Study of the tribological performance of Ti6Al4V textured with pyramidal dimples by electro discharge machining

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Abstract: Surface texturing has demonstrated to be a useful technique for improving the tribological performance of surfaces in contact. In particular, in this research it has been applied to the Ti6Al4V titanium alloy, with poor tribological behaviour, by creating different texturing densities with pyramidal geometries. Additionally, these geometries have been obtained through sinking electro-discharge machining processes, scarcely addressed in the scientific literature. In dry sliding conditions, the results obtained show an improvement of about 65% in the coefficient of friction, while in lubricated contact, the improvement in the lubricant retention capacity results in the formation of an abrasive paste formed by the lubricant and the wear debris, which worsens tribological behaviour.

Keywords: Ti6Al4V, EDM, Texturing, Tribology.

1. Introduction

In the last decades, the understanding of certain surface phenomena has played a fundamental role for the advances in very diverse fields, such as electronics, energy, or tribology. This has resulted in the development of new properties and functionalities on the surface of materials, mainly given by the generation of structured or textured surfaces in a controlled manner, and the search for new manufacturing technologies capable of apply them at different scales [1].

Among the metallic materials, Titanium alloys are very attractive in many industrial sectors, such as aerospace or biomedical, due to their excellent physico-chemical properties, like high strength, low density, high corrosion resistance, and biocompatibility [2]. Nevertheless, their low plastic deformation ratios reduce their applications, due to unstable friction coefficients and other undesirable wear mechanisms [3,4].

One way to overcome these limitations can be given by the texturization of contact surfaces. On the one hand, texturing reduces contact areas, while basic geometries or dimples retains detached abrasive particles [5]. On the other hand, surface geometries can act as reservoirs that help to retain lubricants, facilitating the sliding behaviour between contact surfaces [6]. This fact is presented as one of the main relevant parameters to obtain better results in tribological applications [7].

Several machining methods have been studied for the application of texturing in metallic alloys. Micro-drilling has been used for manufacturing micro-hole patterns [8,9], micro-milling for machining micro grooves [10], while vibration assisted milling and turning have been performed to obtain dimples along the machining tool-paths [11,12]. However, the application these conventional machining processes in surface texturing limits the type of dimple geometry and its replication across the surface.
That is why, although the previous processes have been applied extensively, currently the most widely used technology for texturing is LST (Laser Surface Texturing) [13]. LST can achieve more complex geometries, with high versatility and speed of application [14-17], but its thermal effects can cause modifications in the microstructure of the substrate, by altering their surface layers with an increase in hardness, that can result in the embrittlement of the components [18].

An alternative method for applying textures, scarcely addressed in the scientific literature, is the Electro Discharge Machining (EDM). The published studies are mainly focused on the study of the texture of eroded surfaces, in both of its variants -Wire EDM (WEDM) or Sinking EDM (SEDM)-, and the relationship with process parameters [19,20]. Nevertheless, there are still very few studies that apply this technology to obtain specific repetition geometries along a surface. However, it may be an ideal technology for texturing processes. On the one hand, the heat induced by these processes is very low compared to laser technologies. On the other hand, it has a high scalability capacity, being possible the application of a single texturing process for large surface areas, with simple or complex dimple geometry and patterns [21-23].

This work examines the feasibility of the SEDM in texturing processes, by applying eroded tetragonal or pyramidal dimple geometries at different densities. Surface modification aims to improve the friction and wear behaviour of the initial surfaces of Ti6Al4V alloy, by a reduction on coefficient of friction (COF) through two different ways: dimples can act as debris trap in dry sliding conditions, reducing abrasion effects, while in presence of lubricants they can act as reservoirs, improving lubricant retention capability on the textured surfaces.

2. Experimental methodology
An experimental methodology has been developed for the texturing of the Ti6Al4V alloy by SEDM and the later tribological study. This methodology allows evaluating the effect of the density of the textures on the behaviour of the friction parameter, through Pin on Disc wear tests in presence and absence of lubricant.

2.1. Samples preparation
Ti6Al4V samples, with the composition shown in table 1, were adapted from a plate to a 50×50×5 mm volume by using an ONA AF25 wire electro-discharge machine. The back and bottom surfaces of each sample were subjected to a metallographic preparation with a Struers Tegrapol-15 polishing machine. Surface conditioning, comprising grinding and polishing steps, guarantees a homogeneous, uniform and flat finished surfaces, free of deformations, with an average roughness (Ra) lower than 0.4 µm, as is required for the standard tribological Pin on Disc tests [24].

| Table 1. Ti6Al4V alloy weight composition (wt%). |
|-----------------------------------------------|
| Element | Al  | V   | Fe  | C   | O   | N   | H   | Ti   |
| wt%     | 6.26| 3.91| 0.18| 0.011| < 0.10| < 0.10| < 0.10| Rest |

2.2. Electrode design and manufacturing
SEDM electrodes were manufactured from an ELLOR® +25 grade isotropic graphite block, widely used in EDM processes due to its fine grain size, low erosion wear and easy machining, allowing to obtain eroded textures with surface roughness (Ra) between 1.60 and 3.15 µm. Its main properties are shown in table 2.

| Table 2. ELLOR® +25 main characteristics. |
|-------------------------------------------|
| Density (g/cm³) | Hardness (Shore) | Electrical resistivity (µΩ cm) | Average grain size (µm) |
| 1.83 | 65 | 80 | 1220 | 9 |
Electrodes were machined to reduce the dimensions up to 50×50×30 mm³, with a geometry that ensures the correct adjustment to an EROWA ER-009222 electrode clamping, figure 1.

Figure 1. (a) EROWA ER-009222 electrode holder. (b) Dimensions of the graphite electrode, in mm.

On the free electrode surface, 45° square pyramidal textures with 0.5, 1.0, 1.5 and 2.0 mm side, were designed. In this way, four types of electrodes, with different pyramidal densities were obtained, as is shown in figure 2.

Figure 2. Drawings of the four types of electrodes designed with arrays of pyramidal geometries with side: (a) 0.5 mm. (b) 1 mm. (c) 1.5 mm. (d) 2 mm.

Electrodes were machined in a Kondia Five 400 high speed machining center, with the maximum rotation speed (24,000 rev/min), and a linear feed-rate of 960 mm/min (0.01 mm/tooth). Pyramidal geometries were obtained by milling first in X and then in Y direction. Different geometries were obtained by varying axial and radial depths. The cutting tool used was a tungsten carbide 4 fluted chamfering mill KENDU HMKEN C449.67 (K-CROM+ coated), using a new cutting tool for each electrode. In figure 3 it can be observed the cutting tool geometry and milling strategy.
2.3. SEDM texturing
Ti6Al4V samples were textured by using an ONA NX3 automated Sinker EDM, with a constant erosion depth, set at 0.25 mm. SEDM process were selected with a criterion for minimum wear erosion of the electrode, by using the parameters included in table 3.

Table 3. Erosion parameters.

| VDI (VDI 3402) | Ra (µm) | Intensity (A) | Voltage (V) | Pulse on-time (µs) | Pulse off-time (µs) | Return time (s) | Working time (s) |
|----------------|---------|---------------|-------------|-------------------|-------------------|----------------|----------------|
| 24             | 1.6     | 4             | 200         | 6.4               | 10                | 0.3            | 0.3            |

The use of the 4 different electrode geometries at 0.25 mm depth allows to obtain four texturing densities, with pyramidal dimples of 0.5 mm side squares, but with different distance between dimples (0, 0.5, 1 and 1.5 mm). Thus, taking into account the total area of the different textures, densities of 100, 25, 11 and 6% are obtained, related with the previous pyramidal textures of side 0.5, 1.0, 1.5 and 2.0 mm, respectively. In each texturing process, a new electrode was used.

2.4. Pin on Disc tests
The tribological tests were carried out on a Microtest MT/60/NI tribometer, using as disc the Ti6Al4V samples (317 HV30), and carbide tungsten (WC-6%Co) balls as pin (1728 HV30), with 3 mm of diameter. Two types of test were developed, in dry and lubricated conditions. In lubricated tests, it was added 0.1 ml of Renolin MR 3 VG 10 oil (0.84 g/cm3 at 15°C), lubricant widely employed in spindles, bearings and metal surfaces in contact. This lubricant was applied manually at the beginning of the test, at a single point of the contact path between the ball and the Ti sample, without re-lubrication during the test. Pin on Disc test parameters are shown in table 4, while a scheme of the tribological test is represented in figure 4.

Table 4. Pin on Disc parameters.

| Normal load (N) | Radius (mm) | Rotation speed (rev/min) | Linear speed (m/s) | Sliding distance (m) |
|-----------------|-------------|--------------------------|--------------------|---------------------|
| 5               | 16          | 500                      | 0.84               | 250                 |

Coefficient of friction (COF) was recorded by the tribometer for each test, with at least 3 repetitions in order to ensure their repeatability. After tribological tests, Pin and Discs were examined in a Nikon SMZ-800 stereoscopical microscope.
3. Results and discussions
In the following subsections main results are detailed, in function of the dry or lubricated conditions, and their comparison. For the plotting of COF, a moving average with period of 150 was applied in order to smooth the curves. The relative standard deviation (or coefficient of variation, COV = standard deviation/average value · 100) among the different repetitions resulted lower than 10% in all cases.

3.1. Influence of SEDM processing parameters on texturing characteristics
The density and distribution of the textures shows a significant influence in the geometrical and dimensional characteristics of the developed pyramids of the modified surfaces. Higher densities of the pyramidal elements provide larger contact surfaces between the EDM electrode and the Ti6Al4V specimen. This condition causes a quick increase of the wear on the outer surfaces of the electrode, and the development of softer geometries of the textured elements, as shown in figure 5.

Under this consideration, can be observed that the lack of the sharp edges of the electrode elements results in the generation of dimples without a high-definition pyramidal shape and lower depth. As shown in figure 5, the density of the textures involves the lack of definition in the shape of the pyramids, softening the edges of the surface. This phenomenon is mainly due to the erosive effect of the EDM process in closest dimples.

The variation of the developed geometries of the textured elements from pyramidal shapes to softer dimples also have a significant influence in the sliding behavior of WC-Co sphere under tribological conditions. As described previously, one of the main functions of the EDM textures consists in the lubricant retention improvement of the surface acting as wear debris reservoirs, for this reason, the modification of the surface characteristics may affect in the tribological performance of the textures.
3.2. Dry sliding wear behavior

All the textured surfaces lead to a significant reduction in the tribological effects, in terms of friction coefficient (COF) values, regarding the initial surface characteristics. An average reduction of approximately 65% in the COF have been reached by the use of pyramidal shape textures under dry friction and sliding conditions, as shown in figure 6. Although lower differences were detected between surfaces with different textures, the use of higher density of pyramidal elements (100% and 25%) shows better results through lower COF values. This consequence is mainly caused by the softening of the pyramidal edges in the surface that promotes a more uniform sliding process.

Reduction in the friction values for modified surfaces confirms that the development of medium scale textures, based on uniform distribution of cavities, may trap the sliding wear debris, that usually shows higher hardness due to come from the WC-Co pin, and the Ti6Al4V subjected to deformation phenomena. Based on these considerations, this process allows to reduce wear particles from the sliding track in the tribological pair contact area, also decreasing the abrasive effect (third body abrasive mechanism) of harder debris.

3.3. Lubricated sliding wear behavior

The use of pyramidal EDM textures under lubricated tribological conditions does not provide a significant improvement in the wear behaviour of the modified surfaces. In contrast to the dry conditions tests results for COF, the lubricated tests have reported that the use of textured surfaces resulted in poorer friction behaviour than untextured surface, as shown in figure 7 (a). In addition, higher concentration of wear particles has been detected in the outer areas of the sliding track, forming a mixture medium with the lubricant oil used, as shown in figure 7 (b).

Figure 6. (a) COF as a function of texture density. (b) Wear effects on sliding track (dry).

Figure 7. (a) COF as a function of texture density. (b) Wear effects on sliding track (lubricated).
Dry experimental tests indicate that the dimple textures act as reservoirs to trap wear debris. When lubricant is used, they can also act as lubricant reservoirs. Based on the COF results for dry tests, it can be considered that the pyramidal cavities retain the wear debris, facilitating the sliding by reducing the particles deposited in the friction track. In the case of lubricated tests, the lubricant previously retained in the pyramidal cavities does not allow the trap of wear debris in these holes, keeping them in the sliding track and causing more unstable and higher COF values, mainly due to the pin encounters more obstacles to advance. This effect is also confirmed by the wear effects, in terms of sliding track size, where the lubricated condition shows higher depth of the track in accordance with the COF behavior, as shown in figure 8. As shown in this figure, wear track depth of the tests with pyramidal textures may show variations, mainly due to the distribution and density of the dimples. Under lubricated and dry conditions, the textures may act as a lubricant retention reservoir, and under dry conditions may act as a reservoir for the wear debris. In both cases the retention ability shows a high dependence from the wear debris volume and the shape of the pyramids (that can be altered for higher density textures).

![Figure 8. (a) COF comparative graph for 100% and 6% densities. (b) Sliding track depth.](image-url)

### 4. Conclusions

In this research, the effects of pyramidal shape texture performed by SEDM on the tribological behaviour of Ti6Al4V surfaces have been presented. On the one hand, wear of the EDM electrode shows dependence of the contact surface of the development textures. A lack of the initial texture geometry has been detected for higher density of textures specimens. On the other hand, a significant influence of the texture density has been confirmed on the friction coefficient and the wear effects, in terms of wear track dimensions. Under dry conditions, a reduction in the COF near to 65% have been reached as an average value for all the types of textures, being higher this improvement for higher density of pyramidal textures.

### Acknowledgements

This work has received financial support from FEDER / Spanish Ministry of Science, Innovation and Universities - State Research Agency, through DPI2017-84935-R project.

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