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Reproduction of fretting wear at the stem—cement interface in total hip replacement

Reproduction of fretting wear at the stem–cement interface in total hip replacement

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The manuscript was received on 12 June 2007 and was accepted after revision for publication on 25 July 2007.

DOI: 10.1243/09544119JEIM333

Abstract: The stem–cement interface experiences fretting wear *in vivo* due to low-amplitude oscillatory micromotion under physiological loading, as a consequence it is considered to play an important part in the overall wear of cemented total hip replacement. Despite its potential significance, *in-vitro* simulation to reproduce fretting wear has seldom been attempted and even then with only limited success. In the present study, fretting wear was successfully reproduced at the stem–cement interface through an *in-vitro* wear simulation, which was performed in part with reference to ISO 7206–4: 2002. The wear locations compared well with the results of retrieval studies. There was no evidence of bone cement transfer films on the stem surface and no fatigue cracks in the cement mantle. The cement surface was severely damaged in those areas in contact with the fretting zones on the stem surface, with retention of cement debris in the micropores. Furthermore, it was suggested that these micropores contributed to initiation and propagation of fretting wear. This study gave scope for further comparative study of the influence of stem geometry, stem surface finish, and bone cement brand on generation of fretting wear.

Keywords: simulation, fretting wear, stem–cement interface, total hip replacement

1 INTRODUCTION

Total hip replacement (THR) is one of the most common and effective procedures performed in the UK and worldwide, with the purpose of dramatically improving the quality of life of patients suffering from hip disorders. With an increasing prevalence of this procedure carried out in younger patients coupled with a longer life expectancy, it is hoped that this total joint system could function well for at least 15–20 years. However, up to 10 per cent of the 60 000 operations performed each year in the UK are to revise prostheses which have failed prematurely. Because of the great efforts made by orthopaedic surgeons and researchers in conducting implant retrieval studies and tissue analyses, aseptic loosening has nowadays been generally accepted as the primary cause of failure of cemented THR, which predominates mechanical malfunctioning of the stem–cement–bone system [**1**, **2**]. 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 [**3**, **4**]. Theoretically, wear can occur not only at the articulating surface but also at other load-bearing surfaces.

The stem–cement interface has been consistently cited as a weak link in cemented THR [**5**, **6**], which functions as a transitional zone between two materials with significantly different mechanical properties. As a result, a low-amplitude oscillatory micromotion at this interface will happen owing to the unmatched strain when physiological loading is applied [**7**, **8**]. 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 articulating interface, with the introduction of cross-linked ultra-high-molecular-weight polyethylene (UHMWPE) and hard-on-hard bearing systems [**9**, **10**]. It is thus considered that wear at the stem–cement interface

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shows an increasing significance in the overall wear of THR.

Consequently, much research has been carried out, focusing on this interface [**11–14**]. It has been demonstrated in clinical studies that fretting wear was detected on polished stems [**15**, **16**], which contributed to early loosening and subsequent failure of cemented THR. However, *in-vitro* simulation to reproduce fretting wear has seldom been attempted. Cook [**17**] was considered to be the first to attempt this, but even then only limited success was achieved. In a previous investigation carried out by Ebramzadeh *et al.* [**18**], a pin-on-disk test was employed in terms of displacement control and static compressive loading, which obviously cannot represent the exact *in-vivo* joint environment of the human hip. This present study hence aims to reproduce fretting wear successfully through *in-vitro* simulation, and to gain an insight into the initiation and propagation of fretting wear on the stem surface, which hopefully may allow further comparative study of the influence of stem geometry, stem surface finish, and bone cement brand on the generation of fretting wear.

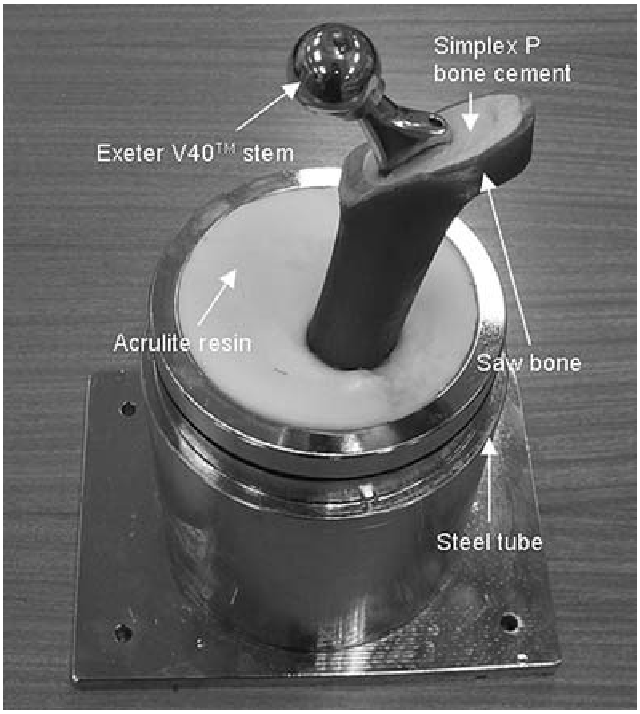

Fig. 1 The test specimen for fretting wear simulation, which is connected to the Instron test machine 1273

2 MATERIALS AND METHODS

A polished Exeter V40™ femoral stem (Stryker Howmedica Osteonics, Newbury, UK) and Simplex P bone cement (Howmedica International Inc., Limerick, Ireland) were used in the present simulation, both of which have excellent clinical track records. The cement was hand mixed according to the manufacturer's instructions and delivered into a reamed sawbone (third-generation composite femur, Sawbones, Malmö, Sweden) utilizing a cement delivery system. The stem was then implanted and the cement cured as instructed to mimic surgical techniques. Acrulite resin (Rubert & Co Ltd, Cheadle, UK) was employed to stabilize this stem–cement–bone system in a steel tube (Fig. 1). A custom-made fixture was designed to enable fretting wear simulation on an Instron test machine 1273.

The simulation was performed in part with reference to the specifications for endurance of hip prosthesis instructed by ISO 7206-4:2002 [**19**]. The stem–cement–bone system was fixated at a position of 10° in adduction and 9° in flexion. The load was applied vertically to the femoral head in compression between 300 and 2300 N in the form of a sine wave, the peak value of which was approximately three times the mean body mass, i.e. 75 kg. The simulation was carried out at 3 Hz for 5×10^6 cycles uninterruptedly, corresponding to approximately 5 years' *in-vivo* wear of the femoral stem. Additionally, 9 g/l saline solution was utilized to represent 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 system was immersed.

Quantification and analysis of fretting wear on the stem were conducted before and after simulation to detect any evidence of surface change, using a Talysurf CCI interferometer at $\times 20$ magnification. Locations of surface measurement were determined through use of Gruen zones, as described by Gruen *et al.* [**20**]. The definition of Gruen zones is shown in Fig. 2. Some selected three-dimensional surface parameters Sq, Sz, Sdq, Ssc, and Sdr were calculated by Surfstand software V3.3. These parameters were further explained in Table 1 and they were utilized to assess fretting wear quantitatively. Subsequently, the stem was cut into small pieces to facilitate observation of surface topography using a JEOL JSM-6060 scanning electron microscope (SEM). Additionally, the sawbone was sawn longitudinally into two equal parts to enable investigation of the cement surface, employing the Talysurf CCI interferometer. Afterwards, the cement was sectioned and gold sputtered to facilitate an SEM study with an energy-dispersive X–ray analysis (EDXA) of any fretting debris on

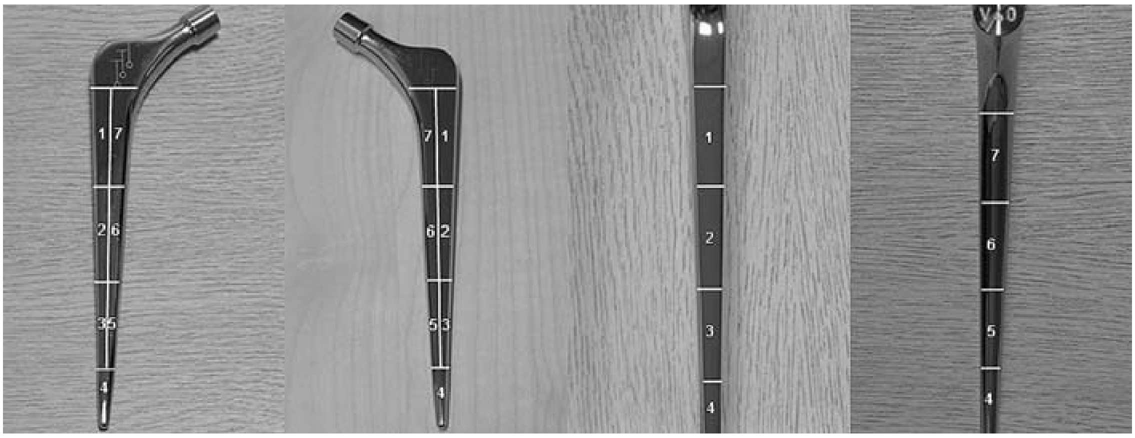

Fig. 2 Definition of Gruen zones on the stem surface, which assist tracking the locations of surface measurement

Table 1 Selected three-dimensional surface parameters to assess fretting wear on the femoral stem

Parameter	Abbreviation	Explanation
r.m.s. deviation of the surface	Sq	A more stable expression of average surface roughness
Maximum height of the surface	Sz	Height between the tallest peak and the deepest valley
r.m.s. slope of the surface	Sdq	r.m.s. value of surface slope within the assessed area
Arithmetic mean summit curvature of the surface	Ssc	Arithmetic mean value of the principal curvatures of the summits within the assessed area
Developed interface area ratio	Sdr	Ratio of the increment of the interfacial area of a surface over the sampling area: tends to zero for smooth surface

the surface. Furthermore, both the stem and the cement were investigated using a Leica MZ6 stereomicroscope. This enabled a much larger area on the surface to be evaluated, which consequently may allow an insight to be gained into initiation and propagation of fretting wear on the stem surface.

3 RESULTS

3.1 Femoral stem

The Exeter V40^{TM} femoral stem was found to be firmly fixated in the cement mantle after simulation. Following cautious extraction by a hammer and cleaning with alcohol, the stem showed evidence of fretting wear on all the surfaces (Fig. 3). The location of fretting wear was summarized as the coverage of the worn areas, evaluated by gross visual inspection (Table 2). These worn areas primarily concentrated on the anterolateral, posteromedial, and underneck zones of the stem surface, which compared well with the results of retrieval studies [**15**, **16**]. The other areas were relatively smooth and appeared undamaged. In addition, there was no evidence of formation of bone cement transfer films, which may be further removed as wear debris even if they were generated in the course of fretting wear simulation.

As can be clearly seen from Table 2, Gruen zones 6 and 7 on the stem posterior surface illustrated evidence of the most severe fretting wear. Therefore, a total of 20 measurements were carried out for each of these two Gruen zones, using the Talysurf CCI interferometer. Figure 4 showed one typical

Table 2 Coverage of fretting wear area in each Gruen zone on the stem surface

	Fretting wear area (%)			
Stem surface	Anterior	Posterior	Medial	Lateral
Zone 1	0	60		10
Zone 2	20	20		90
Zone 3	30	0		10
Zone 4	0	0	0	0
Zone 5	10	10	0	
Zone 6	30	80	10	
Zone 7	10	90	80	

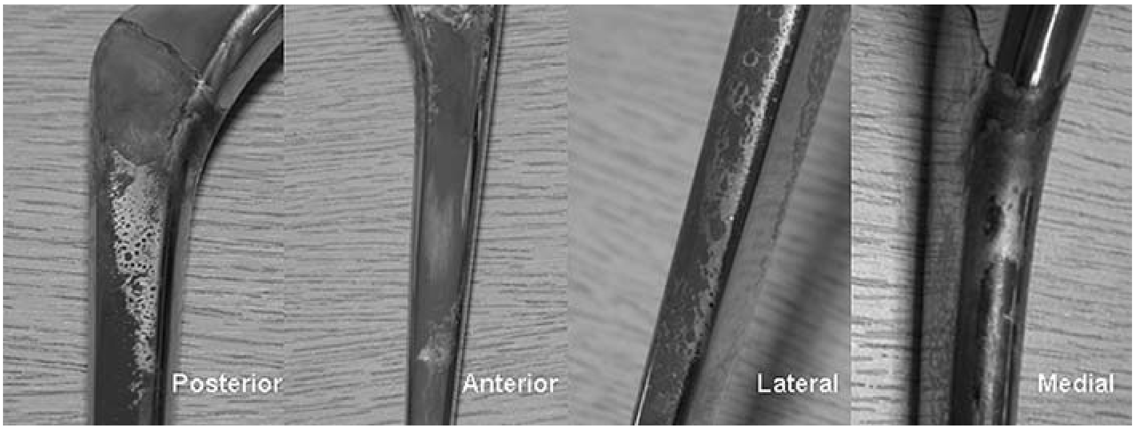

Fig. 3 Fretting wear generated on the stem surface after simulation, while no presence of bone cement transfer films is detected

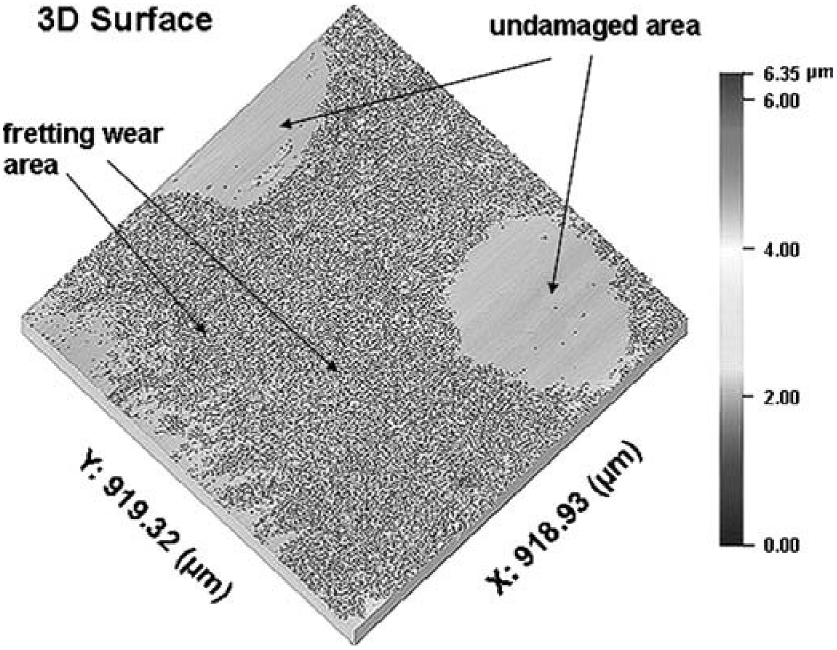

Fig. 4 Comparison between the fretting wear area and the undamaged area on the stem surface after simulation, the fretting zones are very rough while the undamaged area remains smooth

measurement performed in Gruen zone 6, which delineated the comparison of surface topography between the fretting wear area and the undamaged area. The values of the selected three-dimensional surface parameters were listed in Table 3, from which it can be seen that the stem surface had greatly changed. The significant increase in Sq, Sz, Sdq, Ssc, and Sdr all demonstrated that the stem was much rougher after simulation.

Figure 5 displayed the surface topography of the fretting zones on the simulated stem and on an explanted stem derived from a retrieval study [**16**], both of which were measured using SEM. The similar pitting and crater features again confirmed that fretting wear was successfully reproduced in the present simulation.

3.2 Bone cement

It was demonstrated from gross visual inspection of the cement surface that there were many micropores present in those areas in contact with the fretting zones on the stem surface, and these areas seemed much rougher than the other areas on the cement surface (Fig. 6). Hence, a total of 20 measurements were performed on the ‘worn’ and ‘unworn’ areas, using the Talysurf CCI interferometer. The mean Sq values were 0.21 μm and 0.04 μm respectively, which

Table 3 Comparison of selected three-dimensional surface parameters of the fretting zones on the stem posterior surface before and after simulation (mean ± standard deviation)

Three-dimensional surface parameter	Gruen zone 6		Gruen zone 7	
	Before test	After test	Before test	After test
Sq (μm)	0.04 ± 0.01	0.42 ± 0.09	0.03 ± 0.01	0.40 ± 0.06
Sz (μm)	1.52 ± 0.50	5.69 ± 1.05	1.32 ± 0.25	5.25 ± 0.90
Sdq	0.03 ± 0.006	0.36 ± 0.04	0.02 ± 0.002	0.35 ± 0.05
Ssc (nm^{-1})	1.80 ± 0.055	47.7 ± 8.0	1.20 ± 0.40	44.0 ± 10.6
Sdr (%)	0.05 ± 0.02	8.50 ± 1.63	0.03 ± 0.01	8.23 ± 2.24

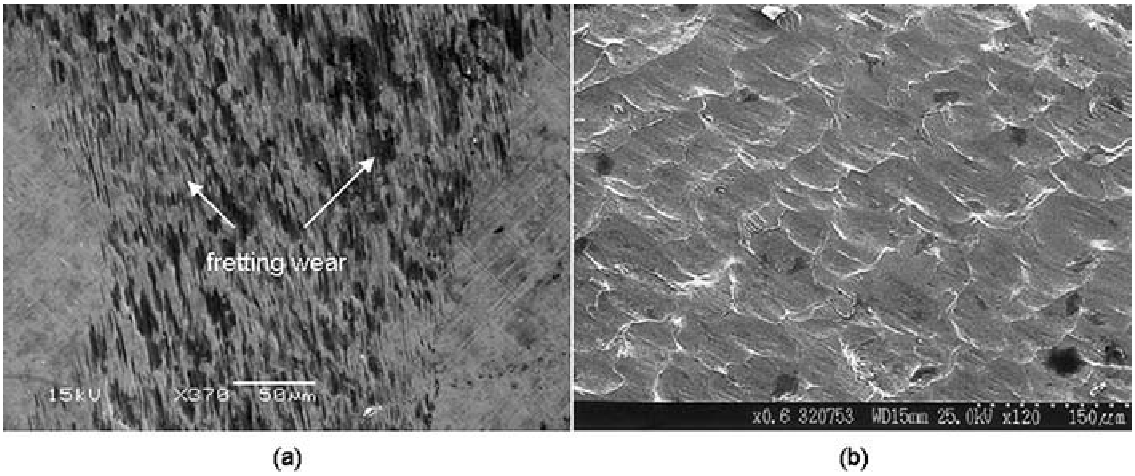

Fig. 5 Scanning electron micrographs showing surface topography of the fretting zones on the stem surface: (a) the femoral stem from the present wear simulation; (b) an explanted femoral stem from retrieval studies

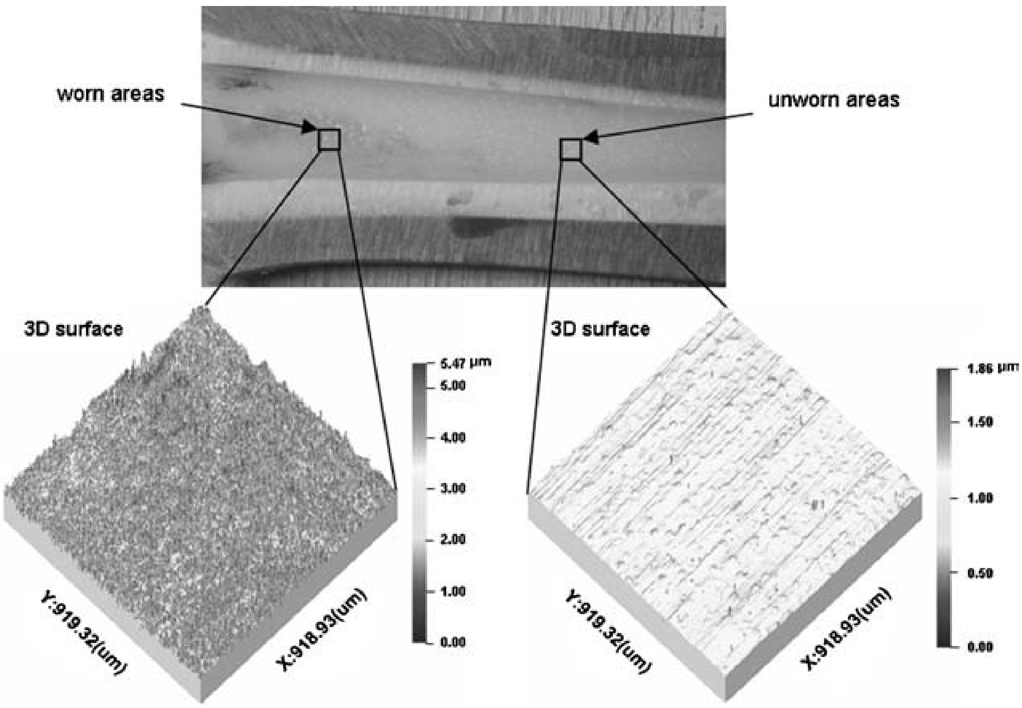

Fig. 6 Comparison between the 'worn' and 'unworn' areas on the cement surface (3D, three-dimensional). The worn areas are in contact with the fretting zones on the stem surface

indicated that the 'worn' areas were severely damaged during the fretting process.

The investigation of the cement surface using SEM showed that there was an amount of fretting debris located in the micropores (Fig. 7). From the corresponding EDXA it was noted that an iron-rich plaque was not detected. This suggested that the debris was cement particles rather than metal particles. This debris was potentially worn off from the cement surface and then retained in the micropores.

To gain a better insight into the initiation and propagation of fretting wear, the Exeter V40™ femoral stem and Simplex P bone cement were further investigated utilizing the Leica stereomicroscope. It was demonstrated on the stem surface that some 'undamaged islands' were surrounded by worn areas, which was in agreement with the result of another study [**17**]. Interestingly, these undamaged 'islands' were found to correspond well to the micropores in the cement surface (Fig. 8). This indicated that these micropores may contribute to initiation and propagation of fretting wear on the stem surface. It is considered that the differential stress distribution across the differing thicknesses adjacent to the edge of the micropores would facilitate interfacial micromotion of the cement relative to the stem under physiological loading. This is essential to the generation of fretting wear on the stem surface.

4 DISCUSSION

It is generally accepted that long-term durability of cemented THR requires meticulous attention to

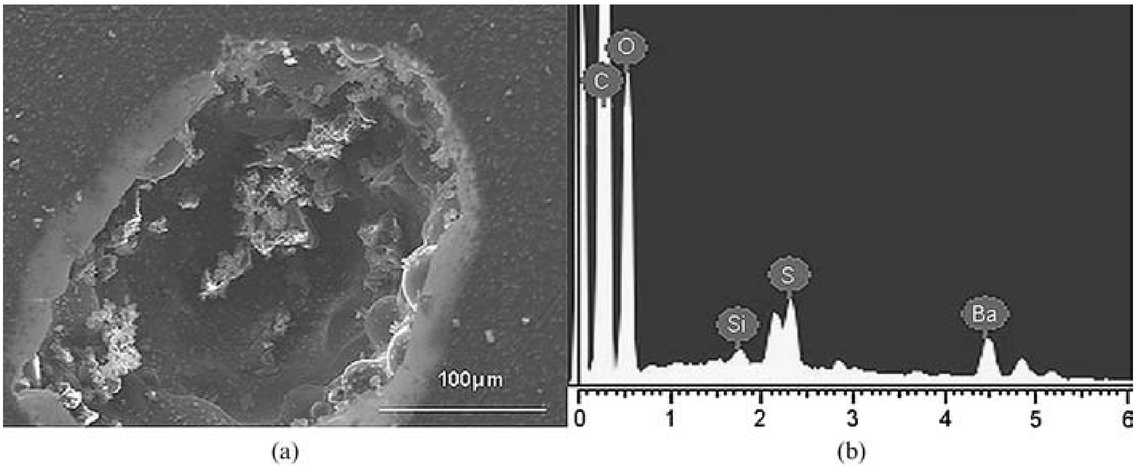

Fig. 7 (a) Scanning electron micrograph showing wear debris located in the micropores in the cement surface; (b) the corresponding EDXA indicates that this debris is cement particles

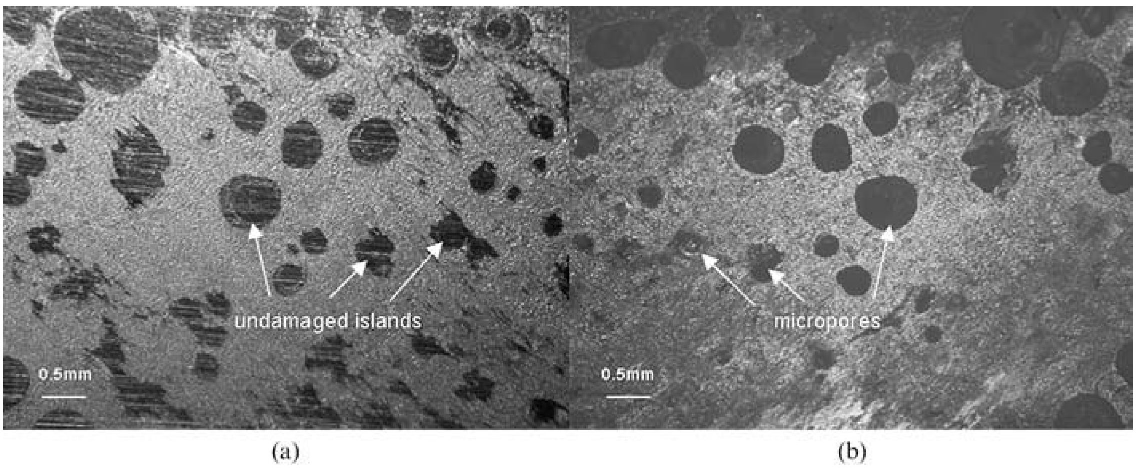

Fig. 8 Optical micrographs of (a) the worn areas on the stem surface and (b) the corresponding zones on the cement surface. The black irregular circles are the 'undamaged islands', which matched the micropores in the cement surface well

three elements and two interfaces, namely the femoral stem, stem–cement interface, bone cement, cement–bone interface, and bone. Previous studies have reached diverse conclusions with regard to which acts as the most significant contributor to the initiation of aseptic loosening [**21**, **22**]. Recently, more and more retrieval studies are showing evidence of debonding at the stem–cement interface, which has strengthened the importance of investigation of this site and has predicted the necessity for further study. Despite its potential significance, fretting wear at this interface has received relatively little concern because much attention has been paid to studying the bulk properties of the components and wear at the head–cup articulating interface. It is not until recently an intensive study on the surface morphology of explanted femoral stems was performed that a deep insight into the wear mechanism at this interface has been gained [**16**]. It was demonstrated that the wear mechanisms behind polished and matt stems were fundamentally different in spite of similar wear locations. For the matt stems, it was typically abrasive wear due to a polishing process, whereas fretting wear dominated for the polished stems with formation of pitting and crater features on the surface.

In-vitro simulation to reproduce fretting wear at the stem–cement interface has been tried previously, but it is considered that, to date, no great success has been achieved. Furthermore, there is no convincing *in-vitro* evidence that the influences of stem geometry, stem surface finish, and bone cement brand on the generation of fretting wear have been established. In this study, fretting wear has been successfully reproduced at the stem–cement interface through an *in-vitro* wear simulation, which was confirmed by the measurements performed using a Talysurf CCI interferometer and by SEM. The wear locations matched well the results of retrieval studies, which also corresponded to the sites where the largest stress is considered to occur under physiological loading. Additionally, there were many micropores present in the cement surface. These micropores, which have been clinically detected previously [**23**], were considered to be formed during the cement mixing, delivery, and stem implantation process. They may lead to a decrease in the interfacial bonding strength at the stem–cement interface and may act as stress concentrators, resulting in the generation of fatigue cracks in the cement mantle. However, no fatigue cracks were observed in the present simulation. This, to a certain degree, was in contradiction to the results of retrieval studies, in which the formation of fatigue cracks in the cement mantle was detectable [**21**, **24**]. Furthermore, these cracks were regarded to be potential channels to transport wear debris to the sites surrounding bone tissues, causing a macrophage response and subsequent aseptic loosening of the femoral component. Although micropore-induced fatigue cracks were not detected, the micropores in the cement surface were found to contribute to the initiation and propagation of fretting wear on the stem surface. It was considered that the stress distribution across those areas adjacent to the edge of the micropores was differential, this would therefore facilitate interfacial micromotion of the cement relative to the stem under physiological loading, which was a prerequisite for fretting wear. Taking this into consideration, the application of ‘modern cementing techniques’, typically vacuum mixing and centrifugation, could in theory not only promote better bonding strength at the stem–cement interface but also retard initiation of fretting wear owing to a significant reduction of porosity [**25**, **26**].

The cement surface was severely damaged in those areas in contact with the fretting zones on the stem surface, with retention of cement debris located in the micropores. However, it was indicated in retrieval studies that metal debris was embedded within the cement mantle, and EDXA demonstrated a similar chromium-rich and iron-rich plaque on the cement surface as was found on the stem surface [**27**, **28**]. The reason why no metal debris was detected in the present study was probably because the femoral stem that was used in this simulation is highly polished. Fretting wear for polished stems, unlike abrasive wear for matt stems, tended to result in less generation of metallic wear debris. This was suggested to be the rationale behind the success of polished stem design. In fact, the optimum surface finish of femoral stem has been debated for many years. Recently, however, it seems that the controversy has intensified as reports have been published on prematurely failed prostheses that exhibit varying amounts of surface roughness and precoating. There are numerous studies showing excellent long-term results of cemented femoral stems using roughened femoral components [**29**, **30**]. Conversely, the Exeter femoral stem using a double-tapered collarless geometry with a polished surface designed to subside within the cement mantle to acquire restabilization also showed excellent long-term survivorship [**31**]. Although clinical studies have demonstrated that wear on the stem was mainly dependent on stem surface finish, there is no convincing *in-vitro* evidence that has been gained to date to support it, and this therefore needs further study.

It should be noted that the frequency was set to be 3 Hz to reduce the test duration in this study, whereas frequencies as high as 5 Hz and as low as 0.75 Hz have been used in previous studies [**12**, **32**, **33**]. The high frequency has been criticized as contributing to frictional heating at the stem–cement interface. This is not a crucial issue in the present study as the stem–cement–bone system was immersed in saline solution. However, the frequency of the simulation does have some effect on the results by influencing the repassivation process of the stem surface. It is considered that the stem–cement interface experiences more severe fretting wear at a higher frequency because there is not enough time for the stem surface to be re-passivated and more unoxidized subsurface metal will be exposed to further fretting wear, but it is considered by the present authors that this is not a significant factor in the present study.

There are several limitations involved in the present study. Firstly, the simulation was carried out without any rest period, as a result of which creep and stress relaxation in the cement mantle was prevented. Secondly, there was no temperature control throughout the simulation, whereas it has been reported that temperature has some effect on the creep performance of bone cement with a higher creep rate observed at body temperature [**34**]. Thirdly, the distal centralizer was not used in this study, while it has been clinically employed when implanting an Exeter femoral stem to allow subsidence and to accommodate creep. All these limitations seem to relate to the creep behaviour of bone cement, which may have some influence on the results. In general, the creep of bone cement leads to relaxation of cement stresses and decelerates damage accumulation in the cement mantle [**35**]. If this process is to some extent constrained, there will be more stress concentrations in the cement mantle (probably around the micropores) which promote fretting wear at the stem–cement interface.

5 CONCLUSIONS

In the present study, fretting wear was successfully reproduced using a polished Exeter V40™ femoral stem and Simplex P bone cement; the wear location compared well with the results of retrieval studies. There was no evidence of bone cement transfer films on the stem surface and no fatigue cracks in the cement mantle after simulation. However, the cement surface was severely damaged in those areas in contact with the fretting zones on the stem surface, with retention of cement debris in the micropores. These micropores in the cement surface, which corresponded to the ‘undamaged areas’ on the stem surface, were considered to contribute to the initiation and propagation of fretting wear. To the present authors’ knowledge, this is the first time that fretting wear has been successfully reproduced at the stem–cement interface through *in-vitro* wear simulation, consequently it gives scope for a further comparative study of the influence of stem geometry, stem surface finish, and bone cement brand on the generation of fretting wear.

ACKNOWLEDGEMENTS

The authors would like to thank Mr A. Kennedy, School of Computing and Engineering, University of Huddersfield, UK, for help with the setting up of the fretting wear simulation and Dr H. Williams, School of Applied Science, University of Huddersfield, UK, for SEM guidance.

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