MICRO-ABRASIVE WEAR BEHAVIOR OF ISO 5832-1 AUSTENITIC STAINLESS-STEEL TREATED BY OPTICAL FIBER LASER 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 ISO 5832-1 austenitic stainless-steel, basing on the wear volume and friction coefficient. Specimens of the selected 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 ISO 5832-1 austenitic stainless-steel increased as a function of the laser frequency – consequently, the wear volume decreased, as predicted by Archard's Law, ii) the relationship between the friction coefficient and the optical fiber laser frequency was not proportional and iii) the best condition to improve the wear resistance of ISO 5832-1 austenitic stainless-steel was obtained adopting an optical fiber laser frequency of 350 kHz, because the wear volume decreased.

Keywords: Biomaterials, austenitic stainless-steel, optical fiber laser, micro-abrasive wear, wear resistance.

1. INTRODUCTION

Recently, the micro-scale abrasive wear test utilizing a rotating ball technique has gained large acceptance in universities and research centers, to be 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 rotating ball micro-abrasive wear test 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.

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

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 comparison with other types of wear tests, because it can be performed with relatively low normal forces (N < 0.5 N) and, in principle, can favour the analysis of the desired tribological behavior.

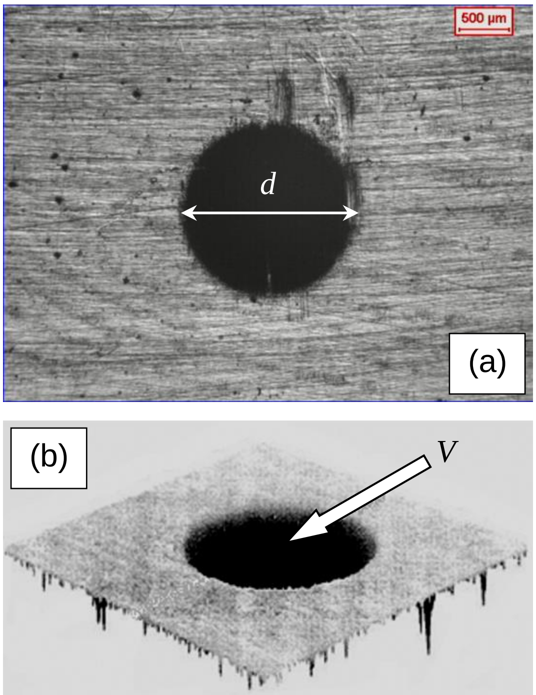

Figure 1. Images of wear craters: (a) *diameter* – d and (b) *wear volume* – V[7].

On 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 the mechanical structure of human parts 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 aim of this present work is to investigate the influence of an optical fiber laser surface treatment process on the tribological behavior of ISO 5832-1 austenitic stainless-steel, in order to find out a process condition that improves its wear resistance for potential biomedical applications.

2. EXPERIMENTAL METHODOLOGY

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

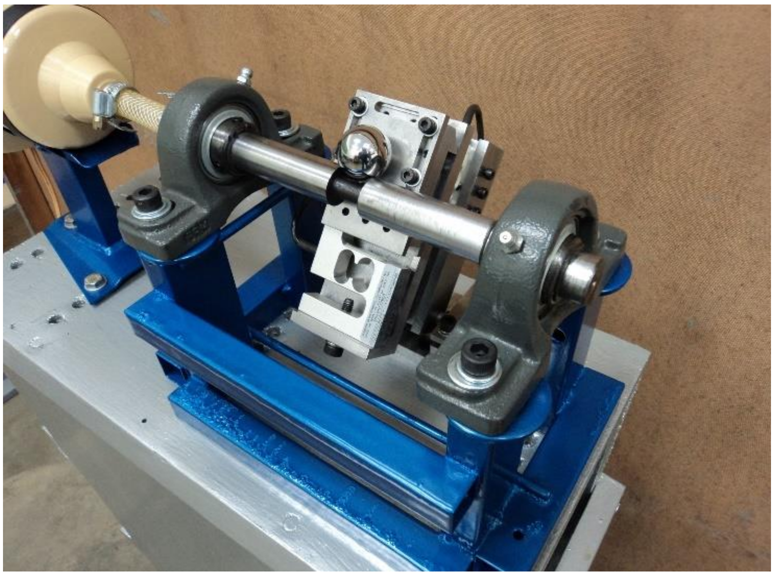

Figure 2. Ball-cratering equipment with "*free-ball*" mechanical configuration used for the micro-abrasive wear tests of this work.

Two load cells were used in the ball-cratering micro-abrasive wear test equipment: one load cell was used to control the normal force (N) and other one was used to measure the tangential force (T) developed during the experiments. "*Normal*" and "*tangential*" force load cells have a maximum capacity of Γ = 50 N and an accuracy of Π = 0.001 N – 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 by other researches(24-27), under different test conditions 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 that, Vickers Hardness tests were conducted on "*non-treated*" and "*treated*" specimens with 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" – standard size).

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

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

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

The normal force value defined for the wear experiments was N = 0.5 N, together with a test ball rotational speed of n = 70 rpm. The abrasive slurry was prepared with an angular shape black silicon carbide (SiC) of average particle size of a_p = 3 μm, under a 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).

3. RESULTS AND DISCUSSION

3.1. Action of the "*grooving abrasion*" wear mode

Figure 3 shows 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).

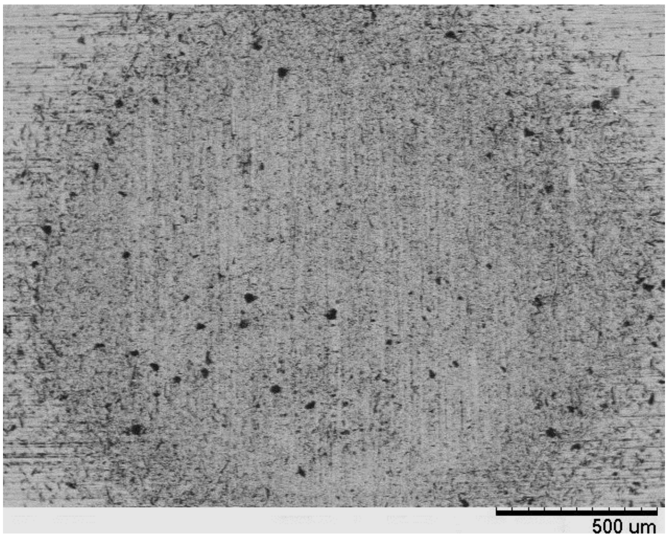

Figure 3. Wear crater generated during the micro-abrasive wear tests.

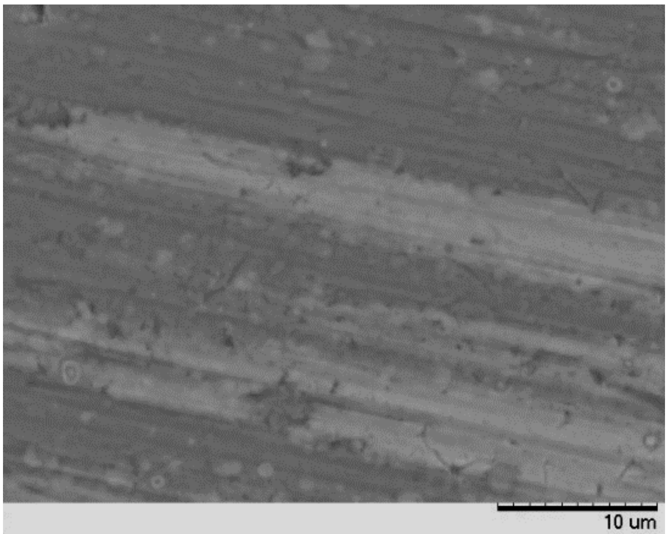

Figure 4. Occurrence of “*grooving abrasion*” wear mode on the surface of a wear crater.

The “*grooving abrasion*” wear mode observed 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). They 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 that this micro-abrasive wear behaviour is due to contact pressure (P) developed on the tribological system “*specimen* + *abrasive particles* + *test ball*”, described by Equation 3.

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

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.

$$A_t = \frac{\pi}{4} d^2 \quad (4)$$

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) is higher. 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. 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

Additionally, Figure 5 presents the behavior of the hardness (H) as a function of the frequency of pulse of the optical fiber laser (f) – H = f(f).

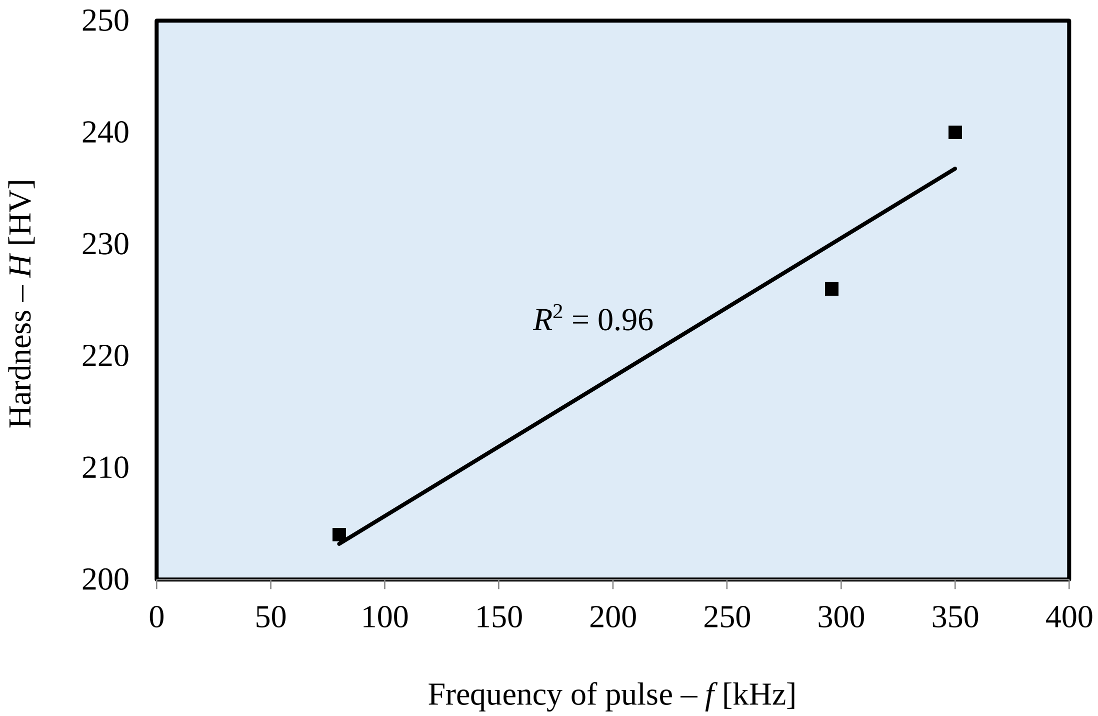

Figure 5. Behavior of the hardness (H) as a function of the frequency of pulse of the optical fiber laser (f) – H = f(f).

3.3. Tribological behavior of the ISO 5832-1 austenitic stainless-steel

From Table 2, it is clear that the hardness (H) increased with the optical fiber laser frequency (f). The hardness increased by about 18% when the frequency was increased by four-fold.

The same results show that the wear volume (V), however, decreased with the frequency (f) – this agrees with *Archard's Law*, expressed in 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].

The friction coefficient (μ) fluctuated between $\mu = 0.10$ to $\mu = 0.15$, which suggests that the relationship between μ and f is not a simple monotonic behavior.

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 lowest value of wear volume of V_3 = 3.7×10^{-3} mm^3, featuring the higher micro-abrasive wear resistance.

4. CONCLUSIONS

The results obtained in this research indicated that:

- The hardness of the "*treated*" surface of the ISO 5832-1 austenitic stainless-steel is a function of the optical fiber laser frequency value ⇒ the material hardness increased with the laser frequency;
- With the increase of the material hardness, the wear volume decreased, as indicated by the *Archard's Law*, where the wear volume is inversely proportional to material hardness;
- The relationship between the friction coefficient and the optical fiber laser frequency is not simple monotonic behavior;
- The micro-abrasive wear results indicated that the tribological behavior was influenced by the frequencies values used for the laser surface treatments. The best condition to improve the wear resistance of the ISO 5832-1 austenitic stainless-steel was obtained at the highest optical fiber laser frequency (350 kHz), causing the lowest wear volume (3.7×10^{-3} mm^3).

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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 sphere of test	
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*