A micro-scale abrasion test to study the influence of counterface roughness on the wear resistance of UHMWPE

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In a common total hip or knee replacement the most used bearing pair consist of a hard smooth metal femoral component articulating against a soft Ultra High Molecular Weight Polyethylene (UHMWPE) acetabular (or tibial) component. The smoothness of the femoral surfaces and their resistance to third-body scratching are critically important for reducing the wear rate of UHMWPE. Experimental work was performed to find out the dependence between UHMWPE wear rate and the metal counterface roughness. The experimental study shows that the wear rate of UHMWPE is approximately proportional to the surface roughness of the counterface raised to the power 5.65.

1. Introduction

UHMWPE is a biomaterial widely used as an antifriction bearing, especially in orthopaedic applications such as hip and knee joint prostheses. One essential feature of this material is its high resistance to wear and low friction coefficient when sliding against metals, ceramics and other materials.

Nevertheless, due to the intense loads and very large sliding distances during their lifetime, joint prostheses wear producing critical amounts of debris. The generation of microscopic (micron size) wear debris from the articulating surface is of major concern since this can induce cellular reactions, bone resorption and osteolysis. One key factor affecting the wear of UHMWPE bearing components is the roughness of the metallic counter-face (usually made from CoCr alloys, stainless steels or ceramics such as alumina or zirconia).

This study focuses on how the counter-face roughness affects the wear rate of UHMWPE used in biomedical applications.

2. Method

In the usual micro-abrasion testing [1] a ball is sliding against the specimen in the presence of abrasive slurry. Here, the role of the abrasive slurry is played by the asperities from the ball surface. This produces a wear scar whose geometry is determined by the curvature of the ball. This allows the volume of the material removed to be calculated from measurements of linear dimensions. Rutherford and Hutchings [1] give the following approximate expression for the wear volume:

$$V \cong \frac{\pi b^4}{64R} \qquad (1)$$

where V is the wear volume, b the diameter of the scar and R ball radius.

Classical theories of wear present the wear volume as being proportional to the normal load L, the sliding distance S and the inverse of the hardness H [2]:

$$V = \frac{KLS}{H} \qquad (2)$$

The proportionality is given by the coefficient K, a measure of the material wear behaviour. Both K and H can be grouped in a parameter $k=K/H$, usually called the wear constant [2].

$$V = kLS \qquad (3)$$

From continuous measurement of the wear scar depth h, or by interrupting the test periodically and measuring the crater diameter b, the wear volume may be deduced as a function of relative sliding distance [3]:

$$V = f(S) \qquad (4)$$

The wear coefficient k, can then be easily determined by substituting V from equation (1) into equation (3).

Several samples were cut from a 10 mm thick sheet of UHMWPE (molecular weight 930). The flat samples were placed in a holder block, which is able to rotate about an axis to make contact with the ball. The ball is rotated about a horizontal axis parallel to the plane of the specimen surface. The sliding between the ball and specimen results in wear of the specimen. Prior to testing the surface of each ball was finished by grinding against

various grit size SiC paper. In this way several different surface finishes were obtained.

The tests were carried out using a commercially available micro-abrasion or ball-cratering testing apparatus (Plint TE66). A schematic diagram of the apparatus is shown in Fig. 1. The diameter of the ball is *25.4 mm* and is made of high-speed steel. The normal contact force exerted on the sample was 5*N* (the maximum load exerted by the apparatus). The size of the wear crater was measured with an optical microscope having a calibrated reticule. The effect of ball roughness was investigated.

The optical measurements were doubled by surface profilometry (Mitutoyo SJ 301). Abrasion tests were conducted at speed of 0.2 *m/s*.

A number of 5 balls were prepared by the following method: five tubes were made from abrasive paper with different grit sizes (100, 360, 600, 1000 and 1600); the tubes have the inner diameter slightly greater then ball diameter (approx. 28 mm); each ball was introduced in its corresponding tube and it was then shaken for about 15 minutes. Each ball was then placed in a labelled plastic bag. The micro-photography of the balls surfaces are shown in Fig. 4.

After this operation, the roughness of each ball was measured with a profilometer (Mitutoyo SJ301). For each ball, six roughness measurements were performed. The roughness results are presented in Table 1 and Fig. 2.
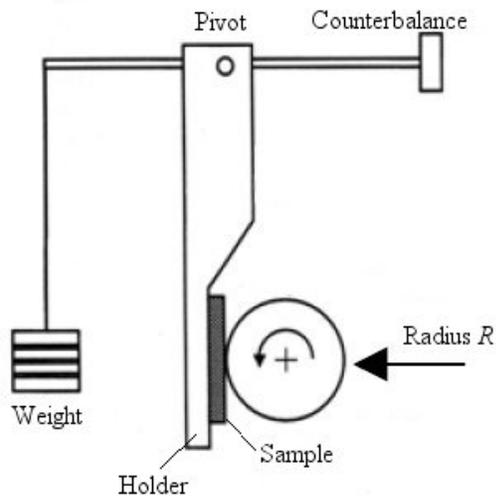
Table 1. Mean roughness measured on the surfaces of the balls.

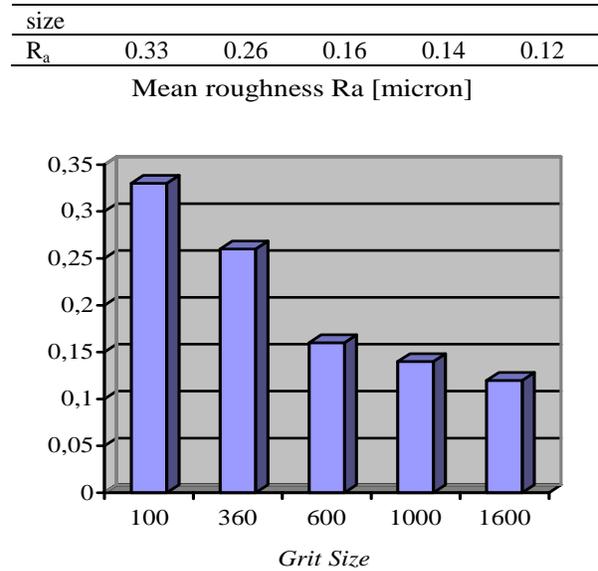| Grit size	100	360	600	1000	1600
R_a	0.33	0.26	0.16	0.14	0.12

Mean roughness Ra [micron]

Fig. 2. Roughness values (R_a) of the ball surfaces.

Worn samples were examined by optical microscopy. Surface profilometry was performed for each wear crater and a typical trace is shown in Fig. 3. The wear crater volume was calculated using equation (1).
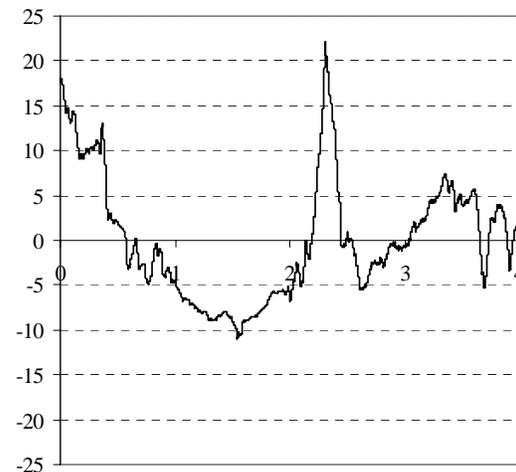

Fig. 3. Surface profile for ball no. 1 (grit size 100) showing large scratches.

Several tests were performed on each sample at separate locations on the surface and could be treated as completely independent, since the wear craters were separated and were sufficiently small (less than 2 mm in diameter). The samples were examined by optical microscopy and contact profilometry.

Fig. 1. Schematic diagram of the micro-abrasion test rig.
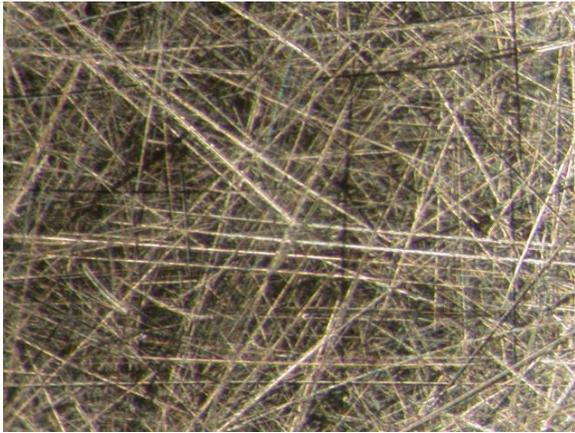
Grit Size 100

Grit Size 360
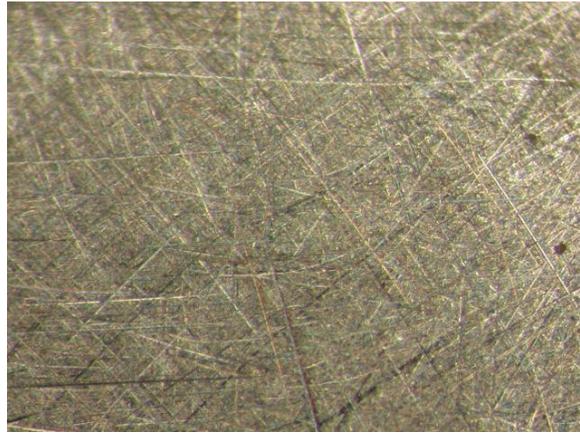
Grit Size 600

Grit Size 1000

Grit Size 1600
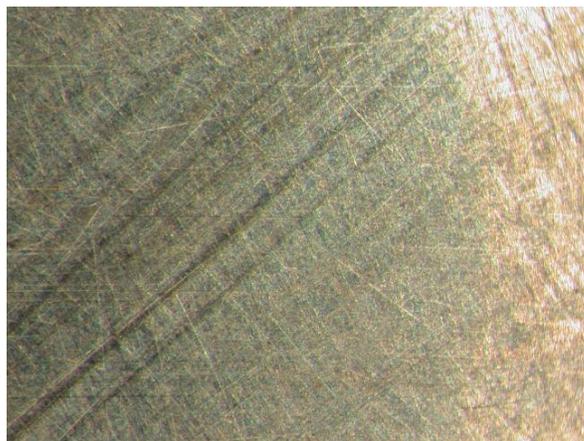
Fig. 4. Micro-photographs of the roughened ball surfaces.

Grit 100 - Ra=0.33um

Grit 360 - Ra=0.26um

Grit 600 - Ra=0.16um

Grit 1000 - Ra=0.14um
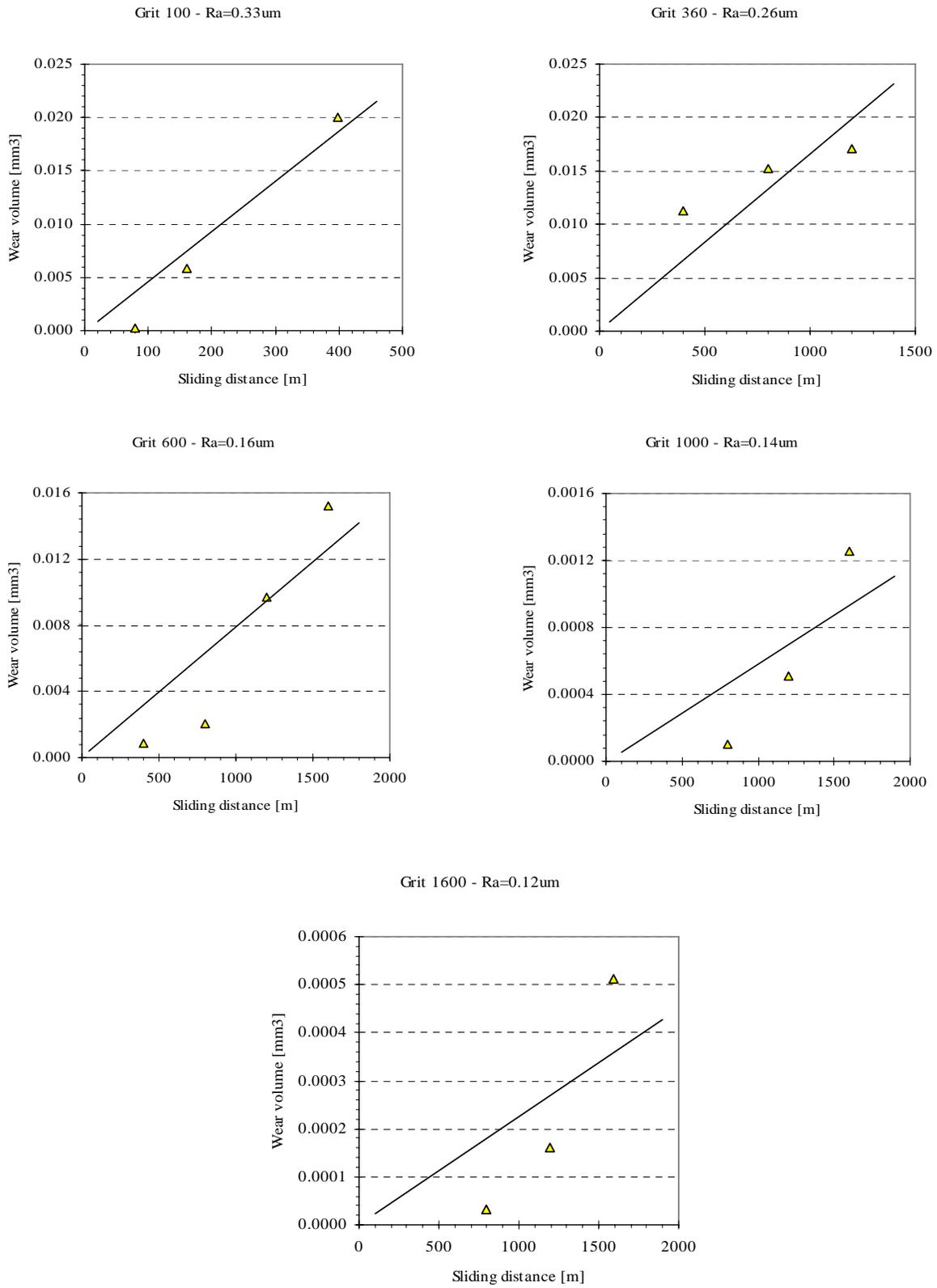
Grit 1600 - Ra=0.12um

Fig. 5. Wear volume vs. sliding distance for the five tests.

3. Results

In the micro-scale abrasion test the wear processes which occur and the wear coefficients which result are strongly influenced by the surface condition (roughness) of the ball used in the test. In the case of small counterface roughness, the main wear mechanism is adhesion. As the roughness increases, the abrasion becomes the predominant wear mechanism.

A linear relationship is expected between the wear volume V and the product of the normal load and the sliding distance ($L \cdot S$) as it can be seen in Fig. 5.

A least-square fit of the experimental data indicates that the wear coefficient can be correlated to the surface roughness by the equation:

$$k = 4.95 \times 10^{-3} \cdot R_a^{5.65} \qquad (5)$$

Fig. 6. Micro-photography of a wear crater produced on the surface of UHMWPE sample (wear diameter is approx. 2 mm).
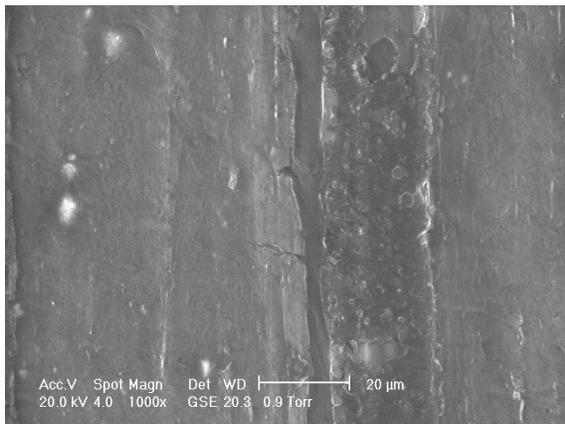

Fig. 7. SEM of a wear scar produced by the ball asperities on the UHMWPE surface.

Wear coefficient [mm^3/Nm]

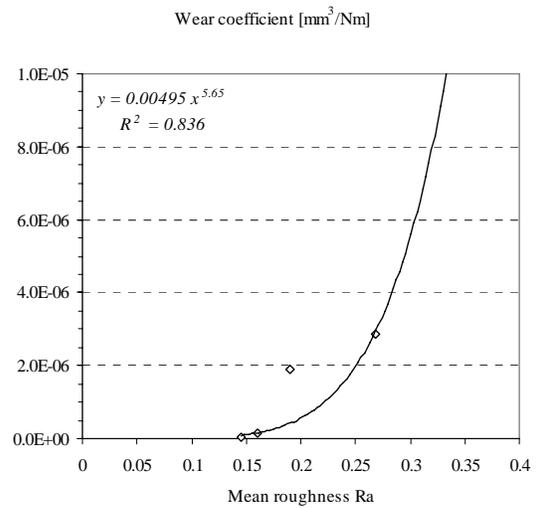$y = 0.00495 \ x^{5.65}$
$R^2 = 0.836$

Mean roughness Ra

Fig. 8. The dependence of the UHMWPE wear coefficient on the mean roughness Ra of the metallic counterface.

Table 1. Comparing results obtained by other authors.

Dowson 1985 [4]	$4 \times 10^{-5} Ra^{1.2}$
Weightman 1986 [5]	$1.5 \times 10^{-6} Ra^{1.37}$
Lancaster 1997 [6]	$7.69 \times 10^{-9} Ra^{0.37}$; $6.29 \times 10^{-9} \exp^{(24.14Ra)}$
Hall 1996 [7]	$9.7 \times 10^{-6} Ra^{0.54}$
Wang 1998 [8]	$3 \times 10^{-5} Ra^{1,79}$
Atkinson 1985 [9]	$1.5 \times 10^{-6} Ra^{-0.23}$
This study	$4,95 \times 10^{-3} Ra^{5,65}$

4. Discussion and conclusions

The influence of metallic surface roughness on the wear of UHMWPE was undoubtedly demonstrated. This study indicates that the wear resistance of UHMWPE is strongly influenced by the counterface finish. The wear rate of UHMWPE was seen to increase with increasing the surface roughness of the counterface. According to these tests, the wear rate of UHMWPE is proportional to the counterface mean roughness raised to a power of 5.56 (equation 5). The presence of grooves inside the wear craters suggests a micro-ploughing wear mechanism.

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