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Characterisation of the wear mechanisms in retrieved alumina-on-alumina total hip replacements

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ABSTRACT

Due to their superior wear performance and biocompatibility compared to alternative polymer/metal prostheses, alumina-on-alumina total hip replacements (THRs) are extensively used for young and more active patients. However, the understanding of the wear mechanisms of alumina *in vivo* remains relatively poor, and there remains little quantitative understanding of the structural and chemical changes at the articulating surface. In the current study, the surface and sub-surface microstructures of retrieved *in vivo* alumina THRs are presented. Severe wear, also called stripe wear, was observed in all cases. The transition between the stripe wear and the mild wear was very sharp. Site-specific cross-section TEM specimens were prepared by Focused Ion Beam (FIB) at the stripe boundary region. The results suggest predominantly intergranular fracture occurred that was restricted to the outer layer of grains below the surface, with transgranular fracture also occurring in the stripe wear region. Cracking was believed to be initiated by extensive dislocation slip. A thin layer of hydroxide was also observed at the extreme surface of the mild wear region by aberration-corrected high resolution transmission electron microscopy (HRTEM). The wear mechanisms are discussed.

1. Introduction

About 2% of people suffer hip problems and need a replacement hip joint. In the UK, at least 50,000 hip replacement surgeries are undertaken every year, and are highly successful in reducing the pain and disability of worn or damaged hip joints. Total hip replacement is one of the most successful applications of biomaterials, with joints commonly lasting more than 10–15 years [1,2]. However, the long-term (> 15 years) performance of the THRs is only achieved in a small proportion of cases. With the increase of younger and high demand patients, as well as an increase in life expectancy, long-term (> 15 years) high performance THRs are increasingly required.

Since the 1960s, metal-on-polymer THRs are by far the most common artificial hip joints in the market [1]. However, due to the osteolysis (bone resorption) caused by polymer wear debris and component loosening, interest in alumina-on-alumina THRs continues to grow [3–5]. Additionally, alumina-on-alumina THRs show a higher survival rate than metal-on-polymer THRs for patients younger than 50 years old [6–8]. With metal debris and ions release from CoCrMo alloys becoming a subject of intense interest due to the higher than expected failure rate of metal-on-metal hip replacements [9–11], alumina or alumina based ceramic THRs are increasingly used for young and more active patients.

Alumina-on-alumina THR was first introduced in the 1970s. However, early problems with the performance of the alumina-on-alumina THRs, such as a high fracture rate, restricted their development worldwide. This was mainly due to poor material quality and hip design. With the development of medical-grade alumina, especially the introduction of ISO 6474 alumina-on-alumina THRs now perform substantially better than the original 1st generation alumina. Although over 2.5 million alumina femoral heads and nearly 100,000 alumina acetabular cups have been implanted worldwide since the first introduction [12], the understanding of the wear mechanisms of alumina *in vivo* remains relatively poor. Since wear plays an important role in limiting the life-time of artificial hip joints it is important to understand the wear mechanisms that operate *in vivo* in alumina-on-alumina THRs in detail.

In the wear of alumina-on-alumina THRs, most of the research undertaken to date has concentrated mainly on the wear performance of *in vitro* alumina hip prostheses. For the *in vivo* studies, the focus of attention has been on key performance indicators such as wear rate, survival rate, with virtually no focus on the microstructure and wear mechanisms. Similarly, for the *in vitro* testing, the output has often been simple parameters such as wear

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rate and general worn surface appearance. Only limited work on the microstructural evolution from wear of alumina-on-alumina THRs has been published [13–23]. A region of high wear, often referred to as 'stripe' wear, on the surface of both alumina acetabular cups and femoral heads has been observed in retrieved *in vivo* alumina-on-alumina THRs [15]. However, wear mechanisms leading to this stripe wear are not clearly understood.

In the current study, surface morphology across the stripe wear of the retrieved *in vivo* alumina-on-alumina THRs was analysed by 3D optical microscopy and scanning electron microscopy (SEM). Sub-surface microstructure was studied using FIB, HRTEM and Electron Energy Loss Spectroscopy (EELS). Wear mechanisms leading to the stripe wear on the worn alumina-on-alumina THRs are discussed.

2. Experimental procedure

2.1. Materials

7 pairs of retrieved alumina-on-alumina THRs were investigated and the details of each pair are given in Table 1. An example of the retrieved *in vivo* alumina femoral head and acetabular cup are shown in Fig. 1. The alumina ceramics used for operations were Biolox® alumina ceramic material with a mean grain size of 3.2 μm and a density of 3.95 g/cm^3.

2.2. Characterisation

2.2.1. Surface characterisation

The worn surface of retrieved *in vivo* alumina-on-alumina THRs were first inspected by naked eye to locate the severe wear region, as shown in Table 1. The surface topography of the retrieved *in vivo* alumina femoral heads was examined by a 3D optical microscope (ContourGT, Bruker, UK).

Due to the difficulty and the size of the samples, it was not possible to investigate all the samples using SEM. Therefore, a pair of retrieved *in vivo* alumina-on-alumina THR was chosen carefully for further SEM investigation that was believed to be representative. The alumina THR chosen had been implanted for 12 years and failed by loosening (head # 7 and cup # 7 in Table 1). The material for the retrieved pair was 2nd generation Biolox with a mean grain size of 3.2 μm and density of 3.95 g/cm^3. The worn surfaces were analysed by SEM (Sirion, FEI Company, Netherlands) operating at 10 kV. The samples were coated with carbon before the investigation to avoid charging.

Fig. 1. A pair of retrieved *in vivo* alumina femoral head and acetabular cup.

2.2.2. Sub-surface damage

Site-specific TEM samples were prepared by an *in-situ* focused ion beam (FIB) lift-out using a Quanta 200 3D FIB (FEI Company, Netherlands) equipped with an *in-situ* tungsten probe (Omniprobe, USA), as shown in Fig. 2. A gold layer was sputtered (Emscope SC 500 A Sputter Coating Unit, UK) on the surface prior to FIB milling to label the original surface and avoid charging. For FIB processing, a 30 kV Ga^+ ion beam was used. Firstly, a carbon stripe was deposited onto the area of interest using a 0.3 nA beam current to prevent damage of the surface due to ion milling (Fig. 2a). Secondly, two trenches were milled on both sides of the carbon deposition using high beam currents (5 nA and 3 nA), as shown in Fig. 2b. Thirdly, the TEM lamella was lifted out using the Omniprobe (Fig. 2c) and attached to a TEM grid *via* carbon deposition (Fig. 2d). Finally, the TEM lamella was further thinned from both sides with low beam currents (varied from 0.5 nA to 30 ρA) until it was electron transparent (< 50 nm), as shown in Fig. 2e.

TEM investigation was carried out using various TEMs, including FEI Tecnai 20 (FEI, Netherlands), Jeol 2010F (JEOL, Japan) and Jeol R005 (JEOL, Japan), all operating at 200 kV. EELS (Gatan, USA) equipped on Jeol 2010F was employed to analyse the cross-section samples. EELS measurements were made in conventional TEM diffraction mode (image coupling to the spectrometer).

3. Results

3.1. Percentage of the stripe/severe wear on the retrieved in vivo alumina-on-alumina THRs

Table 1 summarises the dimension of the stripe wear on the worn surface of retrieved *in vivo* alumina-on-alumina THRs. Although they had failed for different reasons, all the retrieved *in vivo* alumina prostheses exhibited stripe wear on the surface. The length of the stripe ranged from 30 mm to 90 mm with

Table 1
The dimension of stripe wear observed on the worn surface of retrieved *in vivo* alumina-on-alumina THRs investigated.

Samples	Length of the stripe (mm)	Max. width of the stripe (mm)	Diameter of the hip prostheses (mm)	Notes
Head # 1	40.0	12.0	32	2 years implanted, failure by dislocation
Cup # 1	40.0	12.0	32	
Head # 2	75.4	25.0	32	8 years implanted,
Cup # 2	50.2	11.0	32	failure by loosening
Head # 3	38	8	38	11 years implanted, failure by loosening
Cup # 3	67.0	7.0	38	
Head # 4	51	30.0	32	1 year implanted, failure by loosening
Cup # 4	50.2	17.0	32	
Head # 5	26.0	9.0	38	10 years implanted, failure by loosening
Cup # 5	39.8	3	38	
Head # 6	32	6	32	1 year implanted, failure by migration
Cup # 6	33.5	12	32	
Head # 7	89.5	23	38	12 years implanted, failure by loosening
Cup # 7	59.7	10	38	