossRef]
7. Pakula, D.; Staszuk, M.; Dziekońska, M.; Kožmín, P.; Čermák, A. Laser Micro-Texturing of Sintered Tool Materials Surface. *Materials* **2019**, *12*, 3152. [CrossRef]
8. García-Martínez, E.; Miguel, V.; Martínez-Martínez, A.; Manjabacas, M.C.; Coello, J. Sustainable Lubrication Methods for the Machining of Titanium Alloys: An Overview. *Materials* **2019**, *12*, 3852. [CrossRef]
9. Etsion, I. State of the Art in Laser Surface Texturing. *J. Tribol.* **2005**, *127*, 248–253. [CrossRef]
10. Łach, Ł. Recent Advances in Laser Surface Hardening: Techniques, Modeling Approaches, and Industrial Applications. *Crystals* **2024**, *14*, 726. [CrossRef]
11. Voswinkel, D.; Kloidt, D.; Grydin, O.; Schaper, M. Time Efficient Laser Modification of Steel Surfaces for Advanced Bonding in Hybrid Materials. *Prod. Eng.* **2021**, *15*, 263–270. [CrossRef]
12. Zhao, W.; Gu, Y.; Yang, Z.; Zhang, Z. Thermoelastic Vibration of Nickel Film Irradiated by Femtosecond Laser: Molecular Dynamics Study. *Coatings* **2024**, *15*, 1. [CrossRef]
13. Montealegre, M.A.; Castro, G.; Rey, P.; Arias, J.; Vázquez, P.; González, M. Surface treatments by laser technology. *Contemp. Mater.* **2010**, *1*, 19–30. [CrossRef]
14. Sristi, N.A.; Zaman, P.B. A Review of Textured Cutting Tools' Impact on Machining Performance from a Tribological Perspective. *Int. J. Adv. Manuf. Technol.* **2024**, *133*, 4023–4057. [CrossRef]
15. Reddy, V.C.; Venkaiah, T.; Nishkala, T.; Yadav, G.M.P. Effect of Textured Tools in Turning Operation: A Comparison with Conventional Tools. *Trans. Indian. Natl. Acad. Eng.* **2021**, *6*, 697–708. [CrossRef]
16. Zhang, C.; Zou, D.; Mazur, M.; Mo, J.P.T.; Li, G.; Ding, S. The State of the Art in Machining Additively Manufactured Titanium Alloy Ti-6Al-4V. *Materials* **2023**, *16*, 2583. [CrossRef]

17. Patel, K.V.; Jarosz, K.; Özel, T. Physics-Based Simulations of Chip Flow over Micro-Textured Cutting Tool in Orthogonal Cutting of Alloy Steel. *J. Manuf. Mater. Process.* **2021**, *5*, 65. [CrossRef]
18. Zheng, K.; Yang, F.; Zhang, N.; Liu, Q.; Jiang, F. Study on the Cutting Performance of Micro Textured Tools on Cutting Ti-6Al-4V Titanium Alloy. *Micromachines* **2020**, *11*, 137. [CrossRef]
19. Gropper, D.; Wang, L.; Harvey, T.J. Hydrodynamic Lubrication of Textured Surfaces: A Review of Modeling Techniques and Key Findings. *Tribol. Int.* **2016**, *94*, 509–529. [CrossRef]
20. Hu, S.; Zheng, L.; Guo, Q.; Ren, L. Influence of Cross-Grooved Texture Shape on Tribological Performance under Mixed Lubrication. *Coatings* **2022**, *12*, 305. [CrossRef]
21. Vazquez-Martinez, J.M.; Del-Sol, I.; Batista, M.; Fernandez-Vidal, S.R.; Hernandez, P.M.; Salguero, J. Experimental Study of Laser Texturing Processes on the Lubricant Retention of Carbide (WC-Co) Surfaces. *Key Eng. Mater.* **2019**, *813*, 55–61. [CrossRef]
22. Lefranc, V.; Baydoun, S.; Gandiolle, C.; Héripré, E.; Vallet, M.; Fouvry, S.; Aubin, V. Heterogeneity in Tribologically Transformed Structure (TTS) of Ti-6Al-4V under Fretting. *Wear* **2023**, *522*, 204680. [CrossRef]
23. Özel, T.; Biermann, D.; Enomoto, T.; Mativenga, P. Structured and Textured Cutting Tool Surfaces for Machining Applications. *CIRP Ann.* **2021**, *70*, 495–518. [CrossRef]
24. Fouathiya, A.; Meziani, S.; Sahli, M.; Barrière, T. Experimental Investigation of Microtextured Cutting Tool Performance in Titanium Alloy via Turning. *J. Manuf. Process.* **2021**, *69*, 33–46. [CrossRef]
25. Kang, Z.; Fu, Y.; Fu, X.; Jun, M.B.G. Performance of Volcano-Like Laser Textured Cutting Tools: An Experimental and Simulative Investigation. *Lubricants* **2018**, *6*, 98. [CrossRef]
26. Suárez-Bustamante, F.A.; Vélez-Restrepo, J.M.; Toro-Botero, F.M. Influencia de Texturas Superficiales Acondicionadas En El Desempeño de Cojinetes Planos Operando En Condiciones HL. *Ing. Investig. Y Tecnol.* **2012**, *13*, 365–374. [CrossRef]
27. Serope, K.; Schmid, S.R.; Sekar, K.S.V. *Manufacturing Engineering and Technology*; Pearson Education Limited: London, UK, 2022; 1312p, ISBN 1-292-42224-6.
28. Saketi, S.; Odelros, S.; Östby, J.; Olsson, M. Experimental Study of Wear Mechanisms of Cemented Carbide in the Turning of Ti6Al4V. *Materials* **2019**, *12*, 2822. [CrossRef]
29. Olander, P.; Heinrichs, J. On Wear of WC–Co Cutting Inserts in Turning of Ti6Al4V—A Study of Wear Surfaces. *Tribol. Mater. Surf. Interfaces* **2021**, *15*, 181–192. [CrossRef]
30. Maressa, P.; Anodio, L.; Bernasconi, A.; Demir, A.G.; Previtali, B. Effect of Surface Texture on the Adhesion Performance of Laser Treated Ti6Al4V Alloy. *J. Adhes.* **2014**, *91*, 518–537. [CrossRef]