



The role of surface pre-treatment on the microstructure, corrosion and fretting corrosion of cemented femoral stems



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ABSTRACT

The use of cemented femoral stems is common practice worldwide with strong clinical data supporting their use. Over the years, different surface processing techniques have been employed to enhance the performance of the stem–cement interface. As a result different clinical outcomes and visual presentation at revision has been observed. Whilst research has focussed on increasing adhesion and better load bearing capacity, the effects of surface processing on the degradation of cemented femoral stems has not been investigated. The aims of this study was to investigate the effects of surface processing on the subsurface microstructure, surface chemistry and tribocorrosion degradation mechanisms of cemented tapered femoral stems subjected to polishing and blasting (Vaquasheen) processes. Cemented femoral stems were orientated and loaded according to ISO 7206-4 for 500,000 cycles in 0.9% NaCl at 37 °C. A three-electrode electrochemical cell was integrated into the mechanical test to facilitate in-situ corrosion measurements. The severity and mechanism of damage were assessed scanning and transmission electron microscopy, X-ray photoelectron spectrometry, solution mass spectrometry and white light interferometry. Surface processing influenced the level of tribocorrosion at the interface with polished surfaces demonstrating higher levels of tribocorrosion and ion release when compared to the blasted surfaces. Surface analysis consistently demonstrated the presence of a SiO₂ layer on the vaquasheened stems thought to originate from the glass bead blast matrix. This resulted in lower levels of corrosion both under static and tribocorrosion assessment. In conclusion, blasted surfaces resulted in lower wear induced corrosion when compared to the polished surfaces. However the total metallic ion levels did not follow the same trend. This is thought to be due to the formation of metallic debris and dissolution of debris due to abrasion of the femoral stems.

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1. Introduction

Recent research has shown that a combination of wear and corrosion at the stem–cement interface can result in the generation of metallic ions and polymer debris along with damage of the femoral stem, counterpart PMMA bone cement and failure due to soft tissue reactions [1–3]. A considerable amount of work has also been performed to improve the interfacial bond between the stem and the cement mantle. Cementing techniques, surface roughness patches, textures and pre-coatings have all been considered in order to achieve reliable fixation according to Webb et al. [4]. The wear and corrosion at the stem–cement interface isn't a recent observation. Willert et al. [5] presented evidence of crevice corrosion of twenty eight cemented titanium alloy Müller straight femoral stems complimented by analysis of the pH of the fluids trapped within the interface. A decrease in the pH indicated that crevice corrosion was evident; exacerbated by a 'pumping' action

of the fluid about the interface caused by mechanical loading. It was concluded that the mechanism of crevice corrosion for these cemented titanium based alloys was not applicable to cobalt and iron based implant alloys.

Depending upon the design philosophy of the femoral stem, different surface finishes have been adopted [6]. For taper loaded femoral stems, such as the Exeter™ (Stryker, USA), CPT™ (Zimmer, USA), C-Stem™ and Ultima TPST™ (DePuy Synthes, UK), a highly polished surface finish is desired. This aids controlled migration and slip of the femoral stem with the minimum generation of debris. An increased surface roughness is generally chosen for composite beam stems to increase interfacial strength and to reduce instances of slip or migration at the interface. It is generally well accepted for these designs to be successful, the bond between the femoral stem and PMMA bone cement must be maintained for long term stability. This is supported by historical evidence of the 'matte' Exeter femoral stems (taper loaded geometry). These were considered unsuccessful due to high incidences of PMMA induced inflammatory reactions due to abrasion at the interface [6]. Whilst all femoral components display some form of wear and corrosion at revision, the different interfacial conditions produce

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very different surface morphologies as demonstrated by Howell et al. [7]. They noted that blasted femoral stems tend to demonstrate light polishing on the medial and lateral edges, whilst polished femoral stems demonstrate high incidences of fretting related damage.

It is only of late that the tribocorrosion degradation, described as material loss owing to mechanical and electrochemical reactions, and the factors influencing this have been considered for cemented devices [8–12]. Recently, fretting-crevice corrosion of polished femoral stems has been implicated in the early failure and high revision rates of taper polished femoral stems [13,1,3]. The occurrence of pain and evidence of metal hypersensitivity have been observed in these cases. Although the wear mechanisms acting at the stem–cement interface are fairly well accepted, they tend to be lesser known and assumed when compared to bearing or taper interfaces. Currently only a few studies exist investigating the role of fretting-corrosion and the influence of system variables at the stem–cement interface [8, 14,11,15]. Recently the authors have presented systematic work outlining the tribocorrosion mechanisms [15,13] and role of system variables such as cement type [12,16] and mixed metal couples [17] on the overall degradation of cemented femoral stems. This study goes further to examine the influence of surface processing on the fretting-corrosion characteristics, subsurface microstructure and surface chemistry of cemented femoral stems through the use of in-vitro tribocorrosion simulations and advanced surface analysis techniques.

2. Materials and methods

2.1. Experimental materials, surface processing and preparation

All experiments were conducted on fully cemented LC (low carbon) CoCrMo Ultima TPS™ (DePuy Synthes, Leeds, United Kingdom) femoral stems (Table 1). Each femoral stem was forged from wrought alloy, any excess material removed, stem-taper machined and then the remaining portions (including the cemented portions) polished by Symmetry Medical (Sheffield, UK). Each femoral stem was then inspected for any signs of imperfections, cleaned and packaged by DePuy Synthes.

In order to replicate the polishing process femoral implants undergo, each sample was polished using a rotating cloth mop and wax to a 'super finished' surface. To roughen the stems, Ultima TPS™ femoral stems were subjected to a process known as vaqua-sheen; a blasting process involving water and glass beads. This will be referred to as the 'blasted' surface in the study. The beads had the following composition (Table 2). It is important to note that all stems tested in this study were from the same forging batch and subjected to the same thermal processes. All test pieces were cleaned, degreased and then passivated as per manufacturer's specifications. In all tests CMW MV (DePuy Synthes, Blackpool, UK) PMMA bone cement was utilised and prepared according to manufacturer's instructions.

The solution used for all electrochemical measurements was aerated 0.9% NaCl solution (pH ≈ 7.4) at 37 °C, prepared using analytical grade reagents and deionised water. This was to simplify the system, removing the metal–protein interface which has recently been shown to influence the rates of corrosion [18]. Throughout this study a three electrode electrochemical cell consisting of a working electrode (WE), in this case the femoral CoCr stem, Ag/AgCl reference electrode (RE) and Pt counter electrode (CE) (Thermo-Scientific, UK).

Table 1
Chemical composition of the Ultima TPS femoral stems tested in this study.

Chemical composition (% wt)										
C	Si	Mn	P	S	Cr	Fe	Mo	N	Ni	Co
0.05	0.19	0.67	0.005	0.0010	27.65	0.30	5.48	0.18	0.24	Bal.

Table 2
Composition of bead blasting material used in this study.

Compound	Chemical formula	Content
Silicon dioxide	SiO ₂	73.00%
Sodium oxide	Na ₂ O	15.00%
Calcium oxide	CaO	7.00%
Magnesium oxide	MgO	4.00%
Aluminium oxide	Al ₂ O ₃	1.00%

2.2. Static corrosion measurements

Potentiodynamic corrosion measurements were conducted using an Autolab PGSTAT101 (Metrohm, Netherlands) to quantify the corrosion characteristics of the femoral stems in the absence of cyclic loading. In order to assess the corrosion properties of the different femoral stems, a flat electrochemical cell was adopted. This enabled 1 cm² area of each femoral stem to be exposed to the electrolyte without the need for sample mounting etc. Each sample was immersed in the tests electrolyte at 37 °C and the E_{corr} allowed settle for 1 h prior to polarisation. Potentiodynamic polarisation was then conducted from –100 mV vs E_{corr} and scanned in the anodic direction at a rate of 0.25 mV/s. At 500 µA/cm² the current was reserved and the scan terminated when the current had reached the resolution of the instrument. Full details of the protocol can be found at [16].

2.3. Fretting-crevice corrosion test arrangement

To evaluate the mechanically enhanced corrosion mechanisms at the stem–cement interfaces a tribocorrosion test apparatus and procedure was developed and conducted in part reference to ISO 7206-4. Full details of the experimental arrangement and electrochemical method have been reported elsewhere [12,15]. In brief, cemented femoral stems were orientated at 9 and 10° flexion and extension, respectively, and subjected to a compressive sinusoidal load (0.3–2.3 kN) at 1 Hz. A 3 electrode electrochemical cell was incorporated into the cell to facilitate in-situ and real time corrosion rate measurements. These consisted of free corrosion potential and corrosion current determined through linear resistance polarisation (LPR) assuming a Stern–Geary coefficient of 0.026. Corrosion currents were then integrated with respect to time to yield the total charge passed and converted to a corrosive mass loss (i.e. material lost from the interface due to corrosion) using Faradays equation using constants given in [12,15].

Inductively Coupled-Mass Spectrometry (ICP-MS) was used to analyse elemental composition of the electrolytes post-test. 1 mL of test electrolyte was diluted to 10 mL with HNO₃ prior to analysis. No effort was made to extract particulate from the electrolyte and so ionic mass measurements represent a combination of ions and particles present in the solution.

Table 3
Surface morphology parameters (22).

Parameter	Abbreviation	Description
Average surface roughness	S _a	Mean height of surface topography
RMS deviation of the surface	S _q	A more 'stable' expression of surface roughness
Max. height to Min. Valley	S _z	Height between tallest peak and deepest valley
Direction of irregularities	S _{sk}	Indicates the direction of surface irregularities; zero for randomly rough surfaces, positive where peaks predominate, and negative where pits predominate

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