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Transmission electron microscopy analysis of worn alumina hip replacement prostheses

P. Zeng [a], W.M. Rainforth [a,*], B.J. Inkson [a], T.D. Stewart [b]

[a] Department of Materials Science and Engineering, University of Sheffield, Sheffield S1 3JD, UK
[b] School of Mechanical Engineering, University of Leeds, Leeds LS2 9JT, UK

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Abstract

Explanted worn alumina orthopaedic hip replacements show characteristic wear regions, ranging from severe wear, dominated by intergranular fracture, to regions in which minimal damage has occurred during articulation. The surface damage accumulation mechanisms are complex and not fully understood. This paper presents a detailed transmission electron microscopy (TEM) study of the surface damage accumulation mechanisms following in vitro tested worn alumina hip replacement prostheses. TEM of focused ion beam cross-section samples indicated extensive surface dislocation activity, which is restricted in the outer grain layer. Except for one example of basal slip, all slips were found to be on pyramidal planes. Both inter- and transgranular cracks were observed in regions of high wear. Grooves, largely associated with third-body abrasion, were generally associated with extensive dislocation activity. Three types of wear debris were seen from the worn surface, namely: granular wear debris, nanocrystalline wear debris and oblong wear debris. Wear debris were shown to arise from grain pull-out and severe plastic deformation at the surface. The observations allow a mechanistic model of the damage accumulations leading to wear and ultimately failure.

Keywords: Alumina; Hip replacement prosthesis; TEM; Wear debris; EDX

1. Introduction

The use of alumina hip prostheses continues to grow (more than 3.5 million alumina components have now been implanted worldwide [1–4]) as a longer-life alternative to standard metal-on-polymer combinations, where life is often limited by osteolysis caused by the liberation of polymer wear particles. Explanted alumina-on-alumina hip prostheses frequently show a localized region of high wear, commonly known as "stripe wear" (first identified by Nevelos et al. [5]) because of the characteristic shape. The stripe wear region is associated with high wear due to intergranular fracture, with a low wear region adjacent [5,6]. While useful and important, the study of explanted joints suffers from uncertainty as the joints have experienced a wide range of differing operation conditions, including time in the patient, patient sex, weight, activity levels and so on. A more rigorous approach is to undertake in vitro testing where all test conditions can be carefully controlled. Early in vitro testing of alumina-on-alumina prosthetics failed to reproduce the "stripe wear" region. Clinically it was shown that hip joint separation occurs during the gait cycle [7]. Fisher and co-workers [8] were the first to demonstrate that a hip simulator could be modified to replicate this micro-separation, which was achieved by applying a force of ~400 N in the lateral direction using a spring combined with a low swing phase load of <200 N. Joints tested in this way exhibited stripe wear, providing a method for in vitro testing that closely replicated in vivo conditions.

It is well known that alumina suffers a time-dependent wear transition from so-called mild wear to severe wear, which is dominated by intergranular fracture [9–14], observed for abrasion [15–17] and for uniaxial dry sliding wear [18,19]. Barceinas-Sanchez and Rainforth [14]

* Corresponding author.
E-mail address: m.rainforth@shef.ac.uk (W.M. Rainforth).

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demonstrated for water-lubricated sliding wear the key role that surface dislocation activity plays in the damage accumulation mechanisms leading to the wear transition. However, it is not clear whether such damage accumulation mechanisms are important in the wear of alumina-on-alumina hip prosthetics. The sliding conditions in hip simulators differ significantly from the uniaxial sliding conditions in three important aspects: (1) articulation is lubricated by bovine serum that gives lubrication conditions from boundary through to elastohydrodynamic [20]; (2) microseparation imparts a degree of impact which abruptly changes local lubrication conditions and surface stress state; (3) sliding follows a complex path more akin to a figure-of-eight motion compared to the conventional uniaxial motion. However, although there have been over four decades of operation of alumina hip prostheses, the understanding of the surface damage accumulation mechanisms remains rather superficial, being derived almost entirely from scanning electron microscopy (SEM) observations of the worn surface morphology. It is important, therefore, to determine the extent to which the knowledge on damage accumulation mechanisms in alumina derived from conventional wear testing is applicable to in vitro testing, where microseparation is included.

In our previous work [21,22], four different wear zones were classified from in vitro tested worn alumina hip prostheses, namely: the mild wear zone, wear transition zone, stripe boundary zone and stripe wear zone. In the current study, detailed transmission electron microscopy (TEM) investigations have been used to identify the wear mechanisms in these different wear zones. These observations indicate the sequence in which the wear processes evolve, leading to the various wear zones observed.

2. Materials and methods

The alumina ceramics used in this work were hot isostatic pressed (HIPed) Biolox® forte alumina (CeramTec AG, Plochingen, Germany) with a density of 3.98 g m^{-3} and an average grain size of 1.8 μm. The purity of the alumina was 99.9% with magnesium oxide (MgO) doping. The nominal diameter of the alumina hip prostheses was 28 mm.

In vitro testing was undertaken in a Leeds Mk II hip joint simulator at Leeds University, UK, the full details of which are given elsewhere [23,24]. The prostheses were placed in the anatomical position and lubricated in a bath of 25% bovine serum. Under normal testing conditions the contact between the femoral head and acetabular cup remained centred in the superior pole at all time. To provide microseparation conditions a small lateral-to-medial load was applied with a spring, which provided 500 μm of medio-lateral motion during the swing phase of the gait cycle. Fourteen tests were conducted for 1–5 million cycles at a frequency of 1 Hz, of which four cups and four heads exhibited stripe wear after 2 million cycles.

The worn surfaces were investigated using a JEOL 6500F FEGSEM and a JEOL 6400 SEM (JEOL, Japan). Atomic force microscopy (AFM) was performed using a Digital Instruments Dimension 3000 Scanning Probe Microscope (Veeco Instruments, US) operating in contact mode. Standard silicon cantilevers with a pyramidal silicon tip were used to acquire images [25].

Site-specific cross-section TEM samples were prepared by the focused ion beam (FIB) ex situ lift-out method. Firstly, places of interest were selected and tungsten was deposited to protect the area of interest. Two trenches were milled at each side of the deposition, initially using a 200 pA beam current, then 100 pA and finished at a beam current of 30 pA to polish the wall until electron transparency was achieved (~150 nm thickness). Finally, the lamella was cut free from the sample and lifted out by a micromanipulator (Narishige Co., Japan) onto a copper grid (200 mesh) with carbon film [25]. In addition, back-thinned TEM samples were also prepared from the worn surface using standard techniques [26]. Ion beam milling from below the worn surface only was undertaken on a Gatan PIPS (Gatan Inc., USA).

TEM was performed on a Philips 430 operating at 300 kV. Dislocation distributions were determined using the weak beam dark-field (WBDF) technique, with $\bar{g}(3\bar{g})$ with $\overline{s_{3\bar{g}}}$ positive, since individual dislocations often could not be uniquely distinguished in bright-field images. Burgers vector analysis was undertaken using the standard $\bar{g} \cdot \bar{b} = 0$, while slip planes were identified through standard trace analysis.

3. Results

Four wear zones were identified on the in vitro tested alumina hip prostheses, as shown in Fig. 1, defined in line with previous work [21,22], namely: mild wear zone (Fig. 2a and b), wear transition zone (Fig. 2c), stripe boundary zone and stripe wear zone (Fig. 2d). With the exception of the stripe wear zone, the appearance of the remaining features was the same on the in vitro alumina acetabular cup and femoral head. The stripe wear region exhibited the same basic features on both head and cup, namely high wear originating from intergranular fracture. However, regions of plastic deformation were also observed on the femoral head, described in detail later. On the basis of the similarities, the results for the acetabular cup are presented in detail, with the important differences shown by the femoral head given.

3.1. Mild wear zone

The mild wear zone, Fig. 2a and b, dominated the majority of the surface. Random scratches could be observed optically, associated with the polishing stage of manufacture of the component. Interestingly, the location of the grain boundaries was clearly visible, presumably left by the hot isostatic pressing (HIPing) during manufacture,