3D Surface Reconstruction and FIB Microscopy of Worn Alumina Hip Prostheses

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Abstract. Interest in alumina-on-alumina total hip replacements (THR) continues to grow for the young and active patient due to their superior wear performance and biocompatibility compared to the alternative traditional polymer/metal prostheses. While alumina on alumina bearings offer an excellent solution, a region of high wear, known as stripe wear, is commonly observed on retrieved alumina hip components that poses concern. These in-vivo stripe wear mechanisms can be replicated in vitro by the introduction of micro-separation during the simulated walking cycle in hip joint simulation. However, the understanding of the mechanisms behind the stripe wear processes is relatively poor. 3D topographic reconstructions of tilted SEM stereo pairs from different zones have been obtained to determine the local worn surface topography. Focused ion beam (FIB) microscopy was applied to examine the sub-surface damage across the stripe wear. The paper presents novel images of sub-surface microcracks in alumina along with 3D reconstructions of the worn ceramic surfaces and a classification of four distinct wear zones following microseparation in hip prostheses.

1. Introduction:
Resistance to wear and biocompatibility make ceramics ideal materials for medical applications involving wear, and they have been in use clinically for over 30 years for the bearing surfaces of alumina hip prostheses. Interest in alumina hip prostheses continues to grow, particularly for younger more active patients, due to the relatively short life of the more traditional polymer/metal prostheses that are prone to osteolysis and late aseptic loosening caused by polymer wear debris [1]. Although over 2.5 million alumina femoral heads and nearly 100,000 alumina acetabular cups have been implanted world wide since the first introduction in 1970s [2], the understanding of the wear mechanisms of alumina in-vivo conditions remains relatively poor. It is well documented that microstructure plays an important role in the wear of alumina [3], however, most of the research undertaken to date has concentrated on producing simple wear data (e.g. wear rate) as a function of
microstructure, rather than understanding the detailed wear mechanisms. This current work seeks to
directly address this deficiency.

Retrieved alumina on alumina hip joints commonly exhibit a region of high wear, commonly called
‘stripe wear’ (which is where the wear debris comes from that results in aseptic loosening). This
‘stripe wear’ can be replicated in vitro by the introduction of micro-separation as part of the simulated
walking cycle. While the origin of stripe wear is clearly associated with the microscale impact
resulting from micro-separation, the wear processes leading to its formation and the wear mechanisms
elsewhere on the joint are not well understood. In the present study, the surface and subsurface
damage microstructure around the stripe wear region of in vitro tested alumina hip prostheses was
analyzed and using serial surface cross-sections, reconstructed into 3D.

2. Experimental procedure

A hot isostatic pressed (HIPed) Biolox-forte alumina acetabular cup and femoral head (manufacturer:
CeramTec AG, Plochingen, Germany) were studied, which had been tested in a hip joint simulator
with microseparation at Leeds University using the procedures given in [4]. The nominal diameter of
the cup was 28 mm. This modern generation of alumina has high density, 3.98 g/m³, and a fine grain
size of 1.8 µm. The worn surfaces of the alumina hip prostheses across the stripe wear region were
investigated using a JEOL 6500F FEGSEM. SEM stereo pairs were obtained at 16º tilt to each other
and reconstructed using MeX software (Alicona Imaging, Austria), providing the 3D topography of
the surface and depth images. Focused ion beam (JEOL 6500 Fabrika) microscopy was used to
determine the sub-surface damage across the stripe wear [5]. Serial parallel cross-sections were milled
and the multiple 2D images were then processed using IMOD software (the University of Colorado,
US) to yield 3D reconstructions.

3. Results and discussion

Fig.1 (a) 3D SEM topographic reconstruction of worn alumina acetabular cup in the mild wear zone
shows an occasional surface pit with parallel grooves. (b) The corresponding depth image of (a) shows
depth changes in the mild wear zone. (c) 3D topographic reconstruction of worn alumina acetabular
cup in the stripe wear zone shows a rough surface with localised smooth grains and grains containing
intragranular pitting. (d) The corresponding depth image of (c) shows depth changes in the stripe wear
zone.

SEM analysis of the worn surface of the alumina hip prostheses showed four different worn surface
morphologies, namely as: a smooth surface, but with fine parallel grooves (mild wear), a highly pitted
surface with grain relief (wear transition), a straight boundary between region exhibiting minimal and severe wear, and the stripe wear region comprising a rough surface.

Fig.1a is an SEM 3D topographic reconstruction of the surface in the mild wear zone, showing a region around one of the occasional pits, with the corresponding depth image shown in Fig.1b. There is evidence of inter-granular fracture within the pit and wear debris trapped inside. The corresponding depth image, Fig.1b, shows that the average depth changes on the surface are less than 200nm, with a maximum change of 1.4μm in the pit. Considering the average grain size of the alumina corresponds to ~1.8μm and the observation of inter-granular fracture, this suggests that the pit was caused by grain pull-out through grain boundary fracture. These features are believed to be the first step of the transition from the mild wear regime (i.e. the area around the pit) to severe wear, which ultimately forms the stripe wear region. Note the parallel grooves associated with the pits, which, unlike the extended parallel grooves else where in the mild wear zone, were located exclusively on one side of surface pits, and became shallower the further they were from the pit, indicating the 3-body abrasion that occurs as a result of particles liberated from the pit as it forms.

Fig.1c is an SEM 3D topographic reconstruction of the surface in the stripe wear zone and Fig.1d is the corresponding depth image. Average depth change was ~200nm with a maximum change of 1μm. The area contained an interesting mixture of grains that had been removed through intergranular fracture, some grains that were remarkably smooth, grains that contained intragranular pits, which tended to be aligned in a common direction, and compacted wear debris. It is the compacted wear debris that tends to reduce the average height change compared to the newly formed pit in Fig. 1a.

Due to the inevitable limitation of the surface investigations in determining the true wear mechanism, further analysis of sub-surface damage of worn alumina hip prostheses was carried out by FIB microscopy [6]. Fig.2a and b are the 3D distribution of the cracks and pores in the mild wear zone, reconstructed from 15 (10 μm × 3 μm) parallel FIB cross-sections cut across a 5 μm wide region. Fig.2a gives the worn surface meshed together from individual sections to give solid rendering, while the subsurface cracks and pores are shown as lines. Fig. 2b shows the same area, but with the microcracks as solid surfaces, pores as open loops, while the surface position is indicated by lines corresponding to the top of each section. Microcracks extended to a maximum of 1 μm beneath the surface. The FIB sections confirmed that the vast majority of cracks were intergranular, and were restricted to the outer first layer of grains. Pores were observed at greater depths, but these would have been associated with the manufacture process rather than wear. Thus, as with Fig. 1a, although the overall wear in this region was regarded as mild, the first surface and subsurface cracks had formed, which led to occasional grain pull-out and therefore surface pitting and consequent additional damage through 3 body abrasive wear.

Fig.2c and d give the 3D distribution of the cracks in the stripe boundary zone, using the same approach to presenting the data as in Fig. 2a and b. Data was collected from 10 FIB cross-sections (10 μm × 3μm) across 5 μm on the surface along the stripe boundary. Intergranular microcracks were observed in the stripe wear side. Interestingly, the depth of crack damage was no greater than in the mild wear regime (Fig. 2a, b), and only extended one grain depth below the worn surface. Thus, the transition from mild wear to this severe wear was simply dominated by the loss of the surface grains through intergranular fracture.

Fig. 2e and f give the 3D distribution of the subsurface microcracks in the stripe wear zone taken from serial FIB cross-sections (20 segmental slices collected across 5 μm). A high population of the microcracks about 1 μm beneath the surface can be clearly seen. Clearly, some of the grains viewed in the SEM in plan view (Fig. 1), which appeared securely attached to the surface were just at the point of being lost through pull-out. Again the depth of observed damage does not extend beyond the surface layer of grains.

The current work has shown that the transition from mild wear to severe (stripe) wear is entirely triggered by intergranular fracture. The first stages of fracture lead to the liberation of surface grains which act as effective 3rd body abrasives. Abrasive grooves are associated with extensive surface dislocation activity [3,7], which leads to further grain boundary fracture, which allows the cycle to be
repeated and accelerated, thus yielding the stripe wear region. However, the question remains as to what induces the first region of grain boundary fracture. Clearly this is promoted by the microseparation (as stripe wear cannot be induced without microseparation) and is therefore associated with the impact nature of the contact. Thus, the conclusion is clear: to extend the life of the joint through the avoidance of severe wear, the surface intergranular fracture toughness must be improved.

Fig.2 3D FIB tomographic analysis of the distribution of the micro cracks in the FIB cross-sections of an in vitro alumina acetabular cup. (a) & (b) are in the mild wear zone, (c) & (d) are in the stripe boundary zone, and (e) & (f) are in the stripe boundary zone. In (a), (c) and (e), the top solid plane is the worn surface, lines represent micro cracks and pores. In (b), (d) and (f), lines indicate the position of the worn surface, while the cracks have been interpolated into solid surfaces, and the subsurface closed lines represented pores.

4. Summary:
The worn surface of the simulated alumina acetabular cup has been classified into four different zones, which form through the following sequence: mild wear, characterised by fine surface grooves; occasional surface pits form in the mild wear region through intergranular fracture; 3rd body abrasive grooves result from the liberation of wear debris from these pits adding to the surface damage leading to further surface fracture; the process repeats leading to the wear transition region, ultimately becoming the stripe wear region. The stripe wear region is dominated by intergranular fracture, although some transgranular fracture is also present. Following surface fracture wear debris becomes broken up and partly fills the pits left. Serial FIB sectioning revealed surface grains with extensive subsurface intergranular fracture, i.e. just before liberation as wear debris. FIB also showed that the surface fracture process spread across the surface, but did not extend below the surface layer of grains.

The methods developed in this study have great potential for developing improved designs and materials that are more resistant to the microseparation stripe wear that occurs clinically in ceramic-on-ceramic hip prostheses.

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