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Tribological Behavior Analysis of the ISO 5832-1 Austenitic Stainless-Steel Treated by Optical Fiber Laser Used for Biomedical Applications

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Abstract: The present work analyzed the influence of an optical fiber laser surface treatment process on the tribological behavior of the ISO 5832-1 austenitic stainless-steel, basing on the wear volume and friction coefficient. Specimen of this biomaterial were treated by alternating the laser frequency, in order to find out a condition that improves its tribological resistance. Ball-cratering micro-abrasive wear tests were carried out with a test ball of AISI 316L stainless-steel, used as counter-body, and an abrasive slurry prepared with abrasive particles of black silicon carbide (SiC) and distilled water. The micro-abrasive wear tests results indicated that: *i*) the hardness of the ISO 5832-1 austenitic stainless-steel increased as a function of the laser frequency, decreasing, consequently, the wear volume, as predicted by *Archard's Law*; *ii*) the friction coefficient did not present a proportional behavior with the increase of the optical fiber laser frequency; *iii*) the best condition to improve the wear resistance of the ISO 5832-1 austenitic stainless-steel was obtained adopting an optical fiber laser frequency of 350 kHz, being reported the lower wear volume.

Keywords: Biomaterials; Austenitic stainless-steel; Optical fiber laser; Micro-abrasive wear; Wear resistance.

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1. Introduction

Recently, the micro-scale abrasive wear test by rotating ball has gained large acceptance in universities and research centers, being widely used in studies on the micro-abrasive wear behavior of materials. The principle of the "*ball-cratering*" micro-abrasive wear test is a rotating test ball that is forced against the tested specimen, in the presence of an abrasive slurry [1-3]. There are two main test devices configurations to conduct this type of micro-abrasive wear test: "*free-ball*" [4,5] and "*fixed-ball*" [6] mechanical configurations.

The aim of the micro-abrasive wear test by rotating ball is to generate "*wear craters*" on the surface of the specimen. Figure 1 presents images of such craters, together with an indication of the crater diameter (d) and the wear volume (V) [7].

The wear volume (V) may be determined as a function of "d", using Equation 1 [8], where "R" is the radius of the test ball.

$$V \cong \frac{\pi d^4}{64R} \qquad \text{for } d << R \tag{1}$$

The micro-abrasive wear test has been applied in the study of the micro-abrasive wear behavior of metallic [1,4,9-12] and non-metallic [2,3,13-19] materials and their micro-abrasive wear behaviors can be expressed based on the wear volume (V) and/or friction coefficient (μ), calculated from Equation 2, where "T" is the tangential force and "N" is the normal force.

$$\mu = \frac{T}{N} \tag{2}$$

Micro-abrasive wear tests conducted under the "*ball-cratering*" technique present advantages in relation to other types of wear tests, because it can be performed with normal forces (N) relatively low (N < 0.5 N) and, in principle, can favour the analysis of the tribological behavior that is desired.

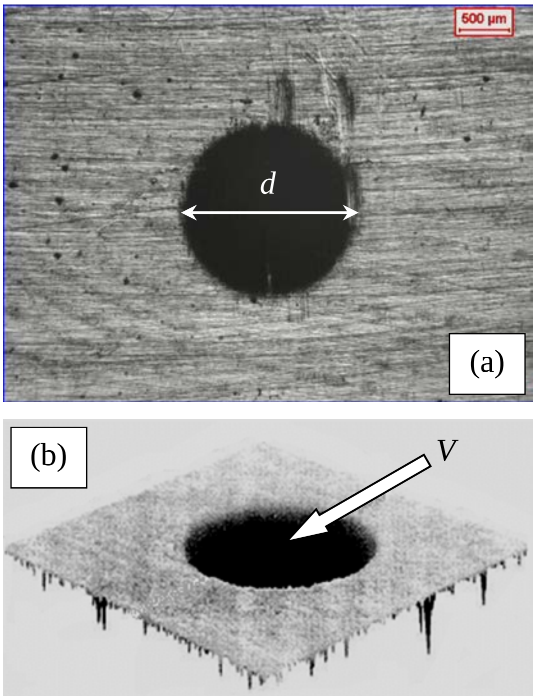

Figure 1. Images of wear craters: (a) *diameter* – *d* and (b) *wear volume* – *V* [7].

In other hand, along the last years, the concept of "*biotribology*" has gained important spotlight in the area, including researches addressing the tribological behavior of human body elements. Then, different laboratory techniques and specialties have been employed to reproduce conditions where there are friction and consequent wear of parts of the mechanical structure human with relative movement.

According to Niinomi, Nakai and Hieda [20], around 70% and 80% of orthopedic implants are manufactured of metallic biomaterials [20] and mounted on to the skeletal system of the human body [21]. In turn, the metallic biomaterials, like stainless-steels, must satisfy two important characteristics: "*biocompatibility*" and "*biofunctionality*" [22].

"*Corrosion resistance*" is one factor that determine the "*biocompatibility*" of an orthopedic implant [23], while "*wear resistance*" is one of the most important factors that determine its "*biofunctionality*".

In view of this important research line – *biotribology* – to people benefit, the purpose of this present work is to analyze the influence of an optical fiber laser surface treatment process on the tribological behavior of the ISO 5832-1 austenitic stainless-steel, in order to find out a process condition that improves its wear resistance to biomedical applications.

2. Experimental detailing

Micro-abrasive wear tests were conducted with a ball-cratering equipment of "*free-ball*" mechanical configuration (Figure 2).

Two load cells were used in the ball-cratering micro-abrasive wear test equipment: one load cell to control the normal force (N) and one load cell to measure the tangential force (T) developed during the experiments. "*Normal*" and "*tangential*" force load cells have a maximum capacity of $\Gamma = 50$ N, an accuracy of $\Pi = 0.001$ N and the values of "N" and "T" appear on a readout system in real time during testing. This ball-cratering micro-abrasive wear test equipment has been previously evaluated during other researches [24-27], where has been selected different test conditions and whose apparatus presented excellent functionality during the experiments.

Surfaces of ISO 5832-1 austenitic stainless-steel specimen were treated with three different frequencies of optical fiber laser (f): $f_1 = 80$ kHz, $f_2 = 296$ kHz and $f_3 = 350$ kHz. After, Vickers Hardness tests were conducted on "*non-treated*" specimen and "*treated*" specimen with the different optical fiber laser frequencies. The counter-body was a test ball of AISI 316L stainless-steel with diameter of $D = 25.4$ mm ($D = 1$").

Table 1 presents the micro-abrasive wear test conditions defined for the experiments.

The normal force value defined for the wear experiments was $N = 0.5$ N, together a test ball rotational speed of $n = 70$ rpm. The abrasive slurry was prepared with black silicon carbide (SiC) with average particle size of $a_p = 3$ μm and angular shape, under the concentration of $C = 5\%$ SiC + 95% distilled water (volumetric values –

by literature [10], this value of abrasive slurry concentration is considered relatively low). For all experiments, the total sliding distance stablished was S = 25 m.

The tribological behavior of "*non-treated*" and "*treated by optical fiber laser*" surfaces of ISO 5832-1 austenitic stainless-steel were analyzed based on the wear volume (V) and friction coefficient (μ).

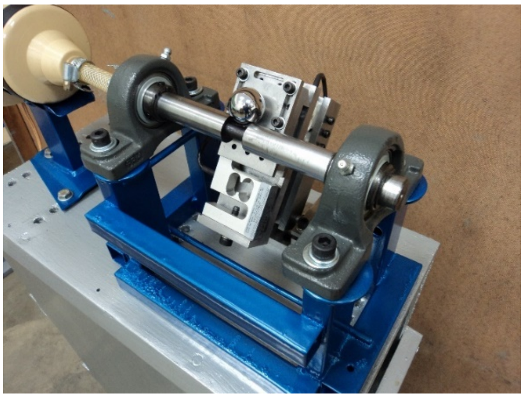

Figure 2. Ball-cratering equipment with "*free-ball*" mechanical configuration used for the micro-abrasive wear tests of this work.

Table 1. Micro-abrasive wear test conditions defined for the experiments.

Test parameter		**Value**
Normal force	– N	0.5 N
Test ball rotational speed	– n	70 rpm
Abrasive slurry concentration	– C	5% SiC + 95% distilled water (in volume)
Sliding distance	– S	25 m

3. Results and discussion

3.1 Results – Regarding to action of the "*grooving abrasion*" wear mode

Figure 3 presents an image of a wear crater generated during the tests. Additionally, Figure 4 shows a wear crater image, being possible to observe the occurrence of "*grooving abrasion*" wear mode, due to low abrasive slurry concentration defined for the micro-abrasive wear experiments of this research (C = 5% SiC + 95% distilled water – in volume).

The action of "*grooving abrasion*" wear mode reported on the surfaces of the wear craters obtained in this work is in qualitative agreement with the conceptualization addressed in the classical work published by R.I. Trezona, D.N. Allsopp and I.M. Hutchings [10], where is explained and demonstrated that low concentrations of abrasive slurries (< 25% abrasive material – in volume) favour the occurrence of "*grooving abrasion*" wear mode.

In other line of discussion, Cozza [28,29] justifies this micro-abrasive wear behaviour basing on contact pressure (P) developed on the tribological system "*specimen + abrasive particles + test ball*" (Equation 3).

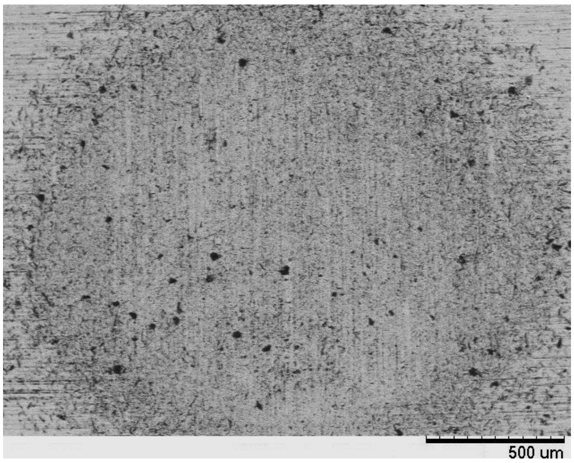

Figure 3. Wear crater generated during the micro-abrasive wear tests.

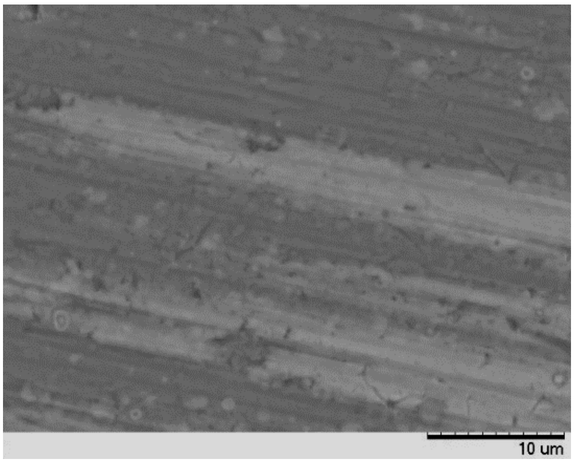

Figure 4. Occurrence of "*grooving abrasion*" wear mode on the surface of a wear crater.

$$P = \frac{\sum_{i=1}^{n_p} \Delta N_i}{A_t} \tag{3}$$

Where n_p is the number of abrasive particles between the specimen and the test ball, ΔN_i is the normal force acting on each abrasive particle and A_t is the total projected area of the wear crater, defined by Equation 4.

$$A_t = \frac{\pi}{4} d^2 \tag{4}$$

Under low concentrations of abrasive slurries (C), a quantity of abrasive particles acting on the wear process, between the specimen and the test ball is reduced; consequently, the normal force acting on each abrasive particle (ΔN_i) é higher. Then, this dynamic condition causes the scratch of the material, due to low capacity of mobility that the abrasive particles acquire under this condition of micro-abrasive wear.

3.2 Results – Values of hardness (H), wear volume (V) and friction coefficient (μ)

Table 2 shows the values of the hardness (H), wear volume (V) and friction coefficient (μ) obtained for the ISO 5832-1 austenitic stainless-steel surfaces, under conditions of "*non-treated*" and "*treated*" with the different optical fiber laser frequencies (f).

Table 2. Values of the hardness (H), wear volume (V) and friction coefficient (μ) reported for the specimen under the conditions of "*non-treated*" and "*treated*" with the different optical fiber laser frequencies (f).

Surface specimen treatment	**Hardness –** H [HV]	**Wear volume –** V [10^{-3} mm^3]	**Friction coefficient –** μ
Non-treated	199	6.2	0.12
Treated ⇒ f_1 = 80 kHz	204	5.4	0.15
Treated ⇒ f_2 = 296 kHz	226	4.4	0.10
Treated ⇒ f_3 = 350 kHz	240	3.7	0.14

3.3 Discussion – Regarding to tribological behavior of the ISO 5832-1 austenitic stainless-steel

Analyzing the values of Table 2, it is possible to note that the hardness (H) increased with the increase of the optical fiber laser frequency (f), considering the condition of "*non-treated*" surface and the conditions of "*treated*" surfaces, where the laser frequency was varied from f_1 = 80 kHz to f_3 = 350 kHz.

Besides, due to increase of the hardness as a function of the optical fiber laser frequency – $H = f(f)$, was reported a decrease of the wear volume (V), according qualitatively to *Archard's Law* (Equation 5).

$$V = \xi \frac{S.N}{H} \tag{5}$$

Where ξ is a dimensionless constant that indicate the severity of the micro-abrasive wear process [30].

In fact, by *Archard's Law*, the wear volume is inversely proportional to material hardness, agreement, qualitatively, with the results obtained in this research.

Regarding to values of the friction coefficient (μ), they varied from $\mu = 0.10$ to $\mu = 0.15$ and they did not present a direct relationship with the hardness (H) of the specimen and/or with the wear volume (V).

Finally, the best condition of optical fiber laser frequency stablished for the surface treatment of the ISO 5832-1 austenitic stainless-steel was $f_3 = 350$ kHz, because this laser frequency condition provided the lower value of wear volume – $V_3 = 3.7\times10^{-3}$ mm^3, featuring the higher micro-abrasive wear resistance.

4. Conclusions

The results obtained in this research indicated that:

1) The hardness of the "*treated*" surface of the ISO 5832-1 austenitic stainless-steel was dependent of the optical fiber laser frequency value – the material hardness increased with the increase of the laser frequency;

2) With the increase of the material hardness, the wear volume decreased, following, qualitatively, the *Archard's Law*, where the wear volume is inversely proportional to material hardness (Equation 5);

3) The friction coefficient did not present a proportional behavior with the increase of the optical fiber laser frequency and consequent increase of the material hardness, *i.e.*, was not observed a direct relationship between material hardness and friction coefficient;

4) The micro-abrasive wear results indicated that the tribological behavior was influenced by the frequencies values used for the laser surface treatment and the best condition to improve the wear resistance of the ISO 5832-1 austenitic stainless-steel was obtained adopting an optical fiber laser frequency of 350 kHz, obtaining the lower wear volume.

List of Symbols – Nomenclature and Units

a_p	Average abrasive particle size	[μm]
A_t	Total projected area of the wear crater	[mm^2]
C	Abrasive slurry concentration	[% SiC + % distilled water]
d	Diameter of the wear crater	[mm]
D	Diameter of the test ball	[mm]
f	Optical fiber laser frequency	[kHz]
H	Hardness	[HV]
n	Test ball rotational speed	[rpm]
n_p	Number of abrasive particles between the specimen and the test ball	
N	Normal force	[N]
ΔN_i	Normal force acting on each abrasive particle	[N]
P	Contact pressure	[MPa]
R	Radius of the test ball	[mm]
S	Sliding distance	[m]
T	Tangential force	[N]
V	Wear volume	[mm^3]

Greek letters

Γ	Maximum capacity of the load cells	[N]
μ	Friction coefficient	
Π	Accuracy of the load cells	[N]
ξ	Dimensionless constant that indicate the severity of the micro-abrasive wear process – from *Archard's Law*	

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