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Metrological evaluation of the tribological behavior of laser surface treated Ti6Al4V alloy

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Abstract

Nowadays, most of the studies conducted on procedures applying to the materials in order to increase the performance thereof, has been based on the improvement of the mechanical properties, favoring its manufacturability. New techniques of surface treatments by thermal processes and coatings, have managed to produce surface microstructures whose behavior under sliding conditions have allowed saving tribological and thermal limitations. This contribution aims at the metrological based evaluation of the friction wear of Ti6Al4V titanium alloys samples to subjected to surface oxidation through laser radiation. For this purpose, several methodology processes have been designed and planned for the characterization and evaluation of the loss of material on the external layer caused by sliding wear, in order to identify the type of predominant wear mechanism and quantify its effects.

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Keywords: Tribological wear; surface treatments, laser irradiation, metrological evaluation, Ti6Al4V.

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1. Introduction

Significant recent advances in the field of materials engineering, as well as the treatments and analysis realized thereof, have conducted to a better understanding of the behavior showed during processing. This fact has favored the search for property improvements of commonly used materials, and the introduction of innovative materials, designed to overcome recently established requirements, and in addition be able to beating limitations under very specific use conditions. Thanks to that, the performance of processes has substantially increased, reflecting this improvement through a decrease in the economic costs based on the employed resources, also trying to maintain at all the time an environmental sustainability trend.

Titanium alloys are among the main groups of materials that have experienced massive growth in terms of increased of use, Rand Corporation (2013), both in the industrial and biomedical applications, Niinomi (1998), Rack et al (2006), where the excellent biocompatibility is the main highlight, being used normally in the implants and prosthesis manufacturing. In the industrial field, the choice of these materials is determined by the excellent relationship between mechanical properties and good behavior at high temperatures. This fact, turns these alloys suitable for the use in environments such as aerospace industry, which require lightweight, high resistance elements, and internal engines components, where titanium shows appropriate functionality at elevated temperature ranges.

Nevertheless, despite the advantages shown by titanium alloys, this group of materials is severely limited in terms of resistance to wear conditions. For this reason, many studies are focused on the modification of determined features of the microstructure and surface composition. In the behavior improvements, faced with the phenomena of friction and wear of manufactured parts from this alloys, are aimed by those studies, Garbacz et al (2008) to Arrazola et al (2009). In this paper, the evolution of Ti6Al4V samples wear are analyzed when properties are modified through thermochemical treatments of surface oxidation, Garbacz et al (2008), Huseyin et al (2011), based on laser radiation processes.

In order to monitoring and controlling the variables involved in the wear process, and setting the same conditions for each of the alloy samples, experimental Pin on Disk tribological test were developed. Thus, friction conditions can be simulated as produced in forming processes such machining, limiting or fixing large number of parameters involved in the cutting process, Kagnaya et al (2009) to Yang (2004).

The highlights of this work has been focused on the metrological aspects involving the analysis of the assessment and quantification of fricative tribological wear, generated between tungsten carbide pin and a surface modified Ti6Al4V alloy disk, and the influence of treatment on behavior under friction and sliding conditions.

2. Experimental procedure

After tribological Pin on Disc tests, modified Ti6Al4V samples wear evaluation was performed by an analysis of the removed material, firstly quantified through the extracted mass of the alloy, and on the other hand from the measurement of the dimensions of the sliding track caused by the pin. For this purpose, the measurement of the weight of Ti6Al4V specimens was made before the test, and after its performing, checking the existing variation generated by the experimental test. Furthermore, using profilometry techniques, and by processing profiles software, an approximation was possible to obtain of the material volume that is removed from the track of sliding, and the accumulated material on the outer edges of the groove, ASTM (2004) to Qu et al (2006).

In a previous stage, an experimental methodology was designed, planned and developed to carry out the selection and adaptation of the work material, the surface modification by laser radiation, the development and planning of tribological tests, and the metrological procedures performed to assess the purposes of sliding wear on the alloy samples.

Figure 1 shows that, after the selection of the material, three main blocks are differentiated in the experimental methodology. Thus in a first stage, laser based surface modification treatments have been performed on Ti6Al4V samples. These treatments induce thermal oxidation on the more external layers of the material. So, different surface nature can be developed onto the samples by applying different radiation intensities. These surface changes promote variations in the characteristics and properties regarding the initial material.
Secondly, Pin on Disk tribological tests have been conducted on the laser modified titanium samples. The same test conditions have been applied to all the probes, in order to evaluate in this way the influence of surface treatments on the behavior of the material.

Finally, once the wear tests are carried out, specific metrological procedures were developed aimed at the study of the relevance parameters in the assessment of friction wear, quantifying the affected volume of material and analyzing the greater influence variables. This can serve to obtain improvements in the alloy performance for hard applications where the extrapolation of study results can be possible.

2.1. Material

Ti6Al4V Titanium alloy (UNS R56400) specimens have been used. The weight element composition (%) of this alloy is included in Table 1.

<table>
<thead>
<tr>
<th>Element</th>
<th>Al (%)</th>
<th>V (%)</th>
<th>Fe</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>%wt</td>
<td>5,5 - 6,5</td>
<td>3,5 - 4,5</td>
<td>0,25</td>
<td>Rest</td>
</tr>
</tbody>
</table>
2.2. Surface treatment

In a first step, the surface of the Ti alloy samples were homogenized by a mechanical polishing process from initial microgeometry conditions of Ra ≈ 1.9μm / Rt ≈ 15.7μm to Ra ≈ 0.1μm / Rt ≈ 0.8μm deviations. This procedure promotes the homogeneity in the absorption of the applied radiation. Subsequently, induced ablation treatment was conducted by a laser marking system Rofin Easymark F20 with application conditions like specified in Table 2.

The alloy samples treatment was carried out under non-protective atmosphere of air with the aim of favoring the thermal oxidation of the external layers of the material structure, thereby increasing the content of stoichiometry titanium oxide TiO₂. For this part, through the variation of the radiation energy density by controlling the scanning speed of the laser system, three kinds of samples can be generated with increasing thickness of the TiO₂ layer, Variola et al (2008), easily distinguishable, thanks to the change of tonality experienced by modifying the outer layer. This layer can range from clear golden tones, to a purplish hue, according to the intensity of radiation absorbed, Variola et al (2008), as shown in Figure 2.

2.3. Tribological analysis

Ti6Al4V alloy samples, treated by surface radiation, have been subjected to tribological Pin on Disc tests. This kind of tests aim to expose the samples to frictional wear conditions. In this case, a tungsten carbide (WC-Co) sphere of 3mm in diameter has been used as Pin, in order to have a first approach to the fricatives problems, which the Ti6Al4V/WC-Co system engages in the machining processes.

The WC-Co pin slides in contact with the titanium samples, following a circular path in which the dynamic contact parameters are set, Figure 3.

In the present study, the test conditions of application have been set for all specimens, regardless of the intensity of thermal treatment that it was subjected, Table 3. This fact has the purpose to possibility of realizing comparative analysis of the wear variables to be used as reference in the evaluation thereof. The equipment Microtest Mt60 NI tribometer has been used to perform Pin on Disk tests, controlled by data logging software Microtest V4.2.

2.4. Metrological evaluation

One of the most relevant parameters for the characterization of the sliding wear effects is the volume of material variation experienced by the probes. Similar studies are commonly used to quantify the wear in these kinds of processes, Montgomery et al (2009). Particularly, in this work, the volume variation can be presented as a decrease of the starting material through the groove or circular wear track.

Table 2. Laser processing parameters.

<table>
<thead>
<tr>
<th>P (W)</th>
<th>f (kHz)</th>
<th>Vs (mm/s)</th>
<th>λ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>70</td>
<td>40-150</td>
<td>1062</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>Focal distance (mm)</td>
<td>Ø Spot (μm)</td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td>185</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. Laser irradiated samples.
Table 3. Tribological test parameters.

<table>
<thead>
<tr>
<th>F (N)</th>
<th>(\omega) (rpm)</th>
<th>V (m/s)</th>
<th>R (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>400</td>
<td>1</td>
<td>15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Distance (m)</th>
<th>Ø Pin (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1000</td>
<td>3</td>
</tr>
</tbody>
</table>

2.5. Metrological evaluation

One of the most relevant parameters for the characterization of the sliding wear effects is the volume of material variation experienced by the samples. Similar studies are commonly used to quantify the wear in these kinds of processes, Montgomery et al (2009). Particularly, in this work, the volume variation has been presented as a decrease of the starting material through the groove or circular wear track.

On the one hand, using Ohaus Pioneer PA214 scale, the weight of each of the samples has been evaluated after the heat treatment of radiation, returning to be measure once the sliding test have been performed. Taking a constant density for the material, the variation of the evacuated volume by friction can be obtained.

Moreover, employing a roughness measurement device, Mahr Perthometer Concept PGK120, two-dimensional form profiles have been obtained, perpendicularly to the tangent of the circular contour, evenly distributed in 10º intervals over the entire sliding path.

3. Results and discussion

Pin on Disc tests carry on a loss of material of the disc sample because of, mainly, the friction in the Pin-Disc interface. This loss can be evaluated by determining the volume changes. Treated and untreated Titanium alloy samples loss of volume (Vp) can be evaluated through the measurement of the samples mass before and after the test wear, making use of ASTM G99-04 standard. Figure 4 plots the Vp values calculated on the samples treated in the test conditions. As a reference, the Vp corresponding to an untreated sample has been also plotted. It should be noted that Vp value presents variations according to the intensity of surface treatment, showing a higher material evacuated volume in the sample which has not been subjected to radiation, relative to the rest of specimens treated by oxidation. This fact shows the treatment improves tribological behavior of the material.

Moreover, it should be pointed out that the low speed treatments show higher amount of displaced material volume. This may be related to the fact that at lower speeds, the laser spot remains longer on each sample point in each scanning pass. Hence may result in damage to the surface in excess, and the generated layer not result so protective as it should. Meanwhile, material losses are obtained over the minimum value at faster speeds. In this case, the explanation is just the opposite. Indeed, at high speeds ranges, the remaining time of the laser spot on the surface of the alloy can be so short that the protective oxide layer can not be formed completely, which would lead to less protection than in the cases where the layer was sufficiently developed.

An evaluation of displaced volume (Vm) has been also carried out in parallel from the evacuated material into the sliding track. It has been performed through the roughness profiles obtained on the wear groove. Figure 4 also plots the displaced volume evaluated by using profilometry. As it can be seen in this figure, similar trends can be observed to those obtained for Vp, which in relative terms allows a first but noticeably different in absolute values
ranges. Facts as these are indicative that the mark left by the pin on the titanium sample are not only due to the loss of material, but also to the plastic displacement of the material out of the thoroidal finger, Figure 5.

Combining information from the contour profiles analysis by several microscopy methods (especially SEM), it can be determined that there are different stages in the formation of the tread, Figure 6. In a first step, deformed Ti6Al4V accumulated against the tool (Pin) is mainly generated because it is not possible to evacuate eroded remains. Subsequently a critical volume of material is reached that results in a displacement of the pin over the deformed material, causing an increase in contact pressure followed by a loss of contact with the groove. On the other hand, it has been detected that a specific part of the material that does not move to the edges of the tread and that is not removed from the sample weight, adheres and deforms along the track of sliding. This happening is the origin of the difference between the deformed and the dislodged material on the wear track causing in addition the difference in measured values for Vp and Vm. Must exist therefore, a part of deformed material that remains in a different area to the outer edges of the sliding tread of the probe. In order to analyze this behavior, using scanning electron microscopy (SEM), explorations have been carried out that have revealed the presence of an alloy layer on the groove path, Figure 7. These depots of alloy residues causes the pin contact on the friction path takes place in a discontinuous way, as explained above, further generating wear instability and resulting lack of homogeneity in the registered friction coefficient values during the tests.

Fig. 4. Material worn volume according to the weight and the wear track dimensions.

Fig. 5. (a) Pin on Disk test wear track; (b) Plastic effect on the sliding.
Fig. 6. Located stages along the sliding way and resulting wear profiles.
4. Conclusions

An analysis has been carried out on the wear evaluation of Ti6Al4V alloy surface modified probes by laser radiation, when submitted to friction conditions through Pin on Disk tribological tests against tungsten carbide (WC-Co) tools. To do this, a methodology have been designed and developed for the surface treatment and tribological test of the samples.

Metrological procedures have been conducted using weight measurements of dislodged material and dimensions of the wear track produced by the pin and the material volume that has broken away from each test. It has been found that a large part of the affected material by the sliding effect is not clear from the titanium sample, producing instead a deformation thereof to the outer edges of the groove.

However, it is noteworthy that a part of the worn material debris is deposited on the own sliding track, generating superposed layers of material that contributes to the existence of a lack of uniformity in the contact surface between the alloy and the pin, causing discontinuities on the displacement and giving rise to instabilities in the friction coefficient and normal force values. In this way, the wear is associated with a weight loss of the probes due to the removed material.

Highest laser intensities (lowest laser speeds) have been found as the most efficient treatments.

Acknowledgements

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Fig. 7. (a) Extruded material volume; (b) Detail of deposited material layer in the disc track.

References


