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Friction and Wear Performance of Biomaterials Alloy AISI 316L and Ti-6Al-7Nb

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We became interested in this work to study the tribological behavior of two total hip replacements steel AISI 316L and titanium alloy Ti-6Al-7Nb tests performed in this work are essays with reciprocating movement. The tribological properties of wear by sliding (reciprocating) for the different samples were evaluated in the air on a tribometer with a tribotester software following standards: ISO 7148, ASTM G99-95a, ASTM G 133-95, with a relative humidity of 33-38% at a temperature 24 to 27°C and a non-lubricated state. The ball 100C6 steel of 10 mm diameter, 835 HV hardness and Young's modulus 310 GPa was chosen as the antagonist to prevent further chemical reactions. Three different speeds (1, 6 and 15 mms⁻¹) and four normal forces (2, 4, 6 and 10 N) were applied, which allowed us to test twelve different conditions. The values of the friction coefficient obtained in this work are confirmed by the bibliographical results and meet the standards imposed by biomedical particularly at the joint surface state of hip prostheses.

Introduction

Metals and alloys have long been used for biomedical applications. Thus, a dental implant wrought iron was discovered about a young man who lived in the Gallo-Roman era. Nowadays, metal biomaterials are used primarily in orthopedics (nails, screws, plates, joints), in dentistry (fillings, dentures, denture parts) and surgery (instruments).

Titanium and its alloys are widely used because of their advantageous properties, particularly their excellent corrosion resistance due to a high chemical inertia, associated with low density compared to steel [1]. In addition they have good mechanical characteristics and relatively high melting temperatures [2]. Therefore, these are materials which find wide applications in the aerospace sector, as well as in the automotive and orthopedic, especially the Ti-6Al-4V alloy. They are also used in chemical reactors due to their vis-à-vis inertia many aggressive environments such as chloride media [3]. And thanks to their biocompatibility with human tissue, titanium alloys are the materials of choice in orthopedics and implants (hip replacement, dental implants, surgical screws etc.) [4]. As in sea water in the human body,

excellent corrosion resistance is due to the formation of a natural self-healing and autopassivante layer of titanium oxide thickness of a few tens of angstroms [5].

Having high hardness and high toughness of austenitic steels are mainly used for artificial joints [6-9] (stems or heads of joints). Also, like 316L alloy (Fe, C: 0.02%, Cr: 17%, Ni: 12%, Mo: 2%), to improve the corrosion resistance, solid solutions into austenite Stable (Ni > 12 to 14%) are used. A concentration of Mo exceeds 2% provides a higher resistance to pitting whereas a low carbon content (0.03%) inhibits the formation of carbides and martensite deformation. Moreover, for surgical instruments such as scalpels, scissors or needles, are often used for chromium steels that withstand higher stresses. So we take as the object of this work to study the behavior of wear and friction of a biomaterial AISI 316L, used as a femoral stem for total hip replacement.

Experimental

The tests carried out in this work were reciprocating tests. The tribometer used is an oscillating ball-on-plane friction device. The tribological properties of sliding wear (reciprocation) for the different samples were evaluated in air on a tribometer equipped with tribotester software according to the standards: ISO 7148, ASTM G99-95a, ASTM G 133-95, with a relative

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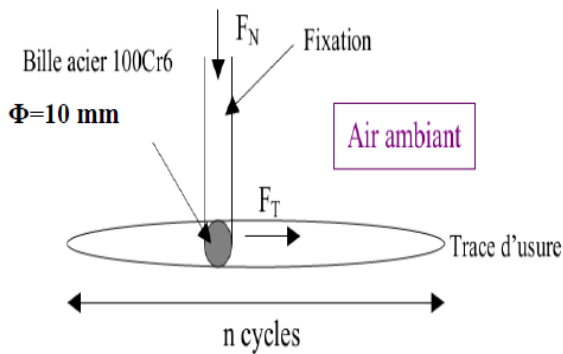


Figure 1: Wear tests conditions

humidity of 33 to 38%, a temperature of 24 to 27°C and a non-lubricated state. The steel ball 100Cr6 of 10 mm diameter, hardness 835 HV and modulus of Young 310 GPa was chosen as an antagonist in order to avoid additional chemical reactions.

Under friction conditions (dry and lubricated) and at ambient temperature, tribological tests of AISI 316L and Ti-6Al-7Nb steel were performed for different loading and speed conditions. Three different speeds (1, 6 and 15 mm.s⁻¹) and four normal forces (2, 4, 6 and 10 N) were applied, allowing us to test twelve different conditions.

Results

Evolution of friction coefficient

The evolution of the friction coefficient in function of the number of cycles in this type of contact for the studied material presents some common features which consist in the fact that there exists a certain incubation time. Depending on the materials and process parameters, this period corresponding to the initial cycles during which the friction coefficient reached a maximum value.

For all samples studied, the instantaneous friction coefficient evolves

according sliding distance and also according to the variation of the operating parameters (figure 2). Any evolution of coefficient of friction during the test is synonymous modifications in the contact zone. It follows that the close monitoring of measuring coefficient of friction during the test may ourselves about the long travel degradation mechanism (participation of the third body in the kinetics of wear). We also have experimentally determined values of the friction coefficient. CFd, CFmini, CFmoy and CFmax under different levels of force Fn and sliding speed, figure 3a includes the average values of the friction coefficient at end of the test under different conditions used to determine the tribological behavior of materials.

An initial analysis of these results (figure 2) shows that the coefficient of friction increases from the first friction cycles this is the transition period or lapping typically observed in this type of test. Subsequently, after going through a maximum (end of the transitional period that we simply will refer to as “transition”), the coefficient stabilizes after a number of variable cycles according to the surface condition and operating parameters. It appears that a small number of cycles necessary for the debris layer is established. The evacuation of the debris is low and in all cases the layer of small-sized oxides is quickly established. The general tendency regarding the number of cycles corresponding to the stabilization is that high normal load, the faster stabilization is reached.

The friction coefficient behavior can be categorized into three characteristic regions the evolution of the friction versus time in these contacts. Being the first is an incubation time (I), the second for a period of change in surface frictional properties (II) and the last in the stabilized condition of friction (III). The diagram (figure 2b) prepared below and figure 2a, summarily show these three CF Change stages:

- The incubation time is the adaptation of the two surfaces by removing surface oxides to give the metal-metal interactions in a rapid increase in CF;

- A transition period characterizes the passage of friction at steady state with the formation of the 3rd body whose life accommodates wear two contact partners.

When the number of cycles increases, loose particles from the

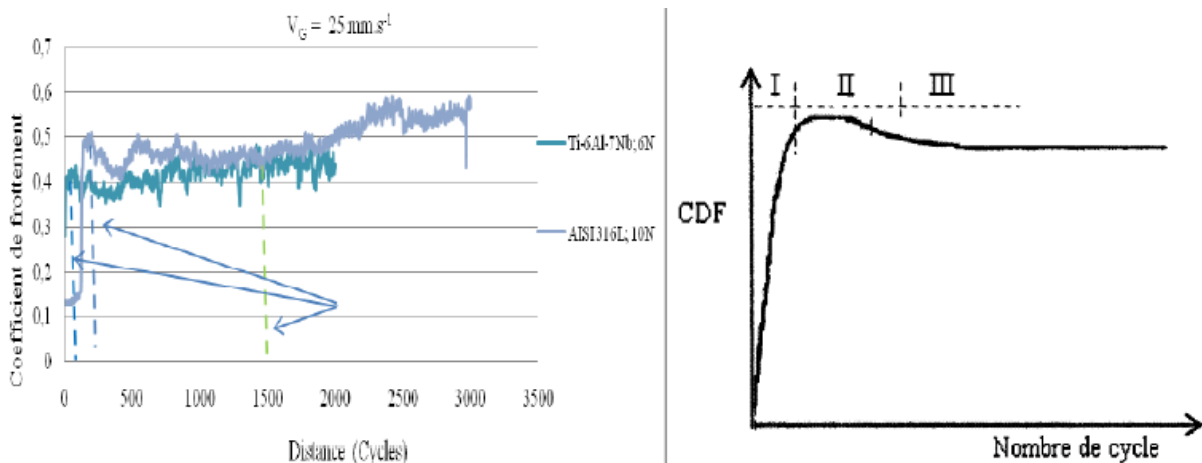


Figure 2: Evolution of friction coefficient of AISI 316L and Ti-6Al-7Nb, example of schemes and regimes of friction

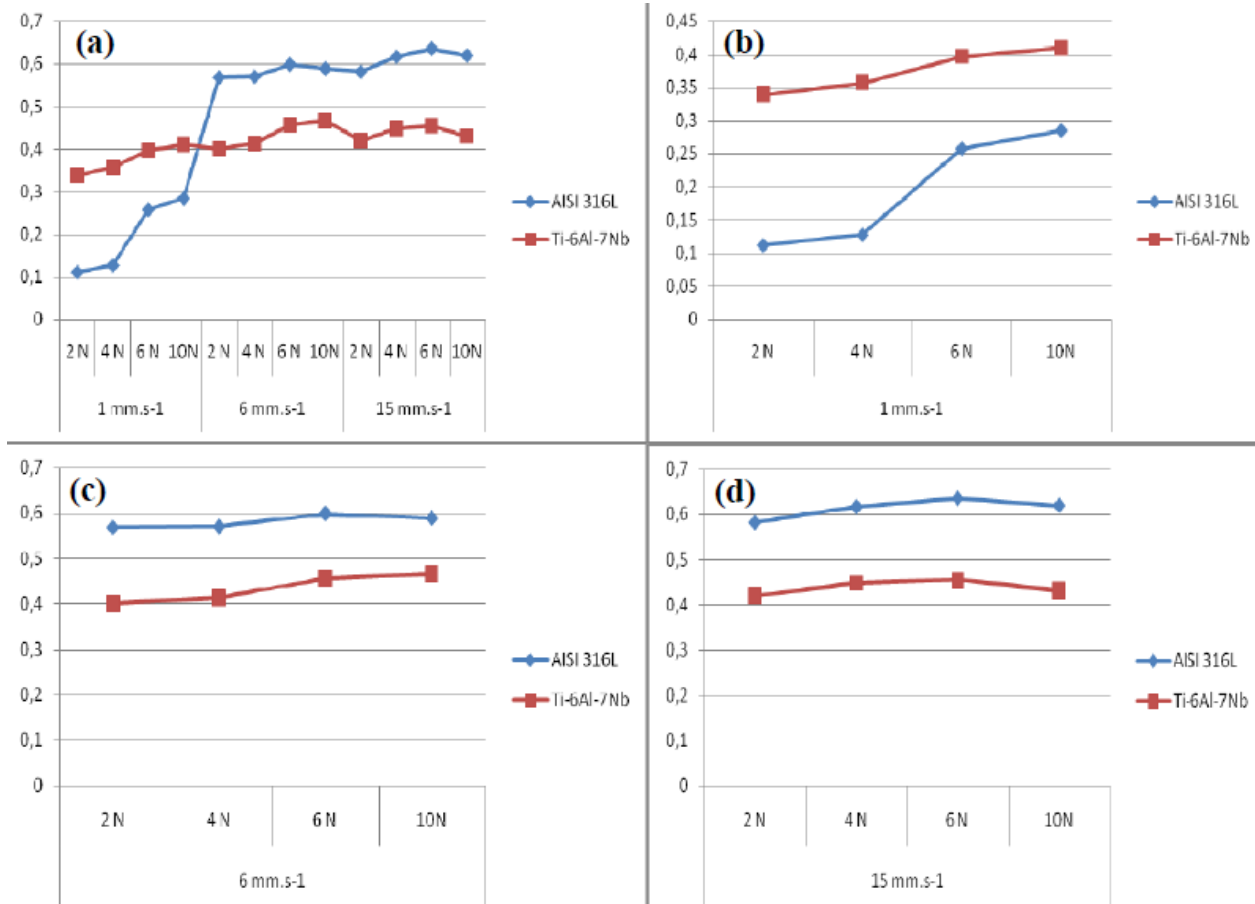


Figure 3: The average values of friction coefficient under different conditions a) recapitulative and under a speed b) 1 mm s⁻¹, c) 6 mm s⁻¹ and d) 15 mm s⁻¹

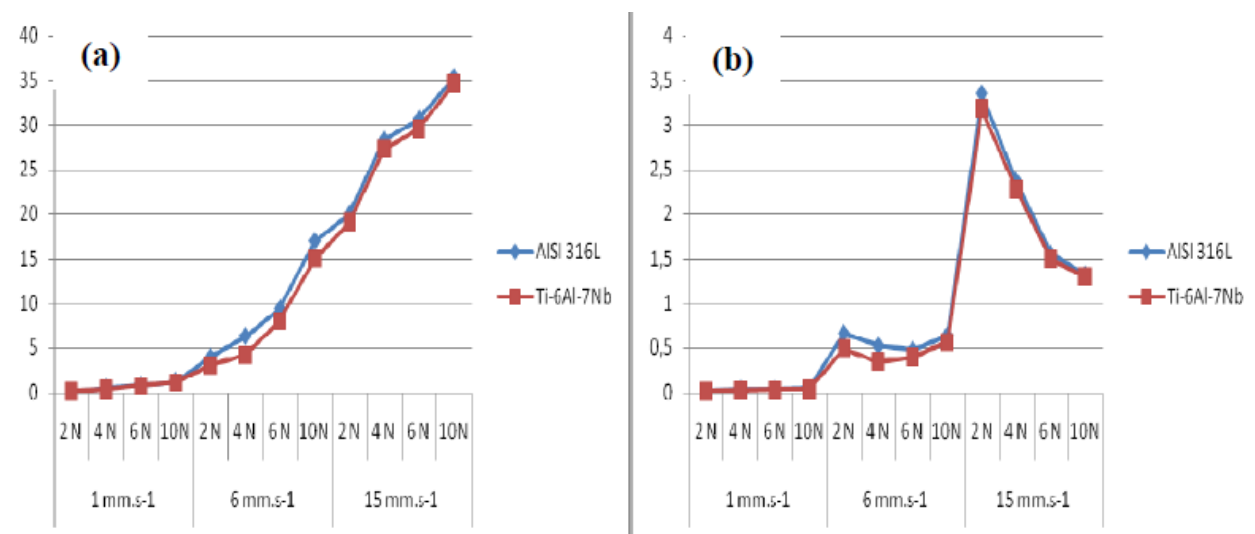


Figure 4: Evolution of: a) wear volume (μm³) and b) wear rate (μm³/N.μm) as a function of load and slip rate

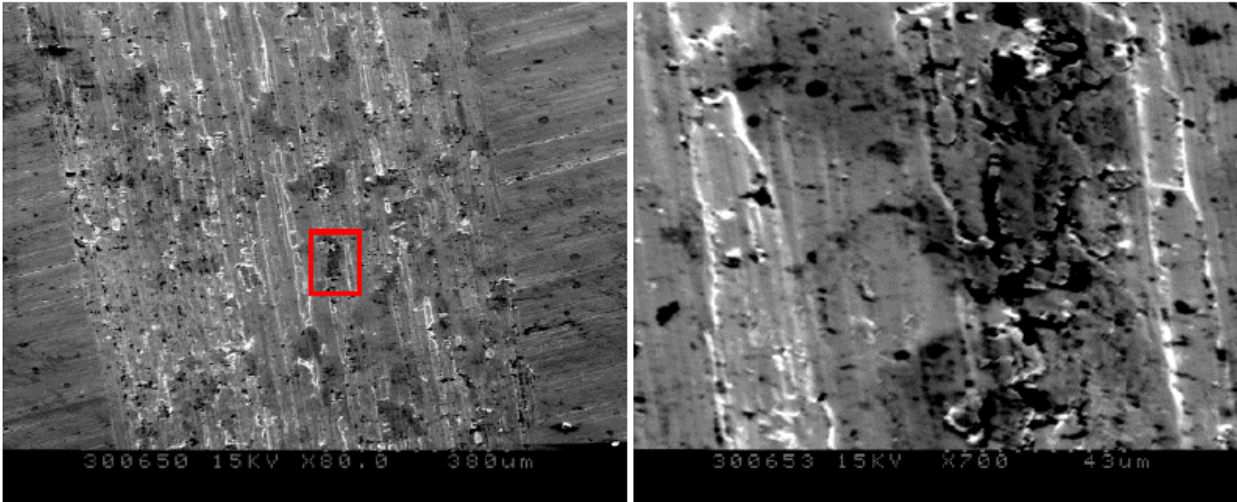


Figure 5: Oxides formed on the surface due to the increase in the temperature of the contact zone

treated surface involved in the kinetics of wear in the contact and we have verified that the situation happens every time a contact two-100C6 steel body samples to a contact three bodies 100C6 sample-steel scrap.

Evolution of volume and wear rate

Under the effect of the stress increase, deteriorating Sample surfaces occurs. The wear becomes more extensive, both in width and in depth, wear remains similar and the width and depth of wear appear unchanged. The wear volume increases almost linearly as a function of the slip speed to reach the maximum 34.6 and $35.3 \times 10^7 \mu\text{m}^3$ for AISI 316L and Ti-6Al-7Nb under the load of 10 N , respectively, at a rate 15 mm s^{-1} .

The wear rate increases almost linearly as a function of the sliding speed to achieve 3.35 and $3.18 \mu\text{m}^3/\text{N}\cdot\text{im}$ for AISI 316L and Ti-6Al-7Nb respectively, under the load of 2 N at a rate of 15 mm s^{-1} .

While the samples show a low wear rate up to 10 N at a speed of 1 mm s^{-1} and do not exceed $0.013 \mu\text{m}^3/\text{N}\cdot\mu\text{m}$. However, their wear rate is greatly increased under a speed of 15 mm s^{-1} and reached a value of about $1.33 \mu\text{m}^3/\text{N}\cdot\mu\text{m}$.

Discussion

Influence of operating parameters

Effect of sliding speed

The obtained results clearly show that the sliding speed has the main effect of acting on the evolution of the wear and friction and this may be due to the elevation of the temperature of the contact zone. Overshoot of a critical speed causes surface melting of the most fusible body.

Increasing the temperature of contact with the speed induced structural transformations and increases the reactivity as function

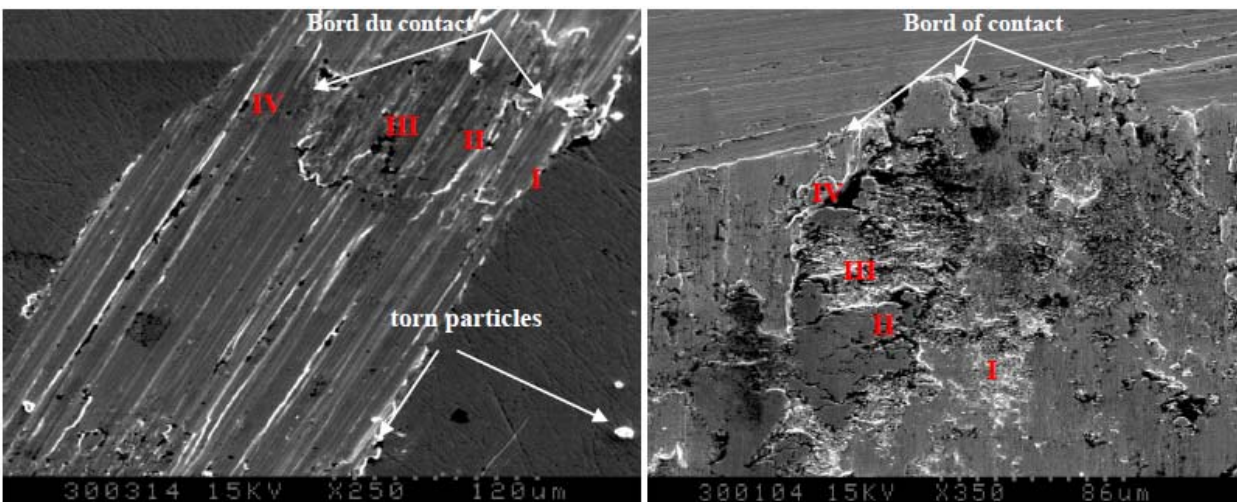


Figure 6: Oxides debris evacuated at the periphery of the contact, a) SS AISI 316L and b) Ti-6Al- 7Nb

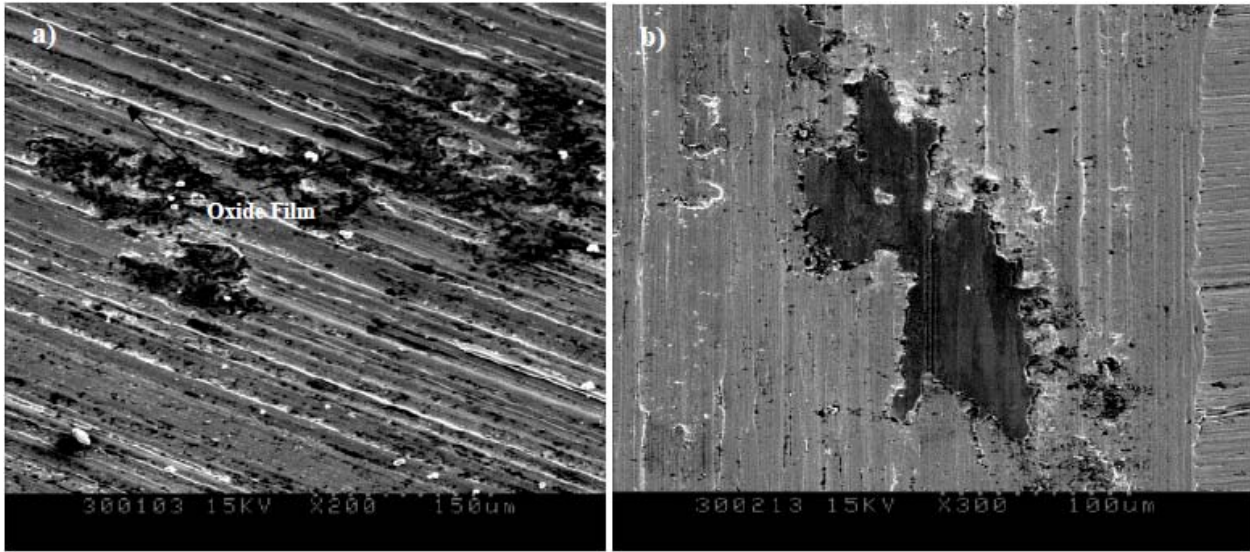


Figure 7: Presence of oxide films and powdered debris in the contact area, a) AISI 316L b) Ti-6Al-7Nb

the environment surfaces. Above a given temperature and thus for sliding speeds above a critical value, the oxide film resulting from permanent oxidation, reconstitutes gradually as it is destroyed by wear. Generally, the friction coefficient decreases with an increase in the sliding speed, which has been already confirmed by *M. Fella* et al. [10].

Moreover, raising temperature of materials in contact influences their wear resistance, and leads to a degradation of their mechanical properties. *Amonton* their shares (1699), *M. Fella* et al. [11, 12] and *Lesquois* [13] found that friction resistance, were related to movement speed. *Desaguilers* (1734) also noted that the friction of the moving body is proportional to speed. *Bochet* (1858) presented a mechanical study to link the value of the sliding friction

coefficient to the speed of movement. It was found that the sliding friction of the intensity decreases as the speed increases. *Galton* (1878) and *Deprez* (1884) also found that the coefficient of friction decreases with increasing speed. *Mercier & Dubois* (1937) were interested in the variations of the friction coefficient with speed. They found that for high speeds, as for high pressure, the variations of the friction coefficient are slower.

Effect of temperature

Raising temperature increases the diffusion rate as a function of pair of materials in the presence and operating parameters such as stress and the movement speed. As a result various forms of energy loss leading to multiple degradation mechanisms resulting in the

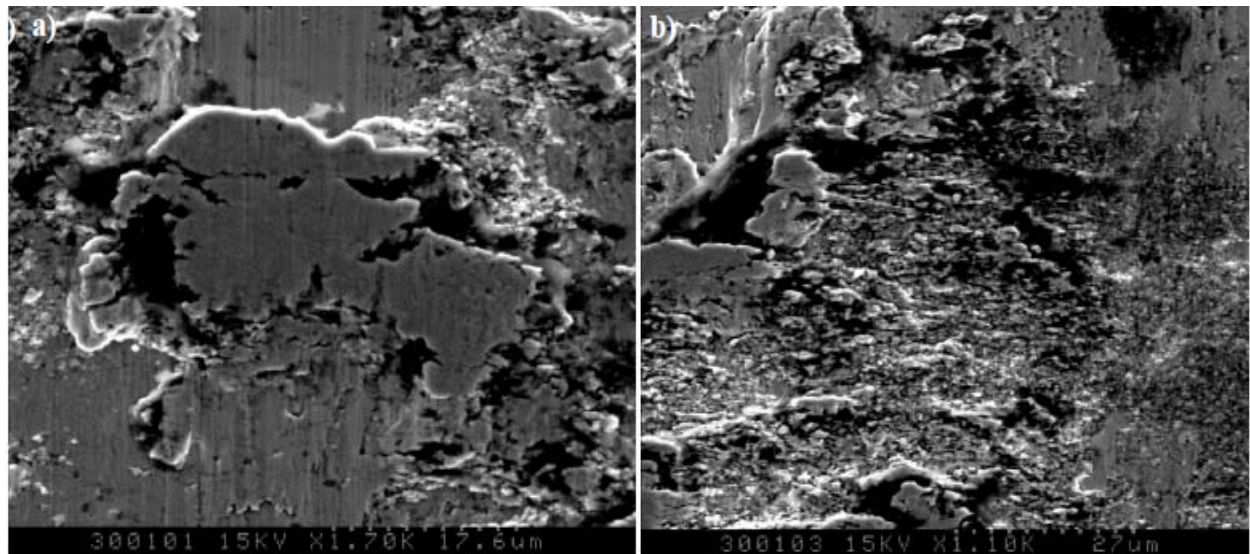


Figure 8: Wear particles torn and oxidized of surface and agglomeration on the contact surface a) AISI 316L and b) Ti6Al7Nb

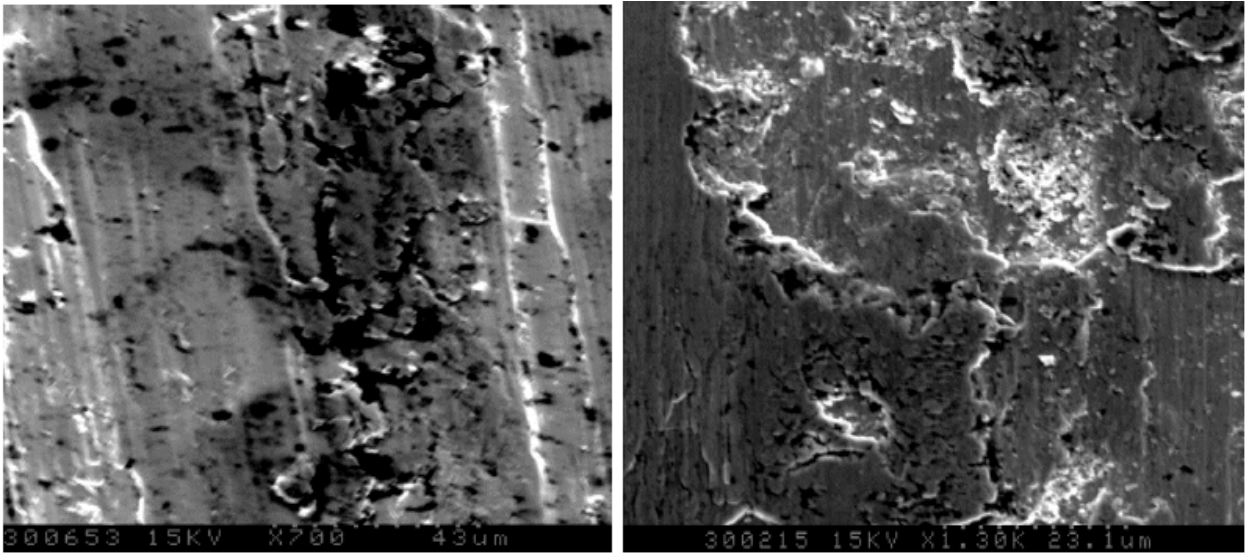


Figure 9: Friction film locally made small scales, and pretend cracked

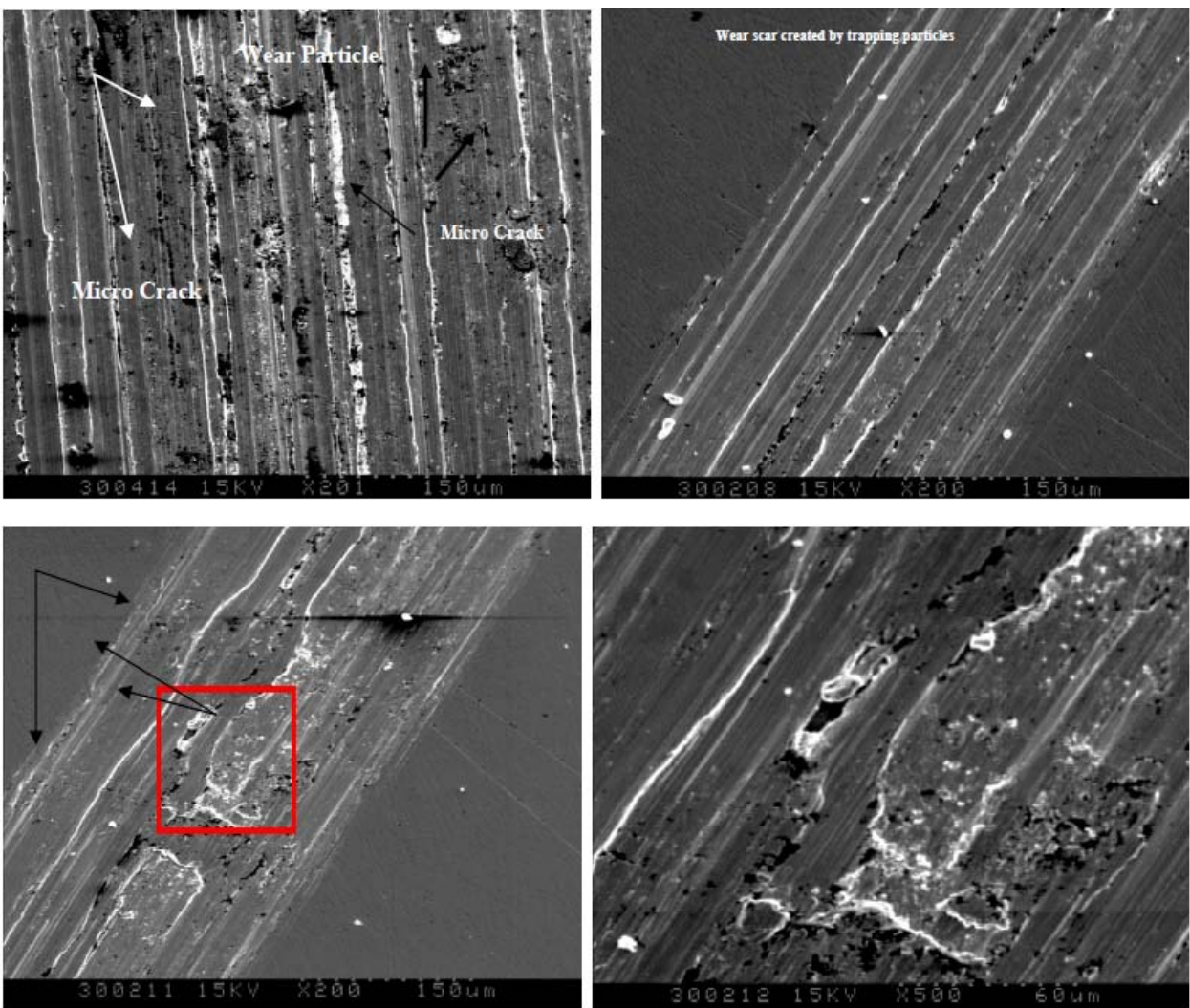


Figure 10: Wear scar created by the trapping oxidized particles then acting as an abrasive.: Training of shavings, and different areas of friction

modification of the contact interface as shown in Figure 5. The same phenomena have been discussed in several publications by R. Holinski [14], Zaidi et al. [15] and Mr. Fellah et al. [16] which highlighted the effect of the evolution of the contact temperature and the frictional force during the initial slip of a tribological system.

Effect of applied load

The obtained results show that for the high contact area, the coefficient of friction is independent of the normal load. However, for very small contact areas when normal force increases, the friction coefficient can either increase [17], or be reduced [18].

According to the first law of Couloumb (1781), confirmed by Morn; "The frictional force is proportional to the total pressure between the two bodies." If Amontons (1699) concluded from his experiments that the friction coefficient is constant, other investigators have suggested otherwise. Vince (1785), for example, deduced from his experiments that the friction coefficient decreases with increasing N pressure and that, for a given pressure, it decreases with increasing pressure P and that, for given pressure, it decreases as the contact area becomes small. Fish said that this is not the total pressure N that affects the value of the coefficient of friction, but the pressure contact surface unit.

Study of wear

Contacts Low-wear

Surface chemistry, the relative hardness and ability to work hardening materials help explain the behavior of the contact pairs. Couples with low wear, 100C6 / 100C6 316L / Ti-6Al-7Nb exhibit good stability for wear resistance. Note that the steel-steel torque (100C6 / 316L) for loads 6 and 10 N wears slightly faster than titanium-steel alloy couple (100C6 / Ti-6Al-7Nb) with a ratio of hardness 2.5 to 3 with the following values (HV 835/318 and 835/355 HV) in the pairs 100C6 / 100C6 and 316L / Ti-6Al-7Nb respectively. The value of this test gives a rough estimate of the difference in resistance to plastic deformation between the two materials as explained by Mr. Fellah [19]. In the case of steel AISI 316L, wear debris from the plate form of stable fine oxide particles and Fe₂O₃ Cr₂O₃ type, these results agree with those obtained by D. Gagnon [20]. This layer forms a solid lubricant. Figure 6, and from the perspective of the tribocouche, steel AISI 316L is an interesting metal in low-load contact [21]: it easily consolidates and wear debris from oxides of Cr and Ni which participate in the formation of the tribocouche that protects the surface of the plate

The trace in figure 6 shows the oxide debris transferred near the track of the sliding steel AISI 316L (Figure 6a) and Ti-6Al-7Nb (Figure 6b) for an amplitude of 5 mm below a load of 6 N to a speed of 15 mm s⁻¹. There are four different areas of damage: zone I, called central Hertz II a compaction particles, the area III is the contact edge and IV the discharge area of the particles out of contact. The distribution of these different zones depending on the evolution of the stress is represented by figure 6.

Large debris is formed in the zone I where the stresses are highest in the area and the shear is the strongest. It is in this central area that is elaborated the damage. It may be noted that this area appears dark electron microscope, indicating that it consists of little oxidized metals. In the next zone II, the surface is formed by fine particles agglomerated and oxidized. This layer is resistant to effort traction and thus protects much of the materials of the area I. The fine particles of IV are from Zone II. The damage is the result of two Independent mechanisms:

- Delamination of zone I and therefore the micro-chip forming;
- Forming by agglomeration of fine particles of an oxidized layer

surface in the zone II. This layer degrades by ejecting generally small debris are the zones III and IV.

Elimination of one of these two mechanisms increases the strength of torque. Analysis of the morphology of wear marks in these areas will give more information on the couple destruction mechanisms.

Morphological study of wear traces

The study traces of wear clarify the friction mechanism including sliding. Pictures taken by SEM illustrate surface degradation mechanisms. The observation of various areas of the friction surface (Figure 7) after contact highlights the significant degradation of the surface, but also the uniformity of degradation mechanisms. The presence of oxide films, promotes the detachment of particles or "lamellae." It is observed during the friction tests, that third body particles, mainly from the surface degradation of AISI 316L and Ti-6Al-7Nb, are present in significant amounts, outside and interior of the friction track and is compacted therein.

In general, for all conditions (except for speed 1 mm s⁻¹) of the tests carried out, it is found that the value of the friction coefficient of the steel AISI 316L is higher than that of Ti-6Al-7Nb. The existence of this high friction is likely due to the formation of difficulty of a third powder body in contact, often sought to reduce friction. The observations of the friction tracks show little third body particles outside the friction surface (Figure 6). On the other hand the presence of oxide films and porosity (Figure 7) promotes its degradation and consequently the formation of powder debris in the contact.

The 100C6 ball plastically deforms the steel plate (AISI 316L or Ti-6Al-7Nb). Under the effect of tangential stresses, particles of the soft material tend to sell the surface of the plate and oxidize in the case of fine particles. The ball hardens the soft material and promotes the incorporation of particles in the soft surface. It will therefore occur forming a micro mechanical alloy surface layer consists of a soft matrix and micro oxidized particles. When the shear stress exceeds the strength of the alloy layer, chip microphones will come off with the production of small debris. An agglomeration of debris will occur on the surface, especially at the periphery of the contact trace (Figure 8).

The sliding wear occurs when two solids are in relative sliding. It causes mechanisms of adhesion, abrasion, fatigue and corrosion. Studies by *Pearson et al.* [36] describe the coexistence of three basic mechanisms of wear in sliding stresses in a corrosive environment (adhesion, abrasion, tribocorrosion). Figure 10 shows the wear pattern observed after sollicitation of an AISI 316L stainless steel and Ti-6Al-7Nb. The wear scars are generated by oxidized particles, trapped in the contact, which then act as an abrasive.

The studied materials undergo large plastic deformation with a degree of hardening high surface or near the surface. Microscopy of these thin and highly plasticized areas reveal that the plastic deformation increases more wear detachment of particles or chips in particular from micro voids that serve as primer sites and propagation of microcracks, these results (Fig. 10) are in agreement with those of *M. Fellah* [23, 24] and *M. Labaiz* [25].

These microcracks proliferate and spread due to cyclic stresses due to the repeated passage of rubbing body. These stresses contribute to the spread of subcutaneous cracks before emerging to the surface. As for subsurface localized cracks in the radio zone, they proceed in parallel with the contact interface during sliding. Two phenomena can explain the formation of small chips: the breaking of the transfer layer or breaking into a subsurface metals

present. Delamination theory based on dislocations stipulates that the formation of the transfer layer is connected both to energy cohesion solid body contact than the adhesion energy at the interface. This was explained by *N. Ohmae* [26] that this phenomenon is of great importance in the detachment of particles and wear chips.

Delamination encountered in the case of steel AISI 316L and Ti-6Al-7Nb is the loss of material in the form of scales, due to cracks which join under the influence of shear to form wafers will be torn from the form of small chips on the surface as it was presented in a study by *M. Fellah* [27]. Figure 10 schematically illustrates the mechanism for a conventional Contact ball-plane where the cracks are nucleated from micro-voids under the surface before spreading and emerge at the contact surface.

N. Kurgan [28] showed that the wear of a steel AISI 316L varies depending on the load and sintering temperature. The spherical pores in the samples increase resistance to wear. In addition, the porosity rate of reduction improves all of their mechanical properties. The same results are in agreement with those obtained by *Junhu Meng* [29] on a AISI 316L steel, at low loads (1, 2 and 5 N) for a distance of 1000 m, at a sliding speed of 0.1 ms⁻¹. Friction coefficient values vary (0.6 to 1) and the wear rate (10⁻¹⁵ to 10⁻¹¹ μm³/N.μm). The formed oxide layer is composed of various favorable iron oxides, such as Fe₃O₄, α-Fe₂O₃, λ-Fe₂O₃ and FeOOH, which cause moderate wear. In the case of sintered stainless steel in hydrogen, the worn surfaces were very rough with very trapped wear debris. The adhesive wear was responsible for the transfer of the material steel AISI 316L to 100C6, which led to the transition from low to high wear as has been confirmed by *N. Kurgan* [28].

Always and for comparison, *CN Kraft* [30] confirmed that titanium wear is lower than that of stainless steel AISI 316L, and that the presence of a lubricant reduces the weight loss that was far from agreement with the results obtained at the end of this work. The different periods and sliding regimes determined at the end of this study are consistent with those obtained by *Zivic F. et al.* [31] in the tribological behavior study of Ti-6Al-7Nb in a load range (100-1000 mN) at speeds (4-12 mm·s⁻¹) in a sliding distance of 30 m. The friction coefficient values obtained by *F.Zivic* varies from 0.3 to 1. In a second study, the same author *F. Zivic* [32] showed that the slip rate showed no influence on the rate of wear.

The Ti-6Al-7Nb alloy exhibited a mass loss less than that of steel AISI 316L as an alternative sliding at low loads (100 to 1000 mN) in different speed limits (4.8 and 12 mm s⁻¹). These results are presented by *D. Iijima* [33] during the evaluation of the wear resistance of Ti and Ti-6Al-7Nb dental application over a distance (10, 50, 100, 150, 200 kc). The alloy Ti-6Al-7Nb exhibited a mass loss (2-6 mg) lower than that of CP-Ti (about 57%). In addition, the observation (SEM) showed that the worn surface of Ti-6Al-7Nb is much smoother than that of CP-Ti. The results indicate that the alloy castings Ti-6Al-7Nb are a good choice for the production of prostheses.

Different wear mechanisms were observed as a function of applied load. At low loads, the wear resistance is improved significantly by the duplex treatment during contact (sliding / rotation), that is to say that abrasion was observed. However, with the increase of the load applied by delamination mechanism of wear and fatigue appeared. *E. DE Las Heras et al* [34] explained in the case of loads applied the highest (1960 N) and at a speed of 220 tr.min⁻¹, delamination is the main wear mechanism observed in samples tested. However the mass loss measured is 0.7 g to 350 m.

The same values are obtained by *L.V. Wilches et al* [35] for four

different loads (5, 15, 30, and 50 N) at a rate of 0.58 m.s⁻¹ in the presence of a physiological medium. The friction coefficient values obtained vary from (0.6 to 0.9). The same coefficients of friction values are obtained by *TM Manhabosco* [36] under a sliding speed of 8 mm·s⁻¹ and an applied normal load of 4 N. In dry sliding conditions, the friction coefficient value varies of (0.3 to 0.7) and the wear volume measured varies (1.2×10⁻¹⁰ to 2.4×10⁻³ m³).

Friction coefficient values range from (0.2 to 0.4) and (10-10 to 10-8 mm3N-1m-1) to the volume of wear are obtained by *Met C., et al.* [37] under a sliding speed of 0.1 ms-1 and normal load variation of 0.5 to 13 N. Two wear mechanisms were observed by *Ohidul MD et al.* [38]: the delamination with low severity and oxidative wear. The authors thought that the titanium alloy of ability to form a protective oxide layer during wear results in the low wear rates in this alloy.

The wear of the sliding contact materials contributes to warming, to dissipate the energy of friction between the two materials. *Mr. Z. Huq et al.* [39] propose a procedure for correlating the wear volume of one of the first body to the energy dissipated during the ball friction test plan. This is justified by the fact that the friction energy generates damage or wear, plastic deformation, fracture and /or tribochemical reaction. Various methods of calculating the energy dissipated and the wear rate in different tribological contacts are proposed in the literature by several authors *M. Huq* [40] *M. Fellah* [41] and *S. Fouvry* [42]. The influence of various parameters of the friction tests, for example sliding mode, normal load and combination of materials were examined. The process of wear in sliding contacts are assumed to be induced by the contact temperature, microstructural changes, tribochemical of film formation, fusion of the contacting surfaces or defects induced by mechanical and thermal stresses [43, 28] .

In fact, the increase of the local temperature and the loss of material in the wear tracks result of energy dissipation in the frictional contact area. The concept of power flux density of friction, QF, was introduced as a means of measuring the degree of frictional heating (energy expenditure) taking place in the contact area of the friction surfaces.

Conclusion

The tribological behavior of the above mentioned materials, and the correlation of their mechanical properties vis-a-vis resistance to a solicitation wear and friction has been studied. wear tests, in point contact reciprocating were used to see the type of wear and quantify the mass loss of a hand and see the variation in the friction coefficient in different load conditions, speed and lubricant, other.

The results obtained show that the instantaneous friction coefficient changes according to the variation of the operating parameters. Any change in the coefficient of friction during the test is synonymous changes in the contact zone. When the number of cycles increases, loose particles from the treated surface involved in the kinetics of wear in the contact and we have verified that the situation happens every time a contact with two bodies in contact with three bodies.

For normal loads given, the results show the increase of the friction coefficient for small sliding speeds 1 mm s⁻¹ (with a maximum value of 0.485) and fall for high speeds (15 mms⁻¹). The friction coefficients for a low speed of 1 mm s⁻¹, relating to Ti-6Al-7Nb are slightly higher than those for the steel AISI 316L. In general, for all conditions of the tests carried out, it is found that the value of the friction coefficient of stainless steel is higher than that of Ti-6Al-7Nb.

The amount of material transferred on the samples does not appear to $1\text{mm}\cdot\text{s}^{-1}$ largest at $15\text{mm}\cdot\text{s}^{-1}$. Moreover, streaks are observed on the wear of the ball facies after applying a load of 10 N, which indicates a real damage of the samples, with removal of material. Under the effect of increased efforts, deteriorating surfaces of samples occurs. The wear becomes more extensive, both in width and in depth. Except for the sample at a speed of $1\text{mm}\cdot\text{s}^{-1}$, the wear remains similar and the width and the depth of wear appear unchanged.

The volume and wear rate of studied materials studied was evaluated by measuring the volume of wear induced by friction with respect to the load applied and the sliding distance. The results obtained show that:

The wear volume increases almost linearly with the slip speed to its maximum 35.3 and $34.6\times 10^7\ \mu\text{m}^3$ for AIS 316L steel and Ti-6Al-7Nb respectively under the load of 10 N to a speed of $15\text{mm}\cdot\text{s}^{-1}$.

The obtained results show that the wear volume depends on the normal load; these experimental results confirm that the Archard law applies to the contact type studied. There is a critical load beyond which the wear increases considerably. In the first part of the curve at low load, the used volume is substantially proportional to the load. The increase in speed results in a wear and moreover probably by increasing the number of contact points and then by increasing the density of junctions. It should be noted that, during sliding at a speed of $1\text{mm}\cdot\text{s}^{-1}$, the wear volumes are very low, if not negligible, and cannot be measured.

The wear rate increases almost linearly as a function of the speed to achieve 3.35 and $3.18\ \mu\text{m}^3/\text{N}\cdot\mu\text{m}$ for AISI 316L and Ti-6Al-7Nb respectively, under the load of 3N at a speed $15\text{mm}\cdot\text{s}^{-1}$. While the samples show a low wear rate up to 10 N at a speed of $1\text{mm}\cdot\text{s}^{-1}$ and do not exceed $0,049\ \mu\text{m}^3/\text{N}\cdot\mu\text{m}$, however their rate of wear is greatly increased under speed of $6\text{mm}\cdot\text{s}^{-1}$ and reaches a value of the order of $0.64\ \mu\text{m}^3/\text{N}\cdot\mu\text{m}$.

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