GENERATION OF FRETTING WEAR DEBRIS AT THE STEM–CEMENT INTERFACE IN TOTAL HIP REPLACMENT

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ABSTRACT

Fretting wear debris generated at the stem–cement interface has nowadays been considered to play an important role in the overall failure of cemented total hip replacement (THR). Those wear debris within a certain size range would transport along bone cement deficiencies to bone tissue, resulting in a significant bone resorption and subsequent aseptic loosening of the femoral component, which is regarded as the primary reason for revision of cemented THR. In order to study the influence of the time period of in vivo service of the prosthesis on generation of fretting wear debris, we performed two in vitro wear simulations using identical femoral stem and bone cement, but applying different loading cycles. By conducting a detailed investigation of the bone cement surface with the use of optical microscope, scanning electron microscope (SEM) associated with energy dispersive X-ray (EDX) analysis, we came to a conclusion that for the specific bone cement studied, sufficient loading cycles were required to dislodge the metallic debris from the femoral stem surface, which indicated that generation of fretting wear debris was indeed influenced by the time period of in vivo service of the prosthesis.

Keywords: femoral stem, bone cement, fretting wear, wear debris

1 INTRODUCTION

Cemented THR is one of the most common and effective procedures performed not only in the UK but also worldwide to treat hip disorders, such as osteoarthritis, rheumatoid arthritis and necrosis. With an increasing prevalence of this procedure carried out in younger patients coupled with a longer life expectancy, it is hoped that cemented THR could function well for at least 15–20 years. However, up to 10% of the 60,000 operations performed in the UK in 2006 were to revise those prostheses that had failed prematurely. In comparison with primary arthroplasty, revision is exposed to a much higher cost and associated with a decisively inferior longevity and a risk of further catastrophic failure. Therefore, great efforts have been made to investigate the scenario behind the failure of cement THR. Due to the significant contribution of both orthopaedic surgeons and researchers in conducting implant retrieval studies and tissue analyses, aseptic loosening has been comprehensively accepted as the primary reason for revision [1]. Aseptic loosening can be mainly attributed to bone resorption, which is activated by a macrophage response to particulate debris generated by wear of the components. Theoretically, wear can occur not only at the articulating head–cup interface, but also at other load bearing surfaces.

The stem–cement interface has consistently been regarded as a weak link in cemented THR, which functions as a transitional zone between two materials with significantly different stiffness, hardness, and elastic modulus [2, 3]. As a result, a low-amplitude oscillatory micromotion will inevitably occur at this interface due to the unmatched strain when physiological loading is applied. Therefore, there is potential for the stem–cement interface to experience fretting wear in vivo. Recently, great progress has been made in reducing wear at the head–cup interface, with the advent of cross-linked ultra high molecular weight polyethylene (UHMWPE) and hard–on–hard bearing systems [4, 5]. It is therefore considered that fretting wear at the stem–cement interface is showing a more and more crucial significance in the overall wear of cemented THR. Indeed, fretting wear at this interface would further induce generation and liberation of wear debris, jeopardising stabilisation of the femoral component. Some wear debris within a certain size range could transport along bone cement deficiencies to bone tissue, where a macrophage response would occur to destroy the bone stock. This consequently promotes aseptic loosening of the femoral component.

Although it has been well documented with regard to fretting wear debris generated at the stem–cement interface across previously published literatures [6, 7], few have investigated the influence of the time period of in vivo service of the prosthesis on generation of wear debris. Therefore, the present study aims to gain some insight into this issue by performing two in vitro wear simulations with the use of identical femoral stem and bone cement, but applying different loading cycles.

2 THE FRETTING WEAR SIMULATIONS

Polished Exeter V40^{TM} femoral stem (Stryker Howmedica Osteonics, Newbury, UK) and Simplex P bone cement (Howmedica International Inc, Limerick, Ireland) were employed in the present wear simulations, both of which have shown excellent clinical track records. The bone cement was hand mixed according to the manufacture's instructions, and delivered into a reamed sawbone (3rd generation composite femur, Sawbones, Malmö, Sweden) utilising a cement delivery system. The stem was then implanted and the cement cured in situ as instructed to mimic surgical techniques. The stem–cement–sawbone structure was stabilised by acrulite resin (Rubert & Co Ltd, Cheadle, UK) in a steel tube at a position of 10° in adduction and 9° in flexion. A custom-made fixture was designed to enable the wear simulations on an Instron 1273 test machine.

The simulations were performed in part with reference to the specifications for endurance of hip prosthesis instructed by ISO standard 7206-4. The load was applied vertically to the femoral head in compression between 0.3kN and 2.3kN in the form of sine wave, the peak value of which was about 3 times of mean body weight. In addition, 9g/l saline solution was utilised to represent the environmental conditions in vivo, and a cylindrical plastic tube was attached closely to the top of the steel tube to hold the saline solution, in which the stem–cement–bone structure was immersed. The frequency for both simulations was set to be 3Hz to reduce the test duration. One simulation was completed to 5 million cycles and the other to 10 million cycles, corresponding to approximately 5 and 10 years' in vivo wear of the femoral component respectively.

Following the wear simulations, the femoral stem was cautiously extracted from the cement mantle and then carefully cleaned with alcohol. The sawbone was removed out of the acrulite resin and sawn longitudinally into two equal parts, the internal surfaces of which were cleaned with alcohol as well to enable observation of the bone cement surface employing an optical stereomicroscope (MZ6, Leica Microsystems Ltd., Wetzlar, Germany). Additionally, the bone cement was further sectioned and gold sputtered to facilitate a scanning electron microscope (SEM, JEOL JSM-6060, Oxford Instruments) study of any fretting wear debris present on the surface. Finally, an energy dispersive X-ray (EDX) analysis was performed to ascertain the element composition of the wear debris.

3 EXPERIMENTAL RESULTS

Both of the two femoral stems demonstrated evidence of fretting wear on the surface and the wear locations compared well with the results of retrieval studies [8]. There were many micropores present in the bone cement surface as well as throughout the cement mantle. These micropores showed a large variety of diversities in both size and shape (figure 1). Particularly, the optical micrograph of the bone cement surface originating from the simulation with 10 million cycles indicated that there were some highly reflective sites around the micropores, which appeared to be metallic wear debris. Figure 2 demonstrated the SEM micrograph of the bone cement surface originating from the simulation with 5 million cycles, from which it was shown that there was an amount of wear debris located in the micropores, and the corresponding EDX analysis indicated that this was just cement particles for an iron-rich (Fe) plaque was not detected. These cement particles were potentially worn off from the bone cement surface by the fretting process at the stem–cement surface, and retained in the micropores afterward. However, there seemed to be neither micro-cracks nor macro-cracks in the cement surface. Figure 3 shows the SEM micrograph of the bone cement surface originating from the simulation with 10 million cycles. Those areas around the micropores were severely worn, and the corresponding EDX analysis confirmed that these worn areas indeed included metallic wear debris for both an iron-rich plaque and a chromium-rich (Cr) plaque were detected. This metallic wear debris could only come from the femoral stem surface, which was dislodged by fretting wear during the simulation due to the application of more loading cycles. Interestingly, it was further indicated that for the metallic wear debris, the ratio of the content of Cr to that of Fe is about 9:1. By contrast, for the original stainless steel stem, the content of Fe is much higher (about 64.5%) than that of Cr (about 17.5%). It was considered that it was the passive layer which had been previously formed to protect the stem surface that was initially worn off from the femoral stem by fretting wear and this passive layer was affluent in Cr rather than Fe. When the superficial material was damaged, a new passive layer was reformed very rapidly as it was very easy for Cr to reform this oxide film. Then the new passive layer was further removed and successive re-passivation continued. This was considered why the metallic wear debris around the micropores contained principally Cr. Additionally, the SEM micrograph of the bone cement surface showed evidently the presence of micro-cracks at the edge of the micropores (figure 4), and these micro-cracks seemed to be initiated from this site and then propagated to its bulk material. This indicated that more bone cement deficiencies will occur with the increase of loading cycles.

4 CONCLUSIONS

This present study investigated the influence of the time period of in vivo service of the prosthesis on generation of wear debris at the stem–cement surface by carrying out two in vitro wear simulations with the use of identical femoral stem and bone cement but different loading cycles. It is considered that the results have gained a deeper insight into this crucial issue and provided evidence which could be used to improve the functionality of cemented THR.

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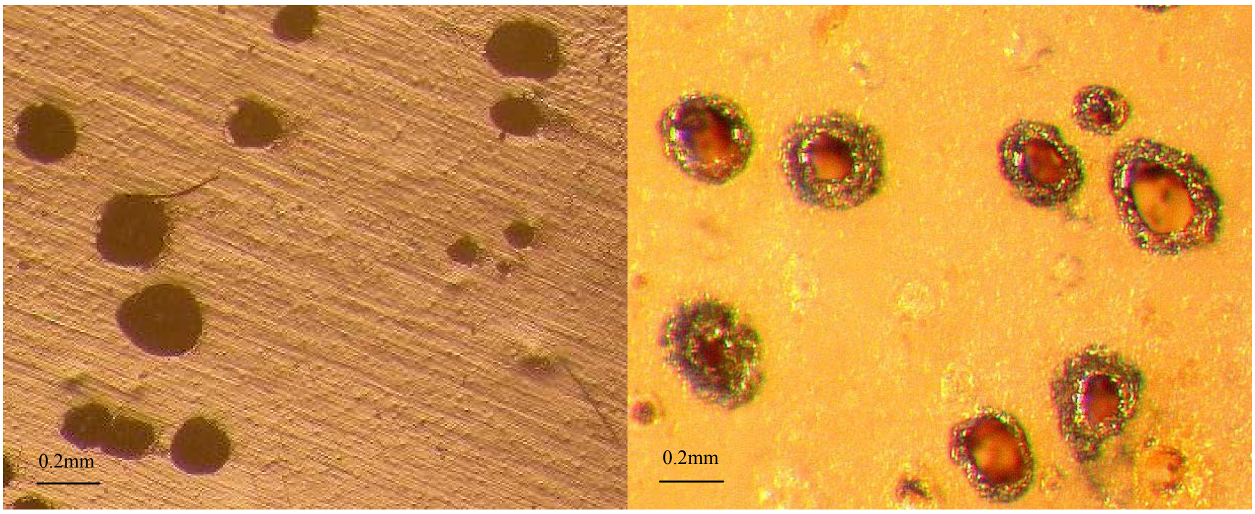

(a) (b)

Figure 1: Optical micrograph of the cement surface showing micropores. (a) The simulation with 5 million cycles; (b) The simulation with 10 million cycles, the reflective sites around the micropores appeared to be metallic wear debris.

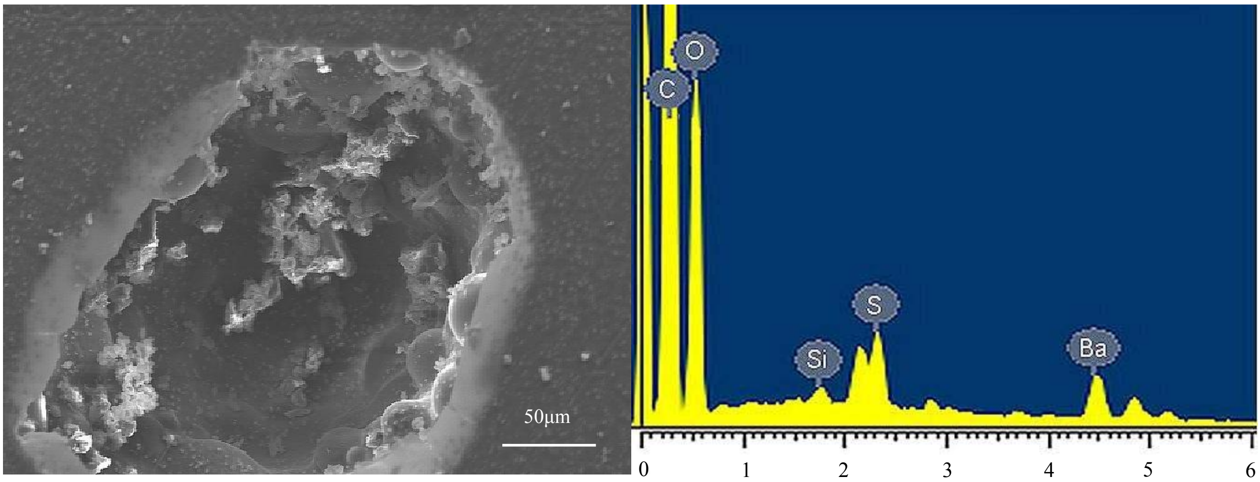

Figure 2: SEM micrograph of the bone cement surface originating from the simulation with 5 million cycles, there was wear debris located in the micropores and the EDX analysis indicated that this was cement particles.

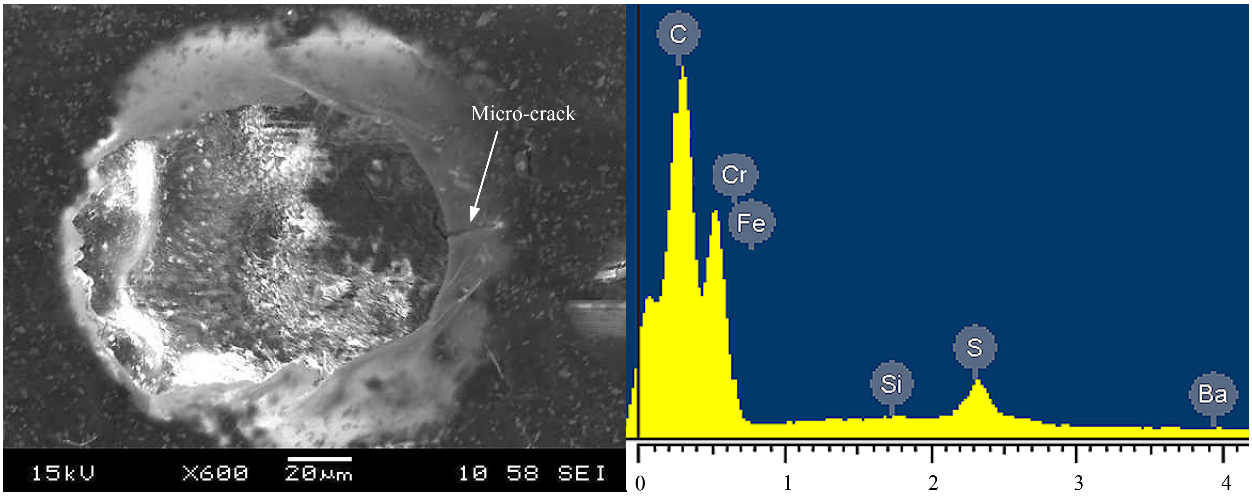

Figure 3: SEM micrograph of the bone cement surface originating from the simulation with 10 million cycles, there was wear debris located around the micropores and the EDX analysis confirmed that this included metallic particles.

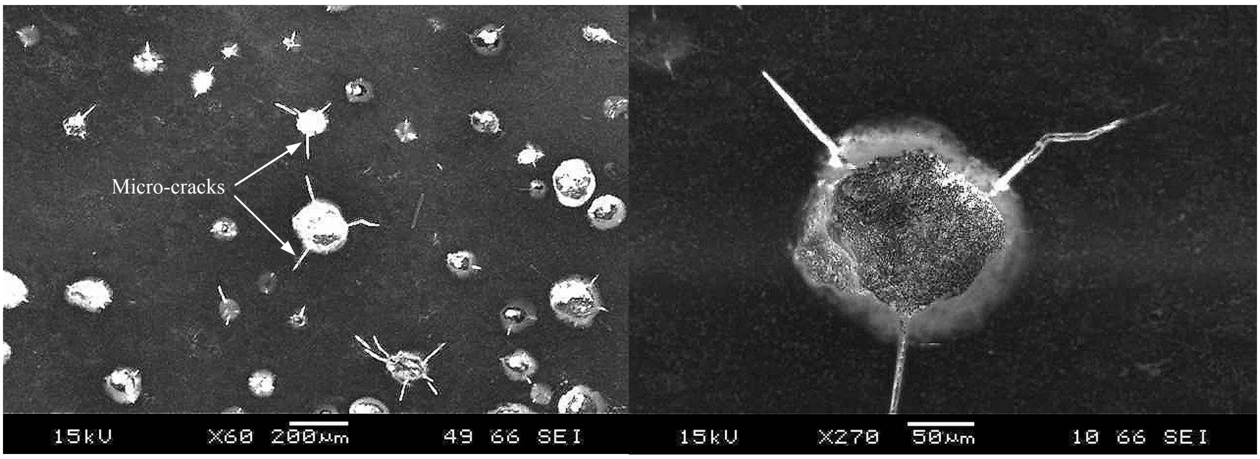

Figure 4: SEM micrograph of the bone cement surface originating from the simulation with 10 million cycles, there were micro-cracks which initiated from the edge of the micropores and then propagated to its bulk material.