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Tribological Behavior of UHMWPE (Disc) against Ti6Al4V (Pin) under Different Lubrication Conditions

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The proposed research work is addressed to the study of the wear behavior of Ultra High Molecular Weight Polyethylene (UHMWPE) under the contact with a rounded pin in Ti6Al4V alloy, which is largely used for production of the last generation of prosthetic implants by electron beam manufacturing (EBM). The wear tests of UHMWPE in contact with a Ti6Al4V pin are carried out dry or in the presence of lubricants fluids that are characterized by tribological tests, wet-ability measurements, and morphological observations of the contact surfaces. UHMWPE wear resistance improves in conditions of lubrication in the order: dry < distilled water < synthetic synovial < bovine serum, according to wettability results. As suggested by the track profiles, the contact action in dry can be mainly due to shear stress while that in lubricant mainly to compressive stress.

1. Introduction

The increasing demand for efficient biomechanical prostheses, used to relieve joint and postoperative damage, have led researchers to focus their studies on the critical variables that significantly affect the biomaterials life. Considering that the synthetic joints must ensure mobility and load capacity, minimizing at the same time friction and wear issues, the use of biocompatible metal alloys, such as those based on titanium, and of the latest generation of polymers have helped to meet the demand of mechanical strength and health safety.[1] Due to their favorable tribological properties, polymers are attractive as materials for implant coatings: among them, UHMWPE is widely used for its excellent physical, chemical, and mechanical characteristics, such as high wear and abrasion resistance, lubricity, and biocompatibility.[2]

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Concerning titanium and in particular its most widespread alloy Ti6Al4V, recent studies have highlighted the ergonomic efficiency of components produced by EBM: see for reference the review carried out by Tamayo et al.[3] Experimental investigations have been performed on the different behavior under various lubrication conditions.[4]

The kind of environment (air, in derived biological fluid or in synovial fluid) and of polymer-metal contact, impact on the prosthesis life.[5] In particular, inadequate conditions causes wear debris which lead to osteolysis and ultimately limits the lifespan of the joints.[6] Dynamism of contact, geometry, and local pressure, are intrinsic variables that can be taken into account in the prediction of the useful life of these innovative systems, as pointed out by several finite element simulations carried out in literature.[7,8] Nevertheless, for the protheses manufactured by the new additive methods, statistical data and objective considerations are lacking if compared to the old standardized procedures. For example, the effects of different lubricants on friction and wear behavior were explored simulating a cervical implant by a disc of Ti6Al4V swinging against a UHMWPE ball.[9] However, this experimental configuration cannot be exhaustive for hip or knee joints.

In order to fill this gap, the present work aims to investigate, by means of the "pin on disc" wear test, the tribological couple consisting of a rotating UHMWPE specimen in contact, under different lubrication conditions, with a Ti6Al4V alloy pin, which was produced by EBM, in the same way of the last generation of prosthetic implants. Materials were characterized by optical morphological observations and wettability measurements to verify its wear UHMWPE resistance under different lubrication conditions: dry, distilled water, and synovial fluids, both synthetic and bovine.

2. Experimental Section

The wear test was carried out by a "pin on disc" tribometer: a metallic pin, made of Ti6Al4V, was located at the end of a supporting rod, which was loaded at the opposite side by a weight of 30 N (**Figure 1**a). For test under lubrication, a drop of the lubricating fluid was deposited by a calibrated pipette on the polymer surface, which was placed in horizontal position (Figure 1b). The pin, long about 5 cm with square section (1 cm side) and provided with a conical tip (Figure 1c), was produced by an EBM Q10 machine through the overlapping of Ti6Al4V

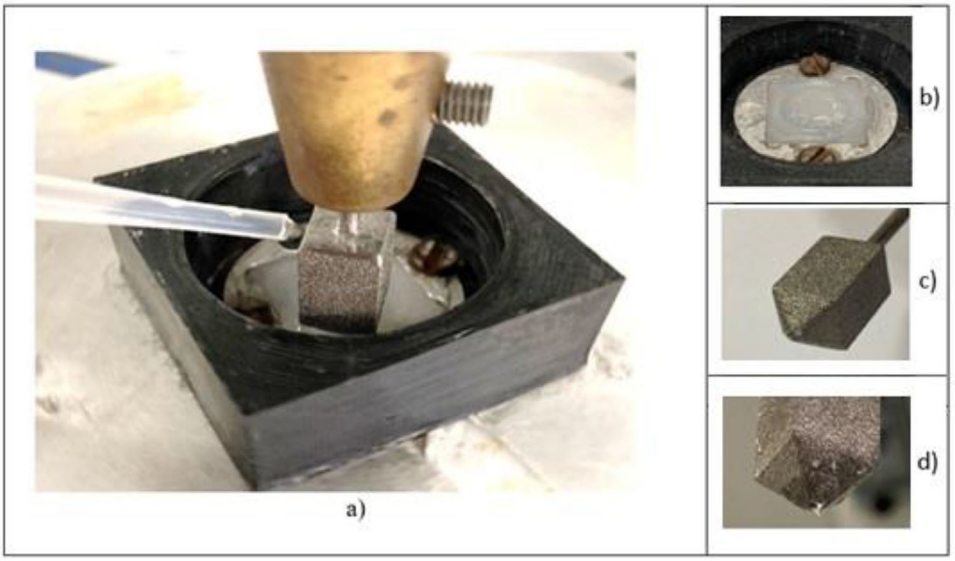

Figure 1. Tribological test: a) "pin on disc" device with graduate pipette for the lubricant supply; b) detail of the UHMWPE specimen and its holder; Ti6Al4V pin respectively after test in wet c) and dry d) conditions.

ELI Grade 23 powder layers[10]; the maximum roughness (R_z), measured on five profiles of the conical tip recorded by digital microscopy, had a mean value equal to 17.5 μm with a standard deviation of 2.5 μm; as regards the metallurgical features of the pin, see the work of Aliprandi et al.[11]

UHMWPE specimens with square shape (20 mm side and 2 mm thick) were produced by compression molding of powders at 200 °C and pressure increasing from 1 to 200 atm (holding time at 200 atm equal to 16 min).

A single specimen was placed inside a holder which could retain fluids (Figure 1b). The pin was a positioned at 7.80 mm from the disc rotation axis; thus, it left on the specimen a circular trace having a diameter of 15.60 mm. The rotation speed was equal to 60 rpm in each test.[12] Wear tests were performed at room temperature under different conditions: dry, in distilled water or synovial fluids, both synthetic (SSF) and natural bovine (BOV). Upon visual inspections after testing, the pin appeared intact (Figure 1c), possibly with polymer residues on the tip in the case of dry conditions (Figure 1d).

Wettability measurements on the polymer surface were performed preliminarily by means of a device provided with a high-definition camera. The acquired images were processed through a software capable to calculate the contact angle (θ) from the drop profile. For each case considered, 10 measurements were performed, calculating the mean value and variance. Observations by digital microscopy were carried out to inspect the wear effects on the polymer and metallic pin contact areas.

The UHMWPE specimens were weighted before and after each wear test, to measure their mass loss Δm (g). To compare the results of the various tests, reference is made to the specific wear rate W_S ($mm^3\ Nm^{-1}$):

$$W_S = \frac{\Delta m}{\rho P L} \tag{1}$$

being ρ (g mm^{-3}) the specimen density, P (N) the applied load, and L (m) the total sliding distance ($L = 2{\cdot}\pi{\cdot}r{\cdot}n$; where r (m) was the track radius and n the total number of revolutions of each test).

3. Results

The results of the wettability measurements on the UHMWPE surface are concentrated around the respective average values, being the standard deviations less than 2°. **Figure 2**a shows the average values of the contact angle for the different lubrication conditions: a hydrophilic behavior ($\theta = 87.39°$) is observed only with the bovine synovial fluid, while it results hydrophobic in the case of distilled water ($\theta = 95.8°$), and synthetic synovial fluid ($\theta = 98.28°$).

The specific wear rates, calculated by Equation (1) in the different tribological conditions, are shown in comparison in Figure 2b. It can be observed that in dry condition W_S is two or three times higher than the values measured in wet conditions. The best tribological behavior is achieved by lubricating with the bovine synovial fluid, according to the high wettability which is due to the similarity of its organic components towards the UHMWPE molecular microstructure. Therefore, UHMWPE absorbs the proteins that are present in bovine serum and not in the synthetic lubricant. Anyway, there is not full agreement in literature concerning the wear measurements in natural lubricant because proteins concentration could change in a wide range with remarkable effects on friction and wear.[13]

The digital macrographs of the pin tip, taken before and after the various tests, are shown in **Figure 3**a,b. In these images the area interested by the contact with the polymer is identified by means of a white circle. The presence of a highly rough surface is intrinsic to the EBM production process, which is based on deposition of powder with grain size between 45 and 100 μm.[11] Furthermore, the comparison of the two images shows the absence of any smoothing effect on the pin tip surface after the various tests, thus demonstrating that the alloy is not worn.

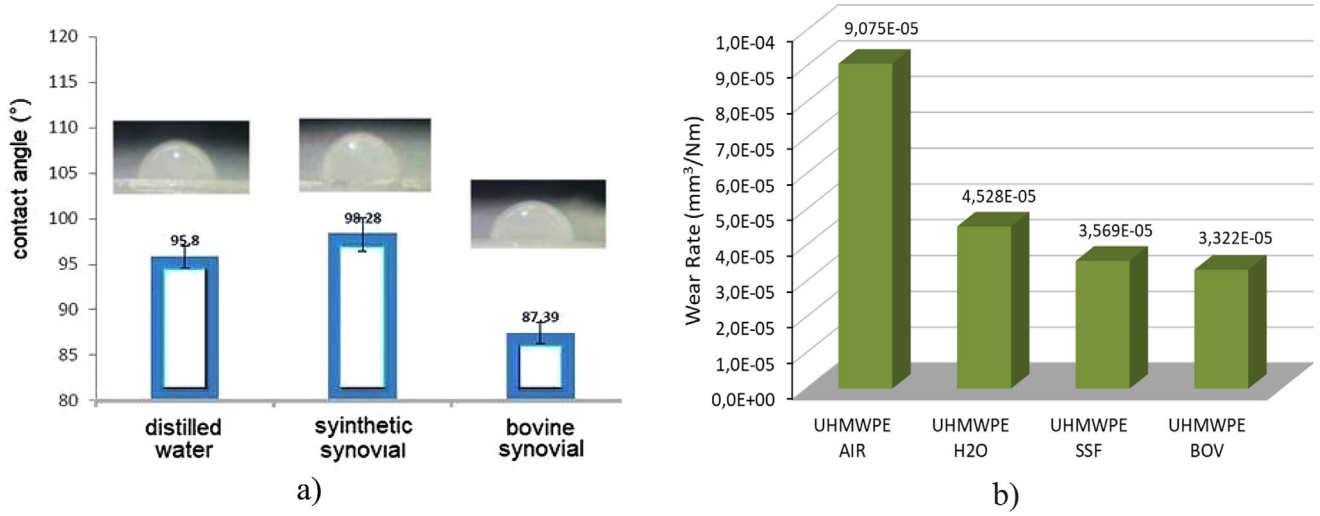

Figure 2. Summary diagrams: a) contact angle of the lubricating fluid on the UHMWPE surface, b) specific wear rate measured in the various lubricating conditions.

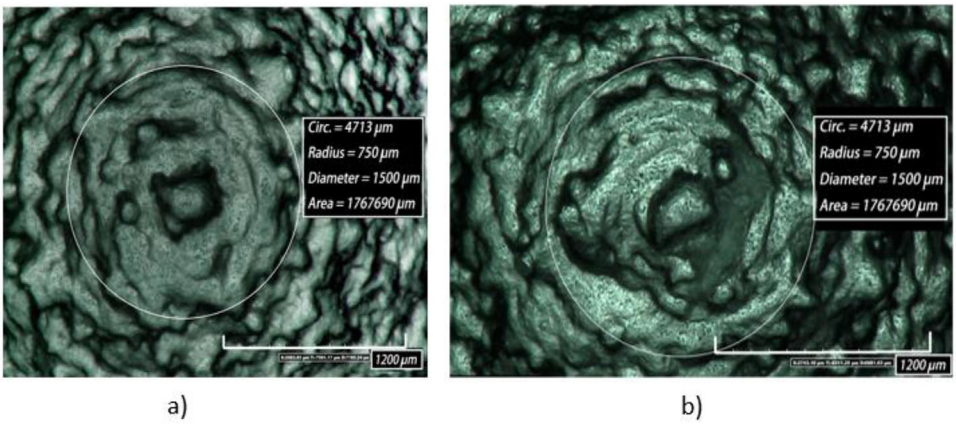

Figure 3. Digital observations of the pin, respectively before a) and after the wear cycles b).

During the wear tests, several polyethylene particles detach and settle on the pin tip, especially in the case of dry wear (see Figure 1d). The reconstruction, through the "tilling" function of the digital microscope, allows to compare the track profile that is imprinted on the polymer surface after the wear test in different conditions of lubrication (**Figure 4**). Dry wear gives rise to the deepest track, which is progressively reduced in the following order: test in water, synthetic, and bovine synovial fluid. When dry, it is the shear stress that acts on the UHMWPE and forms a deep wear track with numerous debris. Instead, the lubricants favor only a compressive stress which plastically deforms the wear track, reducing the production of debris.

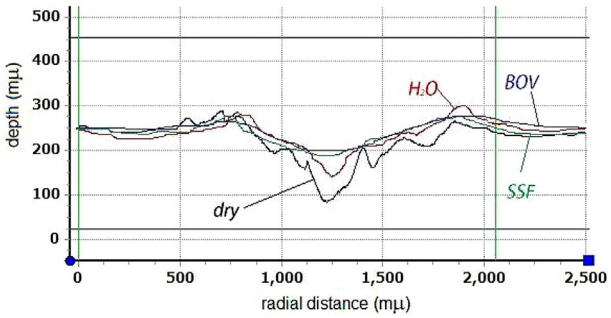

Figure 4. Track profiles obtained on the polymer surface after wear tests in different lubricating conditions.

4. Conclusion

This paper investigated the tribological pair UHMWPE/Ti6Al4V-produced by EBM. UHMWPE showed hydrophilic affinity towards bovine synovial fluid proteins, which is therefore able to wet and penetrate the surface of the polymer with a reduction in wear of over 60% compared to dry. The penetrated fluid plasticizes the macromolecular chains, resisting better the wearing action of the metal tip than the other lubrication conditions analyzed (in the order: dry < distilled water < synthetic synovial < bovine serum). When dry, a shear stress acts on the UHMWPE

which forms a deep wear track with numerous debris. Instead, the lubricants rather favor a compressive stress that plastically deforms the wear groove, reducing the production of debris.

Finally, the Ti6Al4V alloy shows no wear effect on the tip surface. More accurate future investigations will completely exclude the presence of potentially dangerous debris and will have to compare the effect of the tip traditionally obtained by casting with this latest generation obtained by EBM.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

lubrication, prosthetic implant, Ti6Al4V, UHMPWE, wear

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