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Tribological characterisation of UHMWPE used in dual mobility total hip prosthesis

I Essefi[1,3], H Hakkouna[1,3], G Ouenzerfi[1], G Mollon[1], S. Hamza[3], E Renault[2], Y Berthier[1] and A-M Trunfio-Sfarghiu[1]

[1]LaMCoS Laboratoire de Mecanique des Contacts et des Structures - INSA de Lyon
[2] WRIGHT Medical France
[3] National Institute of Applied Science and Technology of Tunis,Tunisia

E-mail: ines.essefi@insa-lyon.fr

Abstract. Total hip arthroplasty represents an effective solution for bone and joint diseases. Nevertheless, the hip prosthesis has a limited lifetime, in the average around fifteen years. Their improvement, especially their dual mobility is the objective of this study. Therefore, our strategy is focused on improving the material by comparing three types of polyethylene to determine the best one from a friction mechanism and wear rate minimization standpoint. A dual mobility hip prosthesis, containing a two-sided steel and cobalt chrome cup, was tested with a TORNIER hip joint simulator in calf serum. The rubbed surfaces were characterized using scanning electron microscopy (SEM), contact angle measurements, atomic force microscopy (AFM) and confocal fluorescence microscopy. All these multiscale characterization techniques (from nanoscale to millimeter and micro- scale) showed that the velocity accommodation mechanism is different from one type of polyethylene to another. The wear in the case of standard polyethylene was noticeable and the particles were large and scattered between the surface of polyethylene, the surface of the cup and in the calf serum. For the crosslinked polyethylene, the particles coming from the wear, were not as large, but they were spread the same way as the first case. Even though it shares the same accommodation principle on the detachment of the material with the crosslinked polyethylene the wear particles for the crosslinked vitaminized polyethylene were large and they were only found on the surface of the polyethylene.

1. Introduction

The total hip prosthesis is an efficient solution for bone and joint diseases despite their limited lifetime. Several paths of research have been addressed by many authors [1-4] to improve the type of materials or the introduction of a new concept in prosthesis. It is known that wear of the UHMWPE part of implants is the primary cause of premature failure of total joint replacements. The recent use of the new types of crosslinked and vitaminized UHMWPE has been developed in order to improve resistance to wear. The crosslinking modifies the biomechanical properties [5]. The vitaminsing reduces the oxidative effect of its particles [6].

The total dual mobility prosthesis has proven its efficiency in preventing dislocations. This type of hip prosthesis has been developed in order to combine the principle of “low-friction arthroplasty” using small femoral heads to minimize wear rate and avoid dislocation problems. They are composed of a CrCo cup which articulates on an UHMWPE insert and a stainless steel femoral head.

In this context, the objective of this study is to establish the influence of the type of polyethylene on the wear and friction of a dual mobility hip prosthesis. For this purpose, three types of polyethylene inserts were tested on a fatigue simulator. Their tribological performance was evaluated using multiscale microscopy techniques. The results obtained can provide adequate recommendation on the choice of dual mobility prosthesis as a function of the type of polyethylene.

2. Experiments

The tested dual mobility total hip prosthesis was provided by TORNIER and is composed of three parts (Figure 1): an acetabular cup in stainless steel with a diameter of 48 mm, an UHMWPE insert with an external diameter of 40 mm and a CrCo femoral head with a diameter of 28 mm.

In this study, a wear test following the ISO 14242-1:2012 standard on the TORNIER double mobility hip prosthesis was conducted in order to compare the wear behaviour of various UHMWPE inserts

-Standard UHMWPE.
-Aged XL UHMWPE 75 kGy.
-Aged XL UHMWPE 100kGy vitamin E.

The inserts were gamma sterilized (25-40 kGy) under vacuum and the head Φ28mm is made in CrCo alloy (TORNIER Manufacturing). The aim of the test was to measure the wear rate of different inserts at 2 million cycles using a calf-serum with protein content equal to 30±2 g/L. The tribological and mechanical properties of these types of polyethylene were also studied comparing with unused samples of UHMWPE.

The tribological observations rely on the tribological triplet which is appropriate for that type of contact. The middle image of the Figure 1 identifies:

- 3 first bodies: Acetabular cup; insert and femoral head.
- 2 third bodies: a lubricant between acetabular cup and insert, and a lubricant between insert and femoral head.

The first and third body reveal 5 different tribological sites (S1-S5) which result on 4 different accommodation speed modes such as the elastic mode M1, the normal breaking mode M2, the shearing mode M3 and the rolling mode M4.

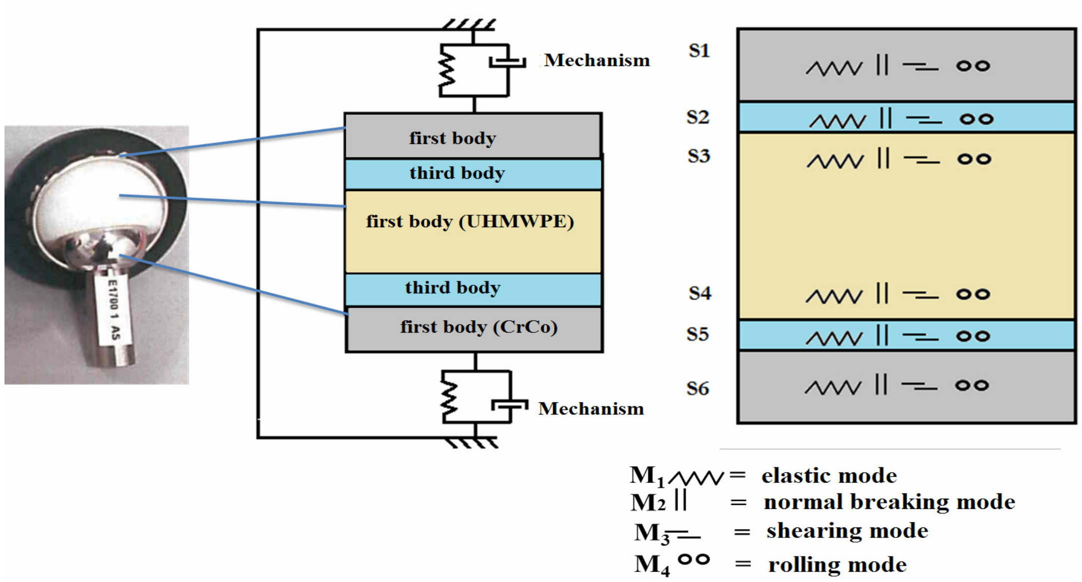


Figure 1. Tribological triplet.

The tribological triplet includes the mechanism, the first body and the third body. The mechanism is mainly identified by a servo hip hydraulic simulator which runs the dynamics and kinetics (Figure 2 and Figure 3).The specimens are oriented in anatomically correct position and the resulting hip joint force is applied versus the cup .Consequently, the direction of the force vector is constant regarding the cup and moves regarding the head. All three in vivo angular displacements are simulated: flexion/extension, abduction /abduction and rotation [7].

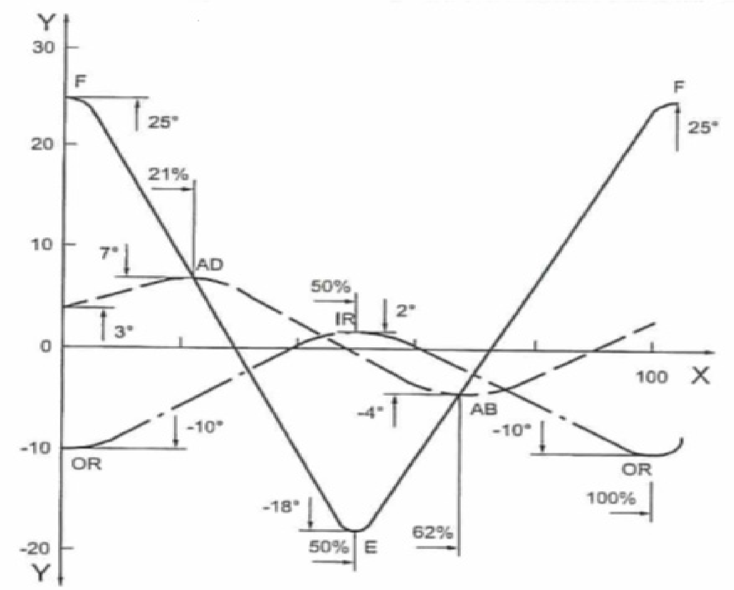


Figure 2. Extract showing rotation versus time ('F' for flexion, 'E' for extension, 'AD' for adduction, 'AB' for abduction,'OR' for outward rotation 'IR'for inward rotation).

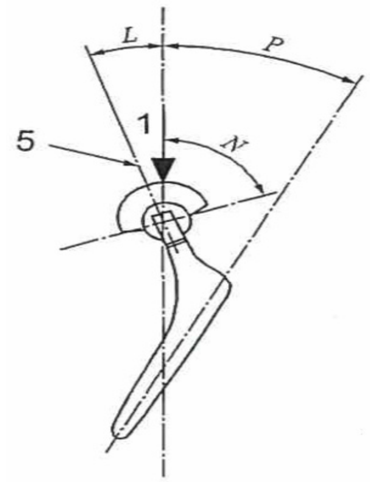


Figure 3. Extract showing load direction in regard to cup.

The tribological observation chiefly denotes the maximum detection of wear behaviour of the UHMWPE insert. The observation of these inserts was achieved by using a:
-3D scanning Coordinate Measuring Machine Zeiss for documenting the volume of the insert
-Rugosimeter (Altisurf 500) and Atomic Force Microscope (Park XE15) for investigating the topography of inserts 'surfaces.
-Optic Numerical Microscope (VHX-2000 F), and Electronic Microscope (FEI Quanta 600) for documenting the surface.
- contact angle measurements.
- Confocal Microscope for analysing the morphology of the wear particles.

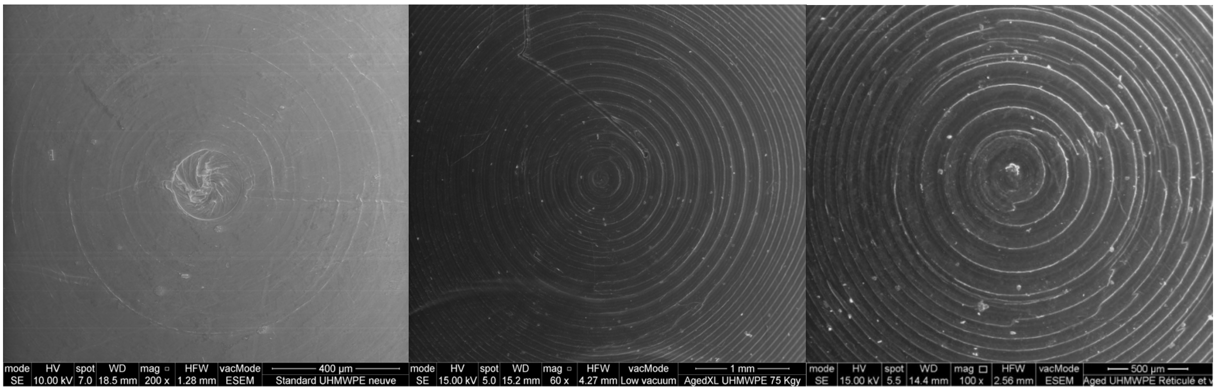
3. Results

3.1 Morphology and surface roughness before friction

In order to compare the worn inserts with their unworn references, we summarized all our results related to the three unworn inserts. Surfaces were observed by scanning electron microscope. Figure 4 shows the uniform aspect of surfaces. The UHMWPE is fully dense but the grooves caused by the machining process can be clearly observed which explains its high roughness (Table 1). Roughness values were determined after extracting more than five profiles from topographies by the rugosimeter.

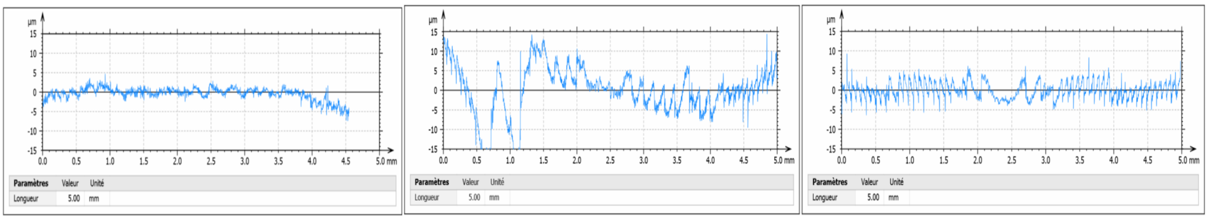
Figure 5 shows the profiles extract from the surface topography. Table 1 presents the average roughness for each insert.

In order to investigate the causes of the differences in tribological behaviour observed with the three inserts, wettability measurements were performed. The hydrophilicity of the materials was assessed through the water contact angles. Values are given in Table 2. It displays standard UHMWPE is the most hydrophobic with a contact angle of 96±3° and the crosslinked and vitaminazed UHMWPE a is the most hydrophilic with a contact angle of 75±5°. This is explained by the chemical structure of vitamin E which contains the OH molecule which is hydrophilic molecule [8].



(a) (b) (c)

Figure 4. SEM images of (a) Standard UHMWPE (b) crosslinked UHMWPE (C) crosslinked and vitaminized UHMWPE surfaces before the friction experiments.



(a) (b) (c)

Figure 5. Rugosimeter profiles of (a) Standard UHMWPE (b) Crosslinked UHMWPE (c) Crosslinked and vitaminized UHMWEPE.

The crystallinity control was carried out by a very small scale AFM to visualize the crystal samples morphology. Figure 6 shows that for the standard UHMWPE crystals size are around 0.5 µm. The crystals size in the reticulated UHMWPE are a bit larger but more homogenous. But, in the reticulated and vitaminized UHMWPE the crystals tend to disappear and leaving behind only few pellet- like size crystals.

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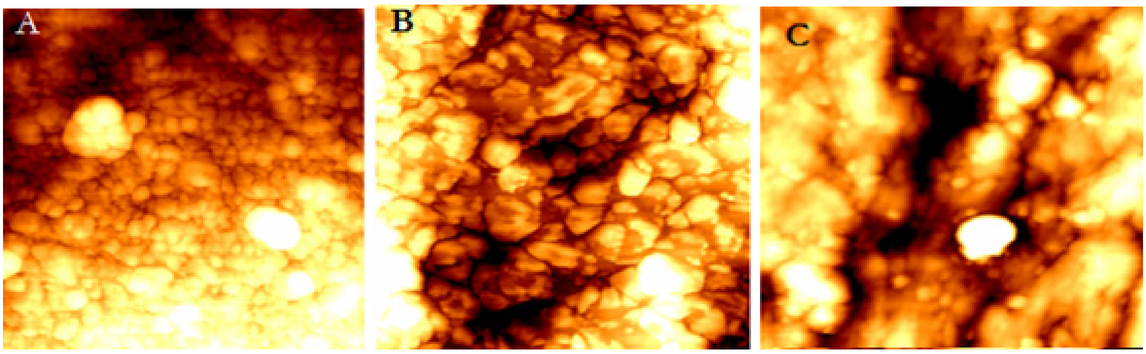
Table 1. Average roughness of surfaces and contact angles of water θ before friction.

	Ra for external surface of insert	θ
Standard UHMWPE	2,66µm	96±3°
Crosslinked UHMWPE	2,85µm	80±2°
Crosslinked and vitaminized UHMWPE	1.5 µm	74±5°



(a) (b) (c)

Figure 6. AFM image shown surface's crystallinity of (a) Standard UHMWPE (b) Crosslinked UHMWPE (c) Crosslinked and vitaminized UHMWPE.

3.2 Mass and volume loss

3D measurment of the inserts was conducted to evaluate the volumetric loss. As shown in Figure 7 the blue curve refers to the insert before friction and the red curve refers to the insert after friction.Table 3 illustrates the internal, external and total volumetric loss for each insert and also the mass loss for each insert. Standard UHMWPE is the insert having the largest loss in volume and mass.

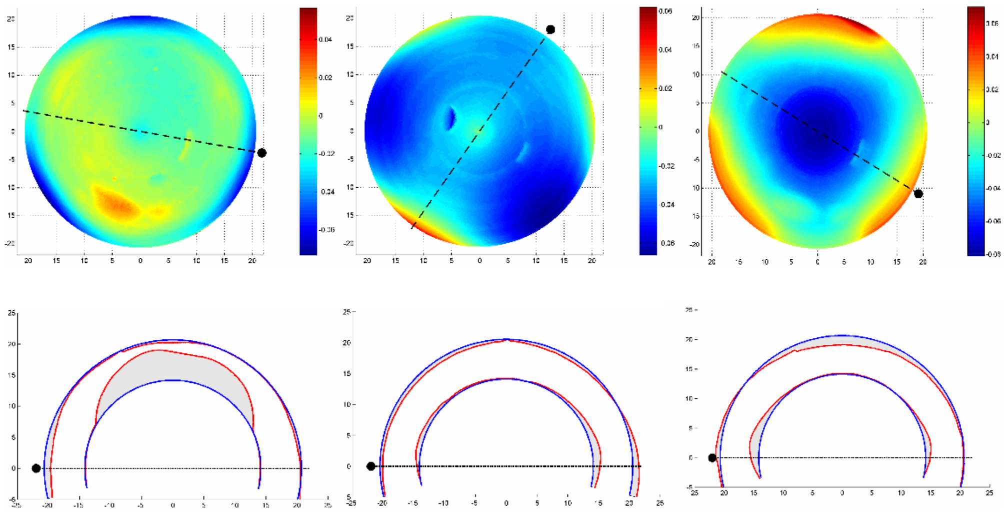

(a) (b) (c)

Figure 7. 3D scanning Coordinate Measuring Machine Zeiss image of (a) Standard UHMWPE (b) Crosslinked UHMWPE (c) Crosslinked and vitaminized UHMWPE.

Table 2. Volumetric and mass loss after friction.

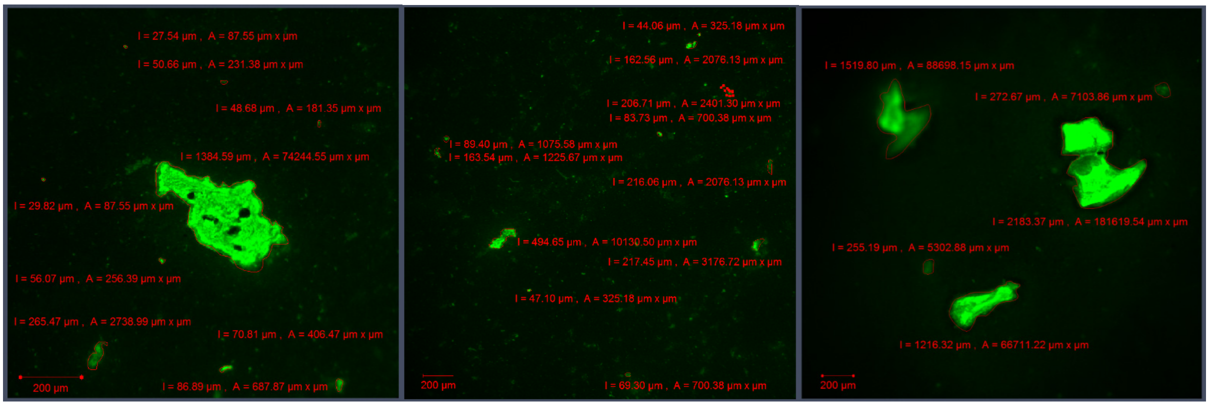
	Volume loss	Mass loss
Standard UHMWPE	157.3 mm^3	59.32 mg
Crosslinked UHMWPE	108.1 mm^3	5.34 mg
Crosslinked and vitaminized UHMWPE	69.5 mm^3	2.72 mg

3.3 Wear particule

3.3.1. Particule isolation protocol. The common practice for wear quantification has been gravimetric, or mass loss evaluation. This method is complexified by the fact that polyethylene tends to absorb small amount of lubricant during testing which may modify the obtained results. An alternative wear quantification method consist of the isolation of wear particles from the lubricant by digestion and filtration followed by the particle analysis .It allows to determine the quantity, size and morphology of particles [9-11].

Wear particles were isolated from serum using the Scott method. Briefly, 10 mL of each serum sample was added to 40 mL of hydrochloric acid (37 % v/v) and mixed with a stirbar for approximately 1 hour at 50°C . The time and temperature for full digestion may depend on the serum type and protein concentration . 1mL of the solution was extracted, added to 100 mL of methanol and filtered through a 0.05µm polycarbonate filter membrane.

3.3.2. Particle analyses. The filter paper with particles were prepared to be observed by the Confocal Microscope. The sizes, shapes, and number of particles are different for each surface of UHMWPE. Figure 8 shows the distribution of particles on filter's surface. It reveals 30% of particles on the standard UHMWPE compared to the filter area, 5% of particles compared to the filter area for crosslinked UHMWPE and 20% of particles compared to the filter area for Crosslinked and vitaminized UHMWPE.



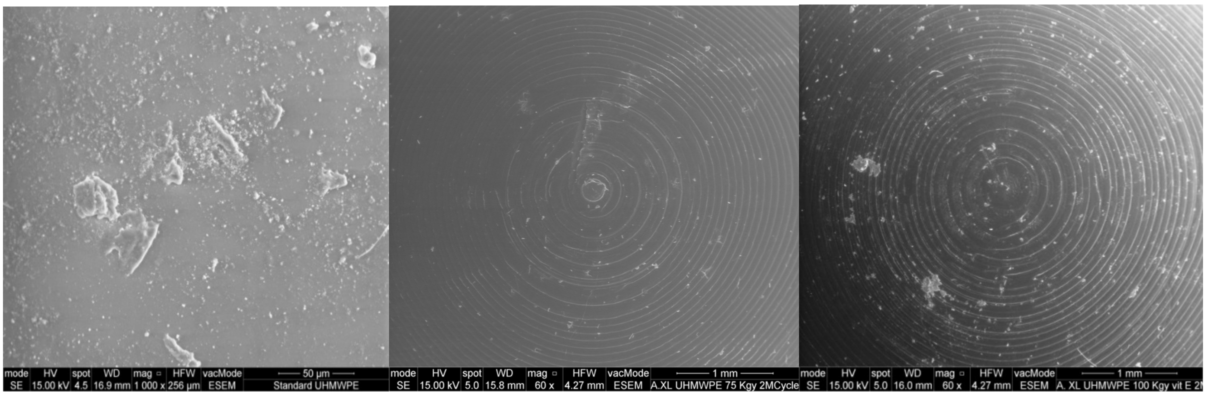
(a) (b) (c)

Figure 8. Confocal microscope image of filter extracted from lubricant between (a) Standard UHMWPE (b) Crosslinked UHMWPE (c) Crosslinked and vitaminized UHMWPE and the acetabular cup.

3.4 Morphology and surface roughness after friction

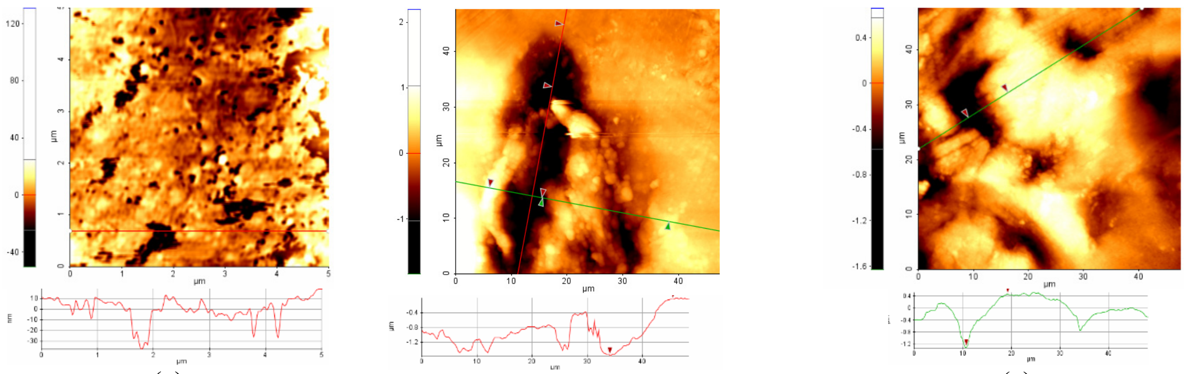
On the worn surfaces of UHMWPE evidences of significantly total demise of stripes and it also shows the presence of a huge amount of particles (10 micron) on the surface in the case of the standard UHMWPE as well as a smooth roughness profile(see Table 2). However, it reveals a decrease in the amplitude of stripes in the case of the crosslinked UHMWPE, with a slight presence of particles on the surface. But in the case of the crosslinked and vitaminized UHMWPE, the friction exhibited a negligible smoothing on the roughness profile and massive sized particles on the surface (Figure 9).

AFM images (Figure 10) shows the smoothing of the plate machine with the appearance of small holes on the surface standard UHMWPE insert, small holes with depth and radius in the micro meter scale on the surface of the plate for crosslinked and UHMWPE, and big holes with depth and radius in the measure of some dozens of micro-metres on crosslinked and vitaminized UHMWPE.



(a) (b) (c)

Figure 9. SEM image of worn surfaces of (a) Standard UHMWPE (b) Crosslinked UHMWPE (c) Crosslinked and vitaminezed UHMWPE.



(a) (b) (c)

Figure 10. AFM image of worn surfaces of (a) Standard UHMWPE (b) Crosslinked UHMWPE (c) Crosslinked and vitaminezed UHMWPE.

Figure 11 shows the profiles extract from the surface topography. Table 3 presents the average roughness of surgaces after friction.

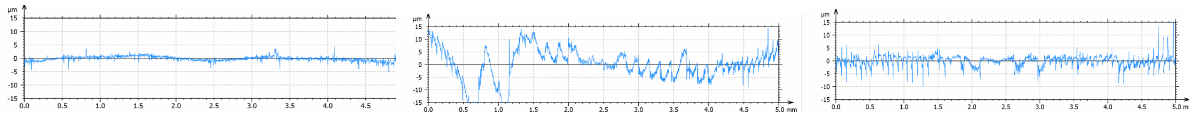


Figure 11. Rugosimeter profiles of (a) Standard UHMWPE (b) Crosslinked UHMWPE (c) Crosslinked and vitaminized UHMWPE worn surfaces.

Table 3. Average roughness of surfaces after friction.

	Ra
Standard UHMWPE	0.33µm
Crosslinked UHMWPE	2,11µm
Crosslinked and vitaminized UHMWPE	1.31 µm

3. Discussions and conclusion

The results demonstrate a highly significant wear on the UHMWPE standard (157.3 mm^3) compared to 108.1 mm^3 reticulated UHMWPE and the 69.4 mm^3 reticulated and vitaminized UHMWPE. This can be attributed to a different behavior or the material, but also to the surface morphology differences. Therefore, it may modify to the lubricant impact: applying low amplitudes of machining stripes can inquire less trapped lubricant, leading to less hydrodynamic lift and more wear. Consequently, less amplitude machining stripes are revealed for standard UHMWPE (~1.2µm compared to 2.2 µm reticulate UHMWPE and ~2.5 µm crosslinked and vitaminized UHMWPE). On the other hand, the volumetric wear of the crosslinked and vitaminized UHMWPE significantly decreased. This might be related to: the wettability difference which enhances the lubrication of vitaminized UHMWPE; the surface adhesion difference: it is clearly higher in the case of crosslinked UHMWPE causing the friction coefficient increase and also the appearance of wear through particles detachment (many pores are displayed on the crosslinked UHMWPE surface after friction). Kinematics difference: the wear of the reticulated UHMWPE is largely more expanded on the external surface of the acetabular cup than on the internal surface (the wear is mainly located on the Zone 2, towards the maximal diameter). This also can be attributed to the friction coefficient (a notable friction coefficient on the internal surface of the acetabular cup may fairly lead the motion towards the acetabular cup external surface). Most probably, these three explanations may be interlinked. The vitamin E improves the wettability, which triggers a decline on the surface adhesion force and alter the kinematics of UHMWPE friction. But such an important and high force can be the reason behind the particles detachment and the increase of the friction coefficient. This triggers the movement motion to move towards the external surface of the acetabular cup. Therefore, a highly significant wear appears on the crosslinked UHMWPE external surface.

4. References

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