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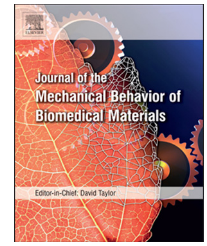

Research Paper

Contact damage failure analyses of fretting wear behavior of the metal stem titanium alloy–bone cement interface

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ABSTRACT

Although cemented titanium alloy is not favored currently in the Western world for its poor clinical and radiography outcomes, its lower modulus of elasticity and good biocompatibility are instrumental for its ability supporting and transforming physical load, and it is more suitable for usage in Chinese and Japanese populations due to their lower body weights and unique femoral characteristics. Through various friction tests of different cycles, loads and conditions and by examining fretting hysteresis loops, fatigue process curves and wear surfaces, the current study investigated fretting wear characteristics and wear mechanism of titanium alloy stem–bone cement interface. It was found that the combination of loads and displacement affected the wear quantity. Friction coefficient, which was in an inverse relationship to load under the same amplitude, was proportional to amplitudes under the same load. Additionally, calf serum was found to both lubricate and erode the wear interface. Moreover, cement fatigue contact areas appeared black/oxidative in dry and gruel in 25% calf serum. Fatigue scratches were detected within contact areas, and wear scars were found on cement and titanium surfaces, which were concave-shaped and ring concave/ convex-shaped, respectively. The coupling of thermoplastic effect and minimal torque damage has been proposed to be the major reason of contact damage. These data will be important for further studies analyzing metal–cement interface failure performance and solving interface friction and wear debris production issues.

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1. Introduction

While joints replacement of current time is designed to last 15 or more years, eventually an artificial joint may succumb to wear and tear and fail over time. The aseptic loosening of replacement implants is the main failure reason of hip, shoulder and humerus replacement, a problem which currently is still unclear (Feeney et al., 1996; Harris, 1995; Konttinen et al., 1997). Although opinions for the causes of the loosening and wear after implantations vary considerably, the continuous fretting wear at the stem–bone cement interface has been widely accepted (Duncan et al., 2009). Especially, different elasticity modulus of contact materials of the stem–cement interface is known to be the major cause of the loose interface and thus the failure of a cemented hip implant. Banaszkiewicz and Zhang demonstrated that the stem–cement interface loosening has been mainly due to the weak adhesive bonding and inevitable de-bonding of the interface (Banaszkiewicz, 2014; Zhang et al., 2014b). The sinking distance of the stem within the cement and physical load and micro-dislocation will not only damage the elastic–plastic characteristics of replacement components (Goodman et al., 2013; Karrholm et al., 1994; Ryd, 1992) but also induce the growth of fibrous tissue (Engh et al., 1992) and production of wear debris eventually leading to the aseptic inflammation within the interface. However, previous studies (Goodman et al., 2013; Lennon and Prendergast, 2001) indicated that the interaction of three factors, cement solidifying technology, body environment and the mechanical fretting of stem–cement interface makes the process of interface wearing more complicated. In addition, due to the tiny interface space and influence of metal shadow, it is also difficult to inspect, even with X-ray and CT scanning, whether there are fretting wears at the interface (Blunt et al., 2009; Cai et al., 2001; Jasty et al., 1997; Nowell and Dini, 2003; Ryd, 1992; Zhang et al., 2012, 2013). Thus, due to the unclear loosening mechanisms of THR and the potential important involvement of fretting wear in the stem–cement interface and THR failures, it is timely and important to investigate the fretting wear characteristics of the bone stem–cement interface.

Geringer and Kim et al. found that the serum albumin not only protected the interface from being worn but prevented its erosion (Geringer et al., 2005, 2012; Landolt and Mischler, 2011; Macdonald, 2013; Yan, 2013), and that the quantity of interface wear concave and convex points increased as the chloride converged (Bryant et al., 2013; Geringer and Macdonald, 2014; Pellier et al., 2011; Zhang et al., 2014a; Zhang and Ge, 2011), which led to the generation of wear particles, with about 80% of the wear particles being less than 100 nm, the major sizes of which were shown to induce the growth of fibrous tissue and osteoclast (Baxmann et al., 2013; Breusch and Malchau, 2006; Dekun, 2011; Sosnovskiy, 2010; Yi et al., 2012; Zhang et al., 2011a). However, despite the above studies, fretting wear behaviors and mechanisms of micromotion of the metal stem–bone cement interface have been hardly investigated.

To date, commercial metal materials of stem can be classified into 3 major types, namely CoCrMo, stainless steel and titanium alloy. Cemented titanium stems were introduced for artificial joint replacement since 1970s. Due to their properties of excellent biocompatibility and being highly resistant to fatigue and corrosion, titanium alloy stems have been widely used in clinical practice of some joint replacements (eg for reverse shoulder humeral adapter trays). However, for cemented titanium femoral stems, although initial short and mid-term results were encouraging (Sarmiento and Gruen, 1985), many studies have found the high elasticity of the titanium alloy stems and a high incidence of clinical and radiological failures particularly in excessive stress area of the proximal cement mantle. Titanium alloys are currently not favored for hip replacements and they have been or are being replaced by CoCrMo and stainless steel (Hinrichs et al., 2003; Kovac et al., 2006). Ironically, however, new problems have emerged for the change of prosthesis material, including increased incidences of complications and pain and the production of wear debris of the new material like CoCrMo which are poisonous and can easily induce the tissue lesions (Madl et al., 2015; Posada et al., 2014). Some clinical and functional evaluation reports evaluating implant survival and health outcomes of total hip arthroplasties have shown that the titanium alloys are higher than the CoCrMo and stainless steel in the Harris and Oxford Hip Score (Edmunds and Boscainos, 2011; Kalairajah et al., 2005; Vasileiadis et al., 2015). As a result, many researchers have renewed interests in studying titanium alloy in recent years. Zhang et al. (2012, 2009, 2011b) demonstrated fretting wear behavior for cemented polished and finish stems but abrasive wear behavior for the roughness stem. Recent work has also revealed that the subsidence volume for titanium alloy stem is lower than that of CoCrMo stem, and that its elastic module is also lower than that of CoCrMo, which can transform a higher physical load to femur through the titanium alloy implants (Akiyama et al., 2013).

Furthermore, in recent years, cemented titanium alloy stems have been reported for excellent clinical and radiographic outcomes. The PHS KC femoral stem (Kyocera Medical, Osaka, Japan) is a Charnley-type straight, collared stem made from a titanium alloy (Ti6Al4V) (Akiyama et al., 2010) and has been shown to have an overall survival of 100% at 7 years of implantation (Akiyama et al., 2011). Similarly, SPII type prosthesis stem made for metal-allergic patients using the composite-beam concept from Ti6Al4V, developed in 1978 and available as a modular system since 1984, has proven in more than 20 years to be one of the most successful cemented hip prosthesis stems (Malchau et al., 2002). Furthermore, some cemented titanium stems used for humeral and shoulder replacements (Beijing Chunlizhengda Medical Instruments Co., Ltd. China) have been adopted for patients in China.

Because of these controversial and conflicting statements about titanium alloy stems, it is essential to analyze the fretting wear behavior of titanium alloys and acrylic cement. Through simulating the flat–flat contact of titanium alloy stem and cement and analyzing wear quantity, wear morphology and distribution of detachment matters within the wear region, the current study investigated fretting wear mechanisms.