Localized Wear Measurements Using Micro-scratching on the Backside of a UHMWPE Knee Prosthesis Insert

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A new wear measurement technique for prostheses by means of micro-scratching has been demonstrated. An ultra-high molecular weight polyethylene surface was prepared with 5 μm deep micro-scratches. Included in a tibial insert of knee prosthesis the surface was worn over 0.8×10^6 cycles of knee flexion in a realistic simulator. Electron and atomic force microscopy shows that the initial micro-scratches are absent after the wear experiment. The images also indicate wear particle re-integration during wear. A variation across the backside was not observed. This supports a non-linear model of the wear-in phase that has been independently confirmed using radioisotope tracing experiments. A long-term wear rate of the tibial insert backside of 0.6 μm per 10^6 cycles has been extracted that agrees with literature values.

1. Introduction

Total knee replacement is a clinically successful treatment for severe arthritis. However, wear-particle generation at the wear interfaces of the knee prosthesis is the main cause for revision surgery [1,2]. Compared to fixed bearing designs, the topside wear between the femoral component and the topside of the polyethylene insert has been highly reduced by novel, rotating platform designs because of reduced contact stress [3]. However, the additional, second wear interface, between insert backside and tibial platform, may cause extra wear particle generation. This backside wear may be significant [3-5].

The contribution of the backside wear to the total wear is unclear. Previous measurement attempts have included imprint depth measurements, coordinate-measuring methods and radioisotope tracing [3,6,7]. This paper demonstrates a promising new technique to measure prosthesis wear that is based on micro-scratching [8]. The technique allows for quantitative local measurements of the backside wear rate that may show variations across the backside of a knee prosthesis insert, with the sensitivity required to study the important wear-in phase.

2. Experimental details

2.1 Micro-scratching

Four cylindrical plugs with a radius of 4 mm were machined from ultra-high molecular weight polyethylene (UHMWPE) and cleaned ultrasonically. The initial average surface roughness of the UHMWPE plugs was measured as (0.50 ± 0.07) μm by atomic force microscopy (AFM) over an area of 100 μm by 100 μm.

The micro-scratching was carried out by a purpose-built apparatus [8]. The tip of the micro-scratcher was a silicon cubic corner tip. The normal load was 5 N and the scratching velocity was 300 μm/s. The scratches were 200 μm long, along a line across the plug surface, as shown in Fig. 1(a). The depth of each micro-scratch was measured by AFM in several locations.

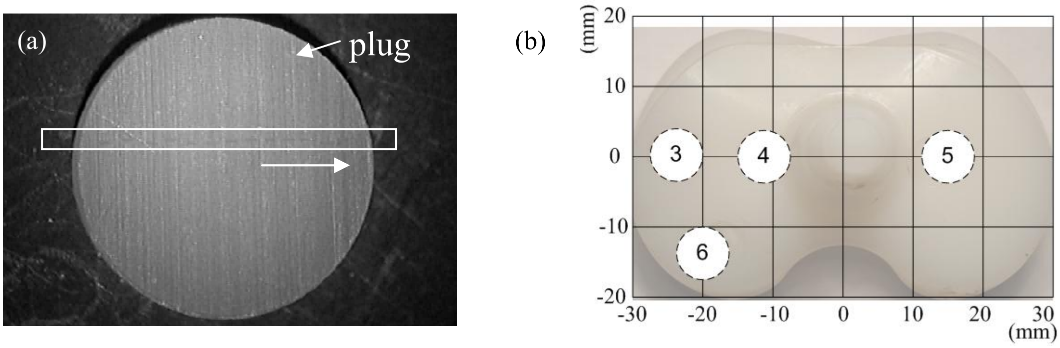

Fig.1. (a) Optical image of a plug prepared with a series of microscratches from left to right and (b) locations of the four plugs 3,4,5,6 in the backside of the UHMWPE tibial insert.

2.2 *In-vitro* knee prosthesis wear simulation experiment

The tibial insert used in the knee wear simulation experiment was a commercial UHMWPE product from Depuy Orthopaedics. The plugs prepared by micro-scratching were carefully recessed into the backside of the tibial insert as indicated in Fig. 1(b). The knee simulation wear experiment was conducted using a single station knee simulator (Prosim). The simulation followed the ISO standard 14243-1. The peak load of the simulation was 2600 N. The frequency was 1 Hz and 800,000 cycles of knee flexion were performed.

3. Results and discussion

3.1 Micro-scratches before wear simulation experiment

A single micro-scratch observed by scanning electron microscopy (SEM, HITACHI) is shown in Fig. 2(a). The micro-scratch grooves are perpendicular to existing machining tracks.

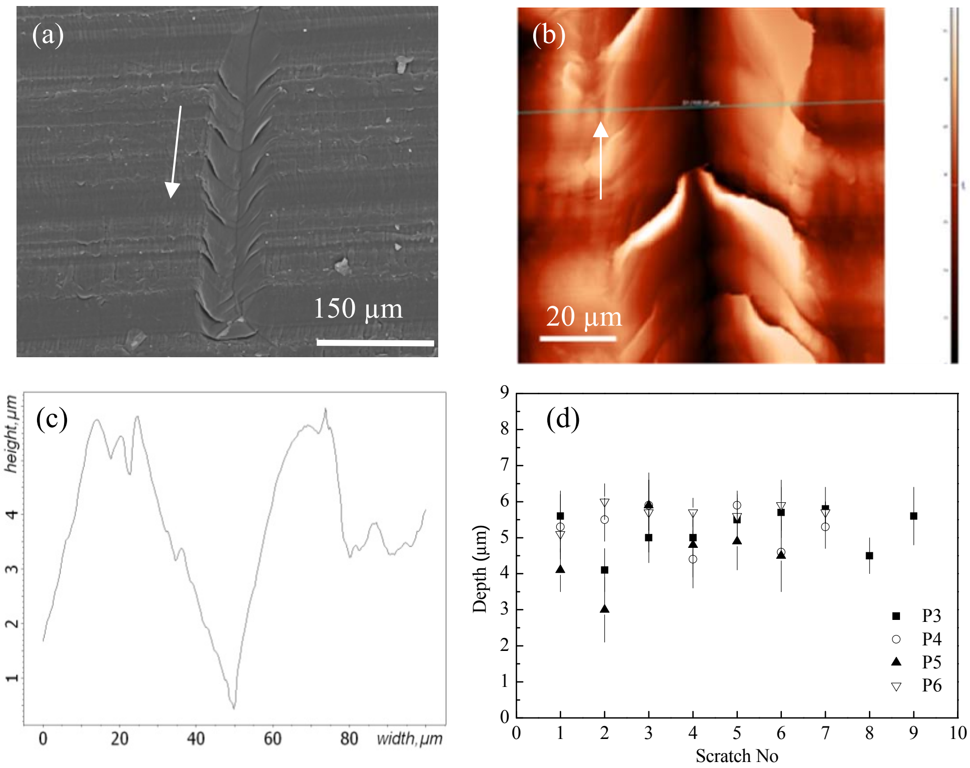

Fig.2. (a) SEM image of a micro-scratch in a UHMWPE plug, (b) AFM image of a partial micro-scratch, (c) Representative cross-section profiles of a micro-scratch and (d) Depth of the micro-scratch on each plug before simulation experiment.

Semi-detached flaps occur where the scratch intercepts a machining track. Detailed features are displayed by the AFM image in Fig. 2(b). The depth of each micro-scratch was measured from the cross-sectional profiles of AFM images such as the profile shown Fig. 2(c). The average depths of these micro-scratches at the four plugs before the wear test were (5.6 ± 0.8) µm, (5.9 ± 0.9) µm, (4.7 ± 0.6) µm and (5.7 ± 0.5) µm, respectively, as shown in Fig. 2(d).

3.2 Micro-scratches after wear simulation experiment

Surface characterization by SEM indicates that, typically, the micro-scratches are absent following the wear experiment. That is, there is no longer any evidence of the microscratches that originally had depths between 3 and 6 µm as shown in Fig. 2(d). This means that at least 6 µm of material was uniformly removed from the backside of the tibial insert during the experiment, corresponding to a wear rate of at least 6 µm per 10^6 cycles, assuming that the rate was constant. Since the backside area of the insert was approximately 1.7×10^3 mm^2 (excluding the area of the central stem), and assuming a density for the UHMWPE of 0.933 g/cm^3, a volumetric wear rate of 10 mm^3 per 10^6 cycles may be derived. 10^6 cycles coarsely represent a year of patient activity. This is a large value. However, it is still consistent with some previous *in-vitro* studies [9,10].

Some SEM images in Fig. 3 show re-integrated UHMWPE wear particles, in-filled wear particles, as well as detached wear particles. The relatively large measured wear rate and the observed in-fill of UHMWPE wear particles may both be understood and can be reconciled by assuming that during the initial wear-in phase the articulating surfaces establish conformity through a polishing process that includes the re-integration of detached material.

In parallel with this work a radioisotope tracing experiment was performed that has been reported elsewhere [11,12] and whose results support this polishing process. This process may occur over a non-linear wear-in phase of 0.3×10^6 cycles during which the wear-rate decreases rapidly to a constant, long-term value of 0.6 µm per 10^6 cycles. In Fig. 4 this latter value and also the larger result of 6 µm per 10^6 cycles, derived in the present work with the microscratching markers, are compared with other results on backside wear rates from the literature [3,9,10,11,13-15]. Considering an apparently strong effect due to the reworking and

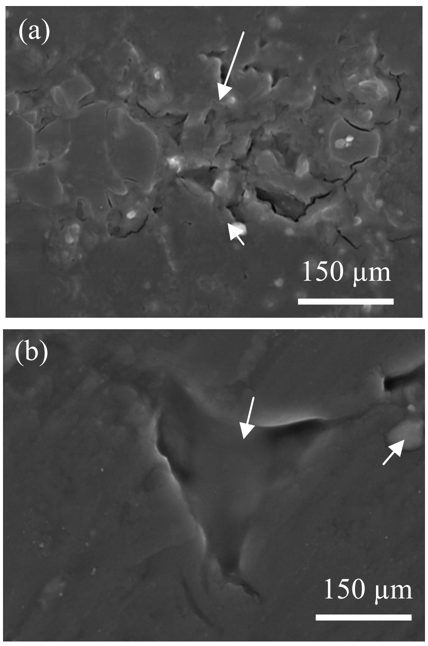

Fig.3. SEM images of the surface of the plugs after the wear test.

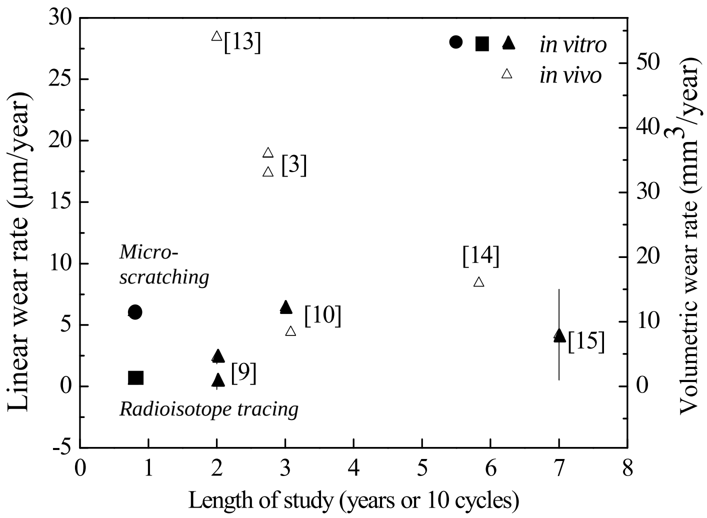

Fig.4. Comparison of the present micro-scratching result at 1×10^6 cycles (●) with the result based on a radioisotope tracing study (■) [11,12] and other literature values (▲) of the backside wear rate of tibial inserts in knee prostheses.

re-integration of material associated with polishing during the wear-in phase, the microscratching result may present a characteristic value of the wear rate during the wear-in phase.

4. Conclusion

A new technique of measuring prosthesis wear has been demonstrated, that can provide position-dependent wear rate information. Ultra high molecular weight polyethylene plugs, carefully fitted into a tibial insert of a knee prosthesis, were prepared by microscratching with a series of 5 μm deep scratches that acted as reference markers in a realistic simulation of knee prosthesis wear. After the knee prosthesis wear experiment, observation by SEM and AFM gave little evidence of the initial micro-scratches on the plugs, which may mean that a complete removal occurred. The evidence suggests that the wear rate does not vary across the backside of the tibial insert. Assuming a constant wear rate over the extent of the measurement gives a wear rate of 6 μm per 10^6 flexion cycles that is consistent with values published by others [9,10,15]. However, in the SEM and AFM images re-integrated or in-filled polyethylene material can often be seen inside remnant features of scratches that appears to be associated with the wear process. This supports a model of the wear-in phase, published earlier [11,12], that assumes a polishing process involving the reworking and reintegration of polyethylene material and predicts a long-term constant wear rate of 0.6 μm per 10^6 cycles. Direct micro-scratching of the insert is feasible, thus avoiding the fitting of plugs. The technique may be applied in future also to studies of top-side wear.

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