EXPERIMENTAL ANALYSIS OF TRIBOLOGICAL BEHAVIOUR OF UHMWPE AGAINST AISI 420C AND AGAINST TIAL6V4 ALLOY UNDER DRY AND LUBRICATED CONDITIONS

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Abstract

Friction and wear behavior of ultra-high molecular weight polyethylene (UHMWPE) sliding against AISI420C austenitic stainless steel and against TiAl6V4 alloy under dry and lubricated conditions were investigated with a reciprocating pin-on-flat tribometer. The tests were conducted by varying frequency of the pin alternative motion and the applied normal load. For the tests in lubricated conditions a fluid containing a large amount of sodium hyaluronate has been chosen. The worn surfaces of the UHMWPE were examined with a 3D optical profiler. By using an electronic precision balance the wear mass loss of the UHMWPE samples was evaluated accordingly. The tribological performances of pairs UHMWPE/AISI 420C and UHMWPE/TiAl6V4 alloy were also investigated for the purpose of comparison. The results show both the values and the behaviour of the friction coefficients for several operating conditions both the resulting wear phenomena.

Key Words: Friction; Wear; Ultra-high molecular weight polyethylene (UHMWPE); TiAl6V4 alloy.

1. Introduction

Over the last few years many studies were developed in the field of lubrication and wear assessment of natural and artificial human joint [1-7] in order to achieve useful tribological information for joint replacements. It is well known that the total knee joint replacements (TKRs) are very complex in their design; they could be designed to resist mechanical stress and fatigue effect due to the normal load applied in a large number of cycles during the gait and during the others activities in the common life. Ultra high molecular weight polyethylene (UHMWPE) tibial bearings articulating against metal or femoral condylar components remain the materials of choice in TKR [8–11]. Due to the functionality of the knee joint, the femoral component must rub against the surface of the tibial insert thus creating friction and wear. The wear of UHMWPE and the resulting wear debris may be embedded in the surface and could remain in the muscle tissue surrounding the implant. These polyethylene wear particles induce a tissue response that results in osteolysis and aseptic loosening [12-14]. Therefore, UHMWPE wear has been one of the limiting factors to the long-term success of TKR [15]. For these reasons in the last years the studies of friction and wear behaviour of UHMWPE are more important and of interest to tribologists. Dong et al. [16] showed that the tribological behaviour of UHMWPE under water lubricated sliding conditions could be significantly improved by surface engineering techniques. In their investigation, a pin-on-disc tribometer has been used to assess the tribological behaviour of UHMWPE when sliding against untreated, PVD diamond-like coatings (DLC), nitrogen ion implanted, 'TO'-treated, and 'OD'-treated Ti6Al4V counterfaces. Lancaster et al. [17] investigate the effect of surface finish of several biomaterials on the wear of UHMWPE using a reciprocating pin-on-plate tester with bovine serum as a lubricant. Xiong en al. [18] investigated the friction and wear properties of UHMWPE rubbing against the modified alloys under lubrication of distilled water using a pin-on-disc tribometer. The choice of a suitable lubricant to mimic in vivo conditions undertaken for prosthetic joint materials has been investigated [19]. Several studies [20-22] have been reported on the effect of the various components of synovial fluid on friction and wear. Gispert et al. submitted the most commonly used joint materials for substitution of hip joints to pin-on-disk tribological tests. In their study four different types of lubricants were used and obtained from solutions of Hanks' balanced salt solution (HBSS), bovine serum albumin (BSA) and hyaluronic acid (HA). In the presence of synovial fluid in human joints the hyaluronic acid does actually increase the lubricant's viscosity whereas the albumin favours the boundary lubrication [23].

In the present study, we compare the tribological behaviour of the UHMWPE (GUR 1050) against AISI 420C austenitic stainless steel and against TiAl6V4 alloy. The tests were carried out by using a reciprocating bio-tribometer in dry and lubricated conditions. As lubricants, we used the biological model fluid: sodium hyaluronate (Hyalgan®). The friction coefficient and the wear were measured with several loads and several frequencies to investigate on the tribological behaviour of the couplings.

2. Experimental

The friction and wear properties of UHMWPE were measured by TR_Bio 282 pin-on-flat reciprocatory DUCOM tribometer. The schematic of the tribometer is shown in Fig.1. The machine can apply a contact loads from 1 N to 20 N. It can operate with a wide range of frequencies from 0.1 Hz to 35 Hz.

2.1. Materials

With purpose of tribologycal comparision, the following materials have been tested: ultra high molecular weight polyethylene UHMWPE (GUR 1050) against austenitic stainless steel AISI 420C and against TiAl6V4 alloy. Table 1 shows the main mechanical properties of the materials.

The austenitic stainless steel AISI 420C pin and TiAl6V4 pin were sphere-shaped with a diameter of 6 mm. Figure 2 shows the spheres of steel and of titanium and the assembly schema in its bracket.

Polyethylene has been cut and polished from a tibial insert in square-shaped 5x5x5 mm.

A pharmaceutical fluid called Hyalgan® was chosen for the test with the lubricant, which contains a large amount of sodium hyaluronate. This one is used to help regenerate cartilage and it is very similar in consistency and in the properties to synovial fluid which materially acts in the knees. The active principle of the HYALGAN is a hyaluronic acid fraction with a high degree of purity and molecular definition, which has particular biochemical, physicochemical and pharmacological properties. Normally, the intra articular injection of HYALGAN in arthritic joints induces a normalization of the viscoelasticity of the synovial fluid and an activation of tissue repair processes at the level of the articular cartilage. In some experimental models an anti-inflammatory activity and analgesic activity of hyaluronic acid has been also highlighted [24]. These properties translate into an improvement in joint function and in the control of the objective and subjective symptoms related to the arthritis disease.

2.2 Tribological tests

Reciprocatory pin-on-flat friction tests have been carried out at controlled room temperature and humidity. Several long tests were made to study the tribological characteristics of metal pins rubbing against UHMWPE flats. There have been a total of 26 tests: 18 for the steel and 8 for the titanium. The tests were performed under dry conditions and under lubricated conditions. Normal loads that were employed varied between 10 N, 15 N and 20 N in a frequency range of 5-10-20 Hz in order to have three fixed values for the mean pressure at the interface. The pressure varies between about 16 MPa and 31 MPa according to the weight of the person and the type of prosthesis [25-26]. By using the well known Hertz's contact theory and an iteration method we have determined the above range.

$$a = 0.908\sqrt[3]{\frac{N}{D \cdot E^*}} \tag{1}$$

$$\frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \tag{2}$$

$$D = \frac{1}{2} \cdot \left(\frac{1}{R_1} + \frac{1}{R_1^{'}} + \frac{1}{R_2} + \frac{1}{R_2^{'}} \right) \tag{3}$$

Where a is the radius of the contact area and N is the normal load applied in the contact. E is the Young's Modulus v is the Poisson's ratio of the respective materials. R and R'

are the radius of the contact area in the x axis and the y-axis. The mean contact pressure is calculated as follows:

$$p_m = \frac{N}{\pi \cdot a^2} \tag{4}$$

The results for each kind of load are shown in the following tables:

The tests were made at the same cycles (30.000) for dry conditions and for lubricated conditions.

3. Friction and Wear

3.1 AISI420C-UHMWPE

The graphs 4-6 show the evolution of the friction coefficients during the test. There are three pairs of figures for three different load values: 10N (Fig 4), 15N (Fig. 5) and 20N (Fig. 6). In each figure it is possible to note the friction coefficient behaviour under dry condition (Fig. 4a) and under lubrication condition (Fig 4-b). The black line represents the frequency of 5 Hz, the red line is the frequency of 10Hz and blue line is the frequency of 20 Hz.

It can be seen that the friction coefficients of all rubbing pairs under dry condition were low at the initial stage, but rapidly increased and stabilized with sliding distance (figures 4-5-6 on the left). Conversely, the friction coefficient under lubricated condition is lower than under dry condition for all loads but its behaviour is different. In fact, it increases quickly and then suffers a slight decrease and then it stabilizes (Figg. 4-5-6 b). In only two cases the behaviour is different: 15 N at 5Hz and 10Hz (Fig.5 b).

Figure 7a shows the dynamical friction coefficients that were measured in the tests carried out under dry conditions for the *AISI420C-UHMWPE* tribological pairs with three different loading conditions.

No correlation can be identified between the load and the friction coefficients. An increase in the friction coefficient can be appreciated due to the frequency. Only in one case, to 15 N in the load and 10 Hz in the frequency, we get a lower coefficient of friction. This may be due to the metal pin rubbing against the UHMWPE operates under fluid dynamic lubrication conditions. Figure 7b shows the dynamical friction coefficients that were measured in the tests carried out under lubricated condition for the *AISI420C-UHMWPE* tribological pairs with three different loading conditions. Obviously, the introduction of hyaluronic acid tends to decrease the values of the friction coefficient. Figure 7b also shows that the friction coefficient increases from motion frequencies of the sphere of 5 to 10 Hz but at 20 Hz it decreases. This probably is due to the nature of the lubricant which is very viscous but at high speed could favour distinct lubrication phenomena. To measure wear, weight measurements were performed before and after each test in order to determine how much material was removed during the dry test only. By using an electronic precision balance the wear mass loss of the UHMWPE samples was evaluated accordingly. The balance was established with an accuracy of 0.01 mg. The figure 8 shows that the wear rates for the AISI420C-UHMWPE contact increase with increasing load and frequency with a small exception in the case of load 15N and frequency of 10 Hz.

The values are increased by a few tenths of microns for different frequency values. That possibly generates a combination of applied loads and speeds that introduce mechanisms of boundary or transient lubrication which deserves future thorough investigation. Furthermore, the worn surface of the specimens was analyzed by a PLu neox SENSOFAR® 3D optical profiler, which provided three-dimensional scans of the tracks. The instrument combines confocal, interferometry and focus variation techniques in the same sensor head. Confocal profilers measure the surface height of smooth to very rough surfaces. Phase shift interferometers measure the surface height of very smooth and continuous surfaces with sub-nanometer resolution. Focus Variation is an optical technology that has been developed in order to measure the shape of large rough surfaces.

A first topographic analysis was made on the profilometer. Once the sample was focused, it was important to ensure that the range for the z scan displacement was appropriate. If the range was too large, the acquisition would take a long time. If the range was too small, some zones in the measurement would have no confocal or interferential information, and the measurement would show "unmeasured" points. Different tries were executed and generally a 60 μm Z range was chosen. A 20× of magnification was utilized, the extended topography option, on the related software, allowed to scan the whole area interested by the tribo-test by automatically moving the specimen in the x-y plane.

Once the image is acquired the software can provide information such as the peak-to-valley, the average surface roughness and many others related to a selected area of interest. Those images showed the UHMWPE surface after the tests in the case of 20N and frequencies of 5, 10 and 15 Hz under dry conditions.

A qualitative analysis was thus obtained by considering how the different surfaces react to the test, how their behaviour changes in relation to the frequency and if there were voids on the worn surface.

3.3 TiAl6V4 –UHMWPE

The Figures 10-11 show the evolution of the friction coefficients during the test. There are two pairs of figures for two different load values: 15N and 20N. In each figure we can see the friction coefficient behaviour under dry condition and under lubrication condition. The red line represents the frequency of 10HZ and blue line is the frequency of 20 Hz.

Figures 12 shows the dynamical friction coefficients, measured in the tests carried out under dry and lubricated conditions, for the TiAl6V4 -UHMWPE tribological pairs with two different loading conditions.

Obviously the introduction of hyaluronic acid tends to decrease the values of the friction coefficient. Both graphs show that an increase in frequency produces a decrease of the friction coefficient for every load condition. Only in the case of 20N an increase in the frequency produces an increase in the friction coefficient under dry condition. This result is congruent with figure 13. In fact, a higher value of the friction coefficient results in an increase of the wear volume.

The figure 13 shows the results of the wear rates for the TiAl6V4 -UHMWPE contact. We can see that not always a speed increase leads to an increase in wear. This is due to the deformation of the tibial component (UHMWPE) that slides the sphere (TiAl6V4) on the plate by compressing thus resulting in less wear.

Figure 14 shows the UHMWPE surface after the tests in the case of 20N and frequencies of 10 and 15 Hz under dry conditions.

4. Conclusion

In this work a tribological experimental investigation was carried out in order to obtain the friction coefficients and the wear rate of UHMWPE against AISI420C steel and of UHMWPE against TiAl6v4 alloy. The tests were carried out under dry and lubricated conditions. As lubricants, we used the sodium hyaluronate fluid: (Hyalgan®). The tests were conducted by using a reciprocating tribometer with several load conditions and with several frequencies of the motion.

Following C.Z. Liu et al., the adhesion in the contact zone and deformation of the polymer are two phenomena occurring in the friction between a thermoplastic and metals [27]. According to the load level, the mechanical and chemical properties and lubricating conditions respectively either the former phenomenon or the latter above-mentioned will occur. The results show that the AISI 420C austenitic stainless steel has marked in dry conditions better values in the wear volume and in the friction coefficient. Friction is greatly reduced by the presence of UHMWPE and this is believed to be due to the formation of a lubricating film of UHMWPE in the contact zone. As the matrix worn, the UHMWPE transfers to the counter face thus leading to the formation of self-lubrication of the contact [27].

All tests demonstrated much lower friction coefficient and lower wear rate in lubricated sliding than in dry-sliding condition. It is believed that this was attributed to the hydrodynamic lubrication phenomena during the sliding of the pin. These phenomena require an accurate tribological investigation that could be made in the future.

When the friction coefficient is monitorized along larger time further information can be retrieved. In the tests carried out with dry condition, the friction coefficient increases quickly independently of the pair and of the loading conditions. The increasing rate is not reproducible as well as the final value of the friction coefficient, which normally stays in the range 0.11–0.14 after a sliding time larger than 15 min (Figures 5,6,7,12,13 on the left). The final value of the friction coefficient for the tests carried out with lubricated conditions stays in the range 0.03–0.08 after a sliding time larger than 15 mins independently of the pair and of the loading conditions (Figures 5,6,7,12,13 on the right). Except for the pair of AISI420C-UHMWPE in the case of load 15N and frequency of 10 HZ (Figure 6 on the right) the friction coefficient increases continuously and the final value, after 15 min, stays in the range 0.09–0.11.

In the same figure, we can observe that the behaviour of the friction coefficient continuously increase, also occurs for frequency of 5Hz and in this case the final value stays in the range observed in the tests under lubricated conditions.

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