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A new finding on the *in-vivo* crevice corrosion damage in a CoCrMo hip implant

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ABSTRACT

A detailed investigation was performed to characterize the fretting wear and corrosion damage to the neck component of a CoCrMo stem from a metal-on-polyethylene implant retrieved after 99 months. The stem was a low-carbon (0.07 wt%) wrought Co-28Cr-6Mo alloy with no secondary carbide phases in the matrix (γ-phase). The original design of the neck surface contained an intentionally fabricated knurled profile with a valley-to-peak range of approximately 11 μm. Roughness measurements indicated that the tip of the knurled profile was significantly damaged, especially in the distal medial region of the neck, with up to a 22% reduction in the mean peak-to-valley height (R_a) compared to the original profile. As a new finding, the channels between the peaks of the profile created an additional crevice site in the presence of stagnant body fluid within the head-neck taper junction. These channels were observed to contain the most severe corroded areas and surface oxide layers with micro-cracks. SEM/EDS, XRD and XPS evaluations identified the formation of Cr_2O_3 as a corrosion product. Also, decobaltification was found to occur in these corroded areas. The findings of this work indicate the important role of the knurled profile in inducing additional crevice corrosion.

1. Introduction

In modular junctions of hip joint implants, particularly the head-neck taper junction, fretting corrosion has been recognized to occur [1–3] mainly due to oscillatory micro-motions caused by mechanical loads and corrosive environment all around the junction [4,5]. At revision of cases with large amounts of metallic wear, there is typically evidence of fluid collection, soft tissue and muscle damage, masses and pseudotumours around the implant, visible damage to the head-neck junction and corrosion products around the junction [6–8]. The particulate debris even in the range of nanosize were also detected in the tissues as a result of fretting wear [9]. Hart et al. [10] reported the presence of chromium(III) ions from debris in the tissues surrounding CoCrMo implants forming Cr(III) phosphate. They also found cobalt in its metallic state; and cobalt(II) and molybdenum(VI) ions in the tissue [10]. Elevated concentrations of cobalt ions as a consequence of fretting corrosion debris have been reported to cause serious health risks for some patients with CoCrMo hip joint implants [11]. It has been reported that both cobalt(II) and chromium(III) ions can cause a macrophage-induced inflammatory response in periprosthetic osteolysis [12,13].

The geometric design of the head-neck taper junction includes a very small angular mismatch [14] creating a crevice at the junction; hence, crevice corrosion can occur inside the taper [15]. In the crevice, a crevice cell is initiated due to oxygen depletion, pH drops and increased concentrations of chloride and phosphate ions to balance metal cations, while outside of the crevice, the oxygen content and the pH value are higher. Shear stresses induced under fretting wear condition as a result of multi-axial loading can disrupt the passive oxide layer onto the metal surfaces [16–18] and such disruption then accelerates corrosion of the alloy [19,20]. This complex interaction between fretting and corrosion has been termed “Mechanically Assisted Crevice Corrosion (MACC)” by Gilbert [15,21].

There have been several retrieval studies to assess the severity of the fretting corrosion damage to the head-neck taper junction based on macroscopic visual inspections and scoring methods [1,22–24]. The advantage of these visual assessments is that a large number of retrieved implants can be examined in order to extract statistically reliable outcomes, particularly when there are several parameters such as head/neck material combinations, geometry and patient characteristics. However, such results are mainly qualitative and may be limited by observer subjectivity [1]. In addition, the detailed mechanisms of fretting and corrosion; and characterization of damage (wear and corrosion compounds) cannot be studied by visual inspections only. A review of the literature confirms that there are a limited number of studies to apply advanced materials characterization techniques with the aim to characterize the surface damage and obtain quantitative results. In a study [25], fretting wear damage to the surface of CoCrMo head and

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titanium neck of two retrieved implants were examined using a RedLux artificial hip joint profiler. The damage to the taper was found to vary around the neck and along the length such that there was evidence of mechanical damage to the machining marks in the contacting region of the head and neck [25]. This study was however limited to wear damage only without investigating the chemical composition of corrosion products.

In another work [26], elemental analyses of energy dispersive X-ray spectroscopy (EDX) on the corroded areas of a CoCrMo neck mated with a Ti-12Mo-6Zr-2Fe stem showed individual chromium, oxygen, titanium, molybdenum and phosphorous elements in high amounts. These results were in agreement with EDX results of a CoCrMo neck/titanium stem interface reported by Lanting et al. [27]. Although the elemental analysis can identify elements in the corroded areas, chemical compounds and type of phases formed in these regions cannot be identified using only this technique. The identification of corrosion products is of paramount importance as it can help in understanding of the local tissue reaction to these corrosion products. For instance, in CoCrMo implants, toxicity of chromium is related to its oxidation states (*e.g.* Cr^{6+} and Cr^{3+}) where different phase compounds can be formed as corrosion products [11].

Based on scanning electron microscopy (SEM) observations, Kop and Swarts [28] reported intergranular and transgranular corrosion in a CoCrMo neck-stem junction. This corrosion mechanism is expected for the studied CoCrMo implant due to its initial microstructure which possesses small carbides distributed evenly in a fine-grained austenitic matrix. Owing to this initial microstructure, the intergranular and transgranular corrosion can be easily developed around the chromium carbide phases. No further chemical composition analyses such as EDX, particularly at the grain boundaries, were performed to favorably support this observation.

Focusing more on the corrosion mechanisms, Ti-6Al-4V/Ti-6Al-4V neck-stem interface was reported to possess severe corrosion damage revealing signs of etching, pitting, delamination, and surface cracking [19]. Also, *in-vivo* hydrogen embrittlement was found as a degradation mechanism for titanium alloy of the interface as a consequence of electrochemical reactions in the crevice of the junction [19]. With further investigations on retrieved Ti-6Al-4V/Ti-6Al-4V neck-stem junctions, Gilbert et al. [29] reported a new *in-vivo* corrosion mechanism termed "Oxide-Induced Stress Corrosion Cracking (OISCC)". Both sides of the titanium interface were attacked by pitting corrosion such that the pits developed into cracks within which oxide formation occurred resulting in tensile stresses which could then propagate the cracks [29].

Although the last two articles presented a detailed analysis on the corrosion mechanism in the neck-stem modular junctions made of titanium based alloys, further detailed studies are required, especially as there are no such reports currently on the head-neck taper junctions made of CoCrMo alloy. In this paper, a CoCrMo neck of a retrieved implant was studied for its *in-vivo* fretting wear and corrosion damage. The neck surface had an intentionally generated knurled profile. The aims were to understand the role of this specific surface profile in fretting wear, and identify corrosion products formed onto the surface of the neck component of this CoCrMo/CoCrMo head-neck junction.

2. Materials and methods

2.1. Implant specifications and retrieval protocol

Ethical approval was granted by the Southern Adelaide Clinical Human Research Ethics Committee to study surface damage to the taper junction of modular implants retrieved at the Royal Adelaide Hospital, Adelaide, Australia. According to the Implant Retrieval, Cleaning and Documentation Protocol developed at the Royal Adelaide Hospital, the retrieved implants were immersed in 70% ethanol for 4 days; and subsequently, washed with running water. The washed implants were then immersed in 4% Biogram solution (polyphenolic disinfectant and detergent with approximately 18% phenol) and left in fume cupboard for 48–72 h. During the decontamination process, biologic debris such as blood or proteinaceous films were carefully removed using a cotton bud without abrasion. An implant with metal-on-polyethylene (MOP) articulation was studied in this work. The head-neck taper interface of the implant was found to possess the most severe wear and corrosion damage in a cohort of thirty retrieved implants that were visually inspected. The implant had a 28 mm diameter Co-28Cr-6Mo femoral head coupled with a Co-28Cr-6Mo stem (CPT, Zimmer, Warsaw, Indiana, USA), and presented a 99-month service life in a 53-year old male patient of 107 kg. The neck component was a 12/14 taper (5°40′) with a purposely generated knurled surface finish, as shown in Fig. 1. The implant was retrieved at revision surgery due to infection.

2.2. Sample preparation

To identify phase compositions and investigate the original microstructure of the implant material, a section of the stem with no fretting corrosion damage was cut from approximately 10 mm away from the head-neck interface using a precision sectioning cutter (IsoMet 1000, Buehler) with a diamond wafering blade. The stem section was then mirror polished using an automatic polishing machine (Tegramin-25, Struers, Denmark) for the subsequent X-ray diffraction (XRD) and scanning electron microscopy (SEM FEI, Inspect F50, USA) evaluations. The polishing procedure was performed using: a silicon carbide foil (220 mesh size) for 70 s at 300 rpm, diamond polishing abrasive with a size of 9 μm in liquid suspensions on a napless cloth for 6 min at 150 rpm, diamond polishing abrasive (3 μm) on a napped cloth for 5 min at 150 rpm, and a colloidal silica suspension with a particle size of 0.3 μm for 3 min for final polishing. After each polishing step, the sample was rinsed with warm water and dried with compressed air. The sample was then etched using a solution of 50 mL H_2O and 50 mL HCl for 5 min.

Energy-dispersive spectroscopy (EDS) analyses of the implant material showed approximately 63.0, 27.7, 5.6 and 0.07 weight percent (wt%) for Co, Cr, Mo and carbon respectively, balanced with other minor alloying elements which are in agreement with the chemical composition for wrought low-carbon CoCrMo alloy [30].

2.3. Surface profilometry

Surface profile and roughness of the neck surface were characterized along eight different paths around the neck (with 45° spacing) using a surface profilometer (WYKO NT9100, Veeco, USA). For each path, multiple points were studied from distal to proximal to obtain surface profiles in localized areas of 1 mm × 1.3 mm. In addition to the 3D surface

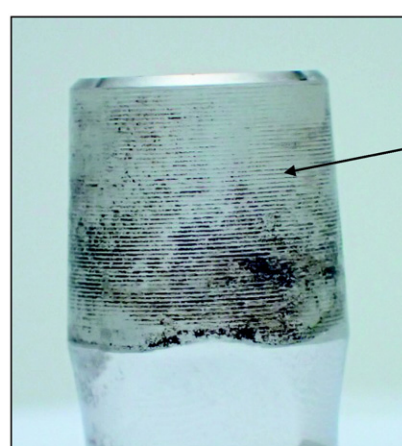

Fig. 1. Neck component of the retrieved implant made from CoCrMo alloy with a 12/14 taper (5°40′) design.