Tribological Evaluation of an Optical Fiber Laser Marked Stainless Steel for Biomedical Applications

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Abstract

The effect of laser marking process on the tribological behaviour of ISO 5832-1 austenitic stainless steel (SS) on the friction coefficient and wear volume using ball-cratering wear tests was evaluated in this work. The laser marking process was carried out with a nanosecond optical fiber ytterbium laser at four different pulse frequencies. For comparison reasons, surfaces without laser treatments were also evaluated. A phosphate buffer solution (PBS) was used as lubricant. The wear tests were carried out during 10 min with PBS drip, solid spheres of AISI 316L SS with 1 inch in diameter and of 52-100 chrome steel, with 2 mm in diameter, were used as counter-bodies. The results indicated that the tribological behaviour is influenced by the laser marking process parameters used, and the wear rate is dependent of the normal force and the type of sphere.

Keywords: Orthopaedic Implants, laser, wear.

1. Introduction

Biomaterials, due to corrosion and even friction against implantable components, bones or other body parts can detach particles, which coming into contact with bodily fluids, are able to be placed in locations far from the removed source causing complications to the patients [1].

Detached particles released from the degradation process may move inertly, through tissue and/or circulatory system or can be actively transported [2, 3], compromising the biocompatibility.

The ISO 5832-1 stainless steel (SS) is one of the metallic materials used for implants manufacture, because of its mechanical and electrochemical properties and low cost [4, 5]. The laser technique is commonly used for identification of the metallic implantable medical device [4-7]. This process involved temperatures above 1600 ºC, which melts the stainless steel surfaces.

In the biomaterials' field for implantable medical or dental devices, tribological tests are of great value in providing an estimate of the normal, tangential and frictional forces in relation to the volume of material that can be detached from the surface, migration and housing of particles.

The micro-scale abrasion test (or ball-cratering wear test) is a useful method to investigate the wear resistance of various materials [8-10].

The ball-cratering wear test has gained large acceptance at universities and research centers and is widely used in studies focusing on the abrasive wear behavior of dissimilar materials [11-15].

The principle of this wear test consists in a rotating ball that is forced against the specimen being tested and a lubricant, PBS in this case, is supplied between the ball and the specimen during the experiments. The aim of the ball-cratering wear test is to generate "wear craters" on the specimen. The wear volume (V) may be determined as a function of b, using Equation 1 [11], where R is the radius of the ball.

$$V \approx \frac{\pi d^4}{64R} \qquad (1)$$

Wear tests conducted under the ball-cratering technique present advantages in relation to other types of tests, because it can be performed with normal forces (N) and rotations of the sphere (n) relatively low ($N < 0.5$ N and $n < 80$ rpm) [16-20].

The aim of this work was to evaluate the tribological behaviour of the ISO 5832-1 austenitic stainless steel (SS), widely used for biomedical applications, marked via an optical fiber laser process with four different pulse frequencies, using two ball-cratering wear methods.

2. Experimental procedure

2.1. Ball-cratering equipment

A tribometer with free-ball configuration was used for the sliding wear tests. Two load cells were used in the ball-cratering 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" forces load cells have a maximum capacity of 50 N and an accuracy of 0.001 N. The values of "*N*" and "*T*" are read by a readout system.

A nanotribometer, Anton Paar - model NTR^2, was also used mainly to observe friction coefficient evolution. These tests were performed in the air, at 25° C, with a counter-body of chrome steel 52-100 rotating ball shape, 2 mm in diameter, during 10 minutes, with normal force of the order of 100 mN, distance equivalent to 2.4 m, and scan speed of 4.0 cm.s^{-1}. Surface analyses were conducted using an optical microscope (Olympus, TM).

2.2. Materials

The tested samples were produced by bars of the ISO 5832-1 austenitic stainless steel (SS) biomaterial (chemical composition (wt%): 0.023 C, 0.78 Si, 2.09 Mn, 0.026 P, 0.0003 S, 18.32 Cr, 2.59 Mo, 14.33 Ni and Fe balance) treated with a nanosecond ytterbium optical fiber laser at four different pulse frequencies, as Table 1 shows. Each sample consisted of 5 (SS) specimens.

Table 1. Frequencies used for laser marking treatment.

Sample	**1**	**2**	**3**	**4**
Laser frequency [kHz]	80	188	296	350

Spheres made of AISI 316L stainless steel, with diameter of *D* = 25.4 mm were adopted as counter-bodies.

2.3. Micrhardness (HV)

The Vickers microhardness analyses were performed in a Fischerscope HM 2000 microhardness instrument, coupled with an optical microscope. The hardness values refer to the average of 5 measurements at a distance of 50 μm between each indentation for surfaces treated by this laser beam and also for the non treated biomaterial.

Table 2 shows the hardness (*H*) of the materials used in this work (specimen and balls).

Table 2. Hardness of the biomaterials used in this work.

	Material	**Hardness**
Sample	ISO 5832-1 SS	88 HRB
Spheres	AISI 316L SS	25-39 HRC

2.4. Wear tests

As a function of the density (ρ) of the spheres material (AISI 316L SS: ρ = 8 g/cm^3) was defined the value of the normal (*N*) for the wear experiments: *N* = 0.25 N.

The ball rotational speed was *n* = 50 rpm and with the diameter *D* = 25.4 mm of the ball, the tangential sliding velocity of the ball is equal to *v* = 0.066 m/s.

An amount of 25 wear tests (5 per condition) were conducted under *t* = 2 min and with the value of *v* = 0.066 m/s was calculated a value of sliding distance (*S*) between the specimen and the ball of *S* = 8 m.

All experiments were conducted without interruption and a phosphate buffered saline solution was continuously agitated and fed between the ball and the specimen during the experiments, under a frequency of 1 drop / 2 s.

Both the normal force (*N*) and the tangential force (*T*) were monitored and registered constantly. Then, the coefficient of friction was determined using the equation 2:

$$\mu \approx \frac{T}{N} \quad (2)$$

3. Results and discussion

3.1. Analysis of the volume of wear – V

Initially are presented images of the specimen submitted to wear tests (Figure 1 and 2). Surfaces treated by laser technique were analyzed by optical microscopy. For comparison reasons surfaces of this biomaterial without laser was also evaluated. These are relevant results to the biomaterial's field, because when manufacturing an implant one has to choose a suitable area to identification number engravings to avoid wear.

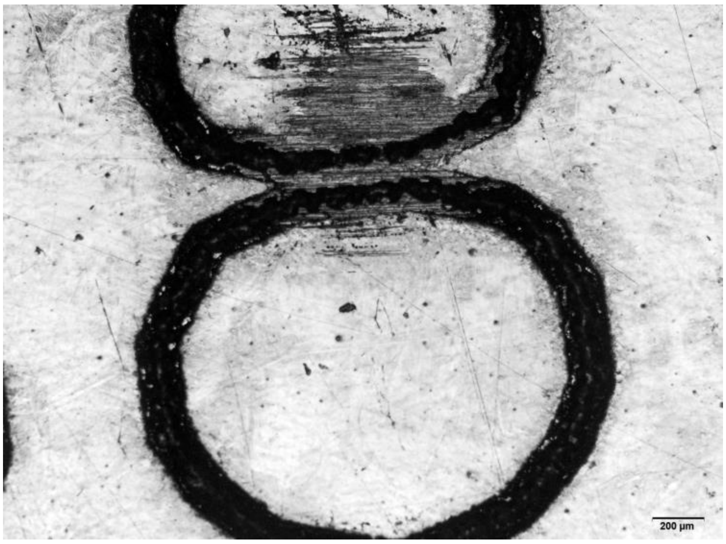

Figure 1. Wear crater obtained at the center of the laser mark.(50x).

In Figure 1, the number eight (8) was marked by laser on the ISO 5832-1 stainless steel's (SS) surface. At the center of the marked number is shown the wear crater. In Figure 2 is shown an enlargement of the wear crater presented previously. This image best exemplifies the surface modification caused by the laser pulses, which melts the surfaces increasing its roughness.

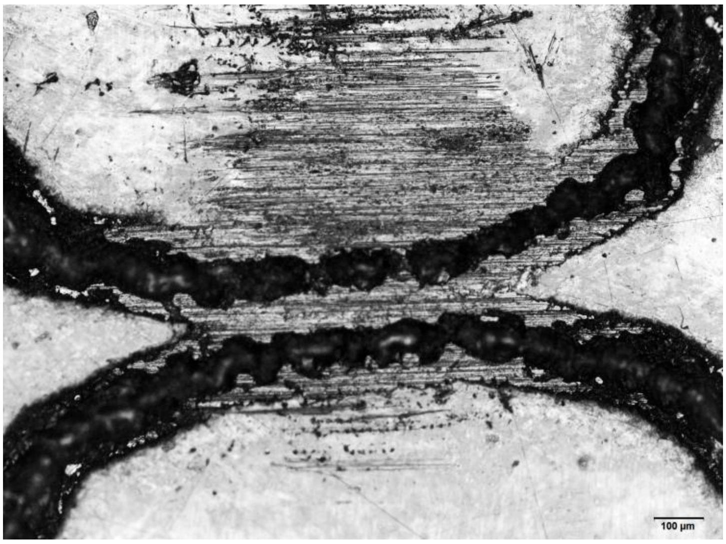

Figure 2. Wear crater obtained at the center of the laser mark.(100x).

Figure 3 presents the wear volume (*V*) behavior for the conditions marked with laser and blank. It is possible to observe that the wear volume decreased when the specimen was treated with laser. This decreasing is associated to a possible increasing of the hardness of the specimen. Table 3 shows the micro hardness measured for every type of sample studied. Each sample was composed of 5 units of laser treated specimens, as well as blank specimens, i.e., without laser beam treatment.

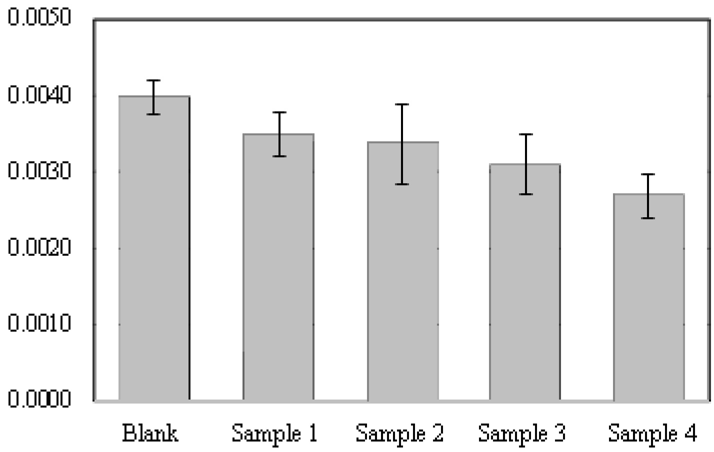

Figure 3. Wear volume (V) [mm³] as a function of the surfaces treated by laser.

Table 3. Micro hardness values for each type of surface finish.

Sample	**Blank**	**1**	**2**	**3**	**4**
Micro-hardness [HV]	199.3	204.3	215.4	226.1	239.9

3.2. Analysis of the coefficient of friction – μ

Figure 4 shows the behavior of the coefficient of friction (μ) for the conditions which the laser treated and non treated (blank) samples.

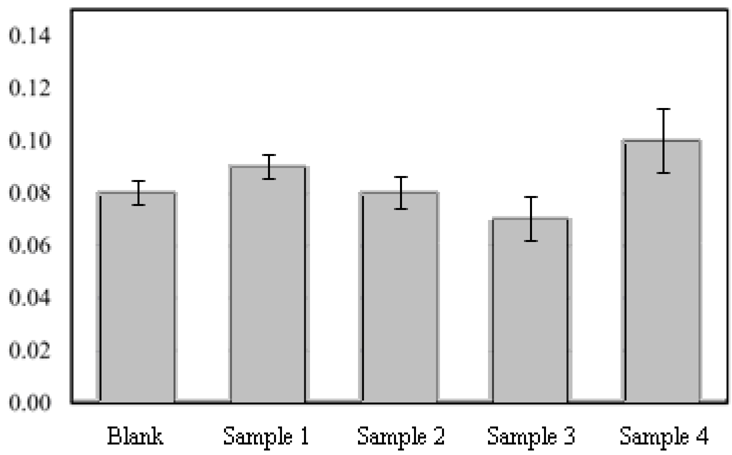

Figure 4. Coefficient of friction as a function of the surfaces treated by laser.

The highest values of wear volume were reported for samples without marks. No direct relationship between wear volume and friction coefficient was observed, *i.e.*, the highest value of wear volume was not related to the higher value of coefficient of friction [21-24].

The laser beam affected area is reduced (only the marked algarism). Another important factor is the positioning of the counter body (sphere) over the sample. For the laser marking condition, the obtained coefficient of friction values are closer to those of the sample without laser beam treatment.

The coefficient of friction values were not constant throughout the tribological test period, as can be imagined. This effect was evaluated and the results of the coefficient of friction variation as a function of the test time are presented in Figure 5, for the laser marked samples and the blank.

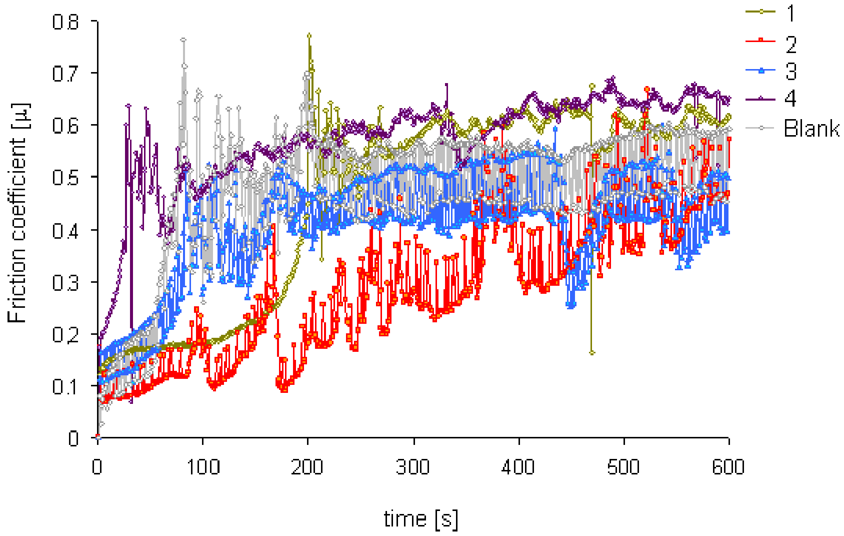

Figure 5. Variation of the friction coefficient as a function of the test time for the laser marked and blank samples.

For surfaces with laser marks (Figure 5), the friction coefficient values are closer to those obtained in the samples without laser treatment.

The friction coefficient values for the untreated samples has shown a rapid increase in the first test periods, and practically stabilize around values close to μ = 0.5, due to the surface being less rough. For all the laser marked samples, there was an increase in the coefficient of friction as a function of the test time; being the highest values obtained for sample 4. Researches have reported magnitudes of these values with the same kind of test under different tribological system [12]. The decrease on the wear volume as a function of the laser pulse frequency rise must be directly associated to the microhardness increase. Hence, for this purpose, the sample treated at the condition 4 presents a better behavior, so that the marked identifications can resist for more time.

4. Conclusions

The tribological behavior was influenced by the type of the laser process used for this biomaterial, and the wear rate was dependent of the normal force. The coefficient of friction shown an increase tendency for all tested conditions. The surface characterization shown modifications due to the high temperatures reached in the laser marking process, which involves the surfaces melting. The results indicated that the wear volume was reduced by the ytterbium optical fiber laser treatment.

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