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A finite element methodology for wear–fatigue analysis for modular hip implants

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ABSTRACT

Fretting of the stem-head joint in a prosthetic hip implant is investigated experimentally and computationally. An FE-based methodology for fretting wear-fatigue prediction in a prosthetic hip implant is developed. Tribological and profilometry tests are performed for two head/stem material combinations: Co–28Cr–6Mo/DMLS Ti–6Al–4V and Co–28Cr–6Mo/forged Ti–6Al–4V. The hardness and wear resistance of DMLS Ti–6Al–4V are shown to be superior to those of forged Ti–6Al–4V. The significance of wear in a hip joint for 10 years of service in a normal weight person for moderately intense exercise is predicted for both material combinations. Both material combination joints are shown to have excellent wear resistance which suggests that the wear debris emission will not be significant.

1. Introduction

A prosthetic hip implant normally contains a long stem implanted in the femur and a spherical femoral head that articulates with the acetabulum. The use of modular interlocking components is a popular design feature of the prosthetic hip joint implant (Hallab et al. [1]). Typically, for a modular head, a cylindrical taper coupling is employed between the stem neck and the head, as illustrated in Fig. 1. This coupling is susceptible to fretting wear (corrosion) and possibly fretting fatigue due to the potential for oscillatory small amplitude displacements under the combined effects of the clamping pressure due to the taper-lock with superimposed ambulatory (cyclic) loading, exacerbated by the in vivo environmental conditions. The resulting fretting wear debris is recognized as a key reason for failure of total joint replacements. The clinical significance of fretting wear debris has been addressed in a number of studies, e.g. Barrack [2], Collier et al. [3], McKellop et al. [4]. Metal debris released from fretting wear can create a local inflammatory reaction in the tissue and eventually contribute to onset of necrosis or osteolysis (Dumbleton et al. [5]). Furthermore, the fretting wear debris created by a femoral stem or head may migrate to the ball–socket interface, resulting in third-body abrasive wear of the bearing surfaces (Hop et al. [6]).

Different materials have been used as prosthetic hip joint components. Experimental work has been carried out to investigate various aspects of fretting in hip joint implants. Duisabeau et al. [7] performed fretting tests in ambient air as well as in Ringer's solution, with Ti–6Al–4V representing the stem material and 316L stainless steel (SS) representing the head material. The results demonstrate that introducing a corrosive lubricant leads to modification of the fretting regime. Furthermore, Duisabeau et al. [7] investigated a hip joint adopting AISI 316L SS as the femoral head and Ti–6Al–4V as the stem neck. It was shown that the 316L SS head exhibited a better behaviour in regard to emission of particles under both fretting and fretting corrosion conditions than the Ti–6Al–4V neck. Hallab et al. [1] investigated the differences in the fretting corrosion of metal-metal and ceramic-metal modular assemblies of total hip replacements. An in vitro comparison of ceramic (zirconia, ZrO_2) and metal (Co-alloy) femoral-head fretting upon Co-alloy stem components was carried out. Greater metal release and potentiodynamic fretting of the metal–metal modular assembly are found when compared to the ceramic–metal modular assembly. Specifically, decreased susceptibility of the ZrO_2/Co-alloy assembly to fretting can be supported by potentiodynamic studies in which both a smaller average voltage drop and a shorter average recovery time were associated with ZrO_2 femoral heads on Co-alloy stems, as compared to Co-alloy heads.

Rapid manufacturing techniques are beneficial for prosthesis production. Direct metal laser sintering (DMLS) is an evolving technique which can produce parts with complex geometries less costly and more rapidly compared with conventional techniques (Gåård et al. [8], Hänninen et al. [9]). The DMLS technology manufactures products from a computer-aided design (CAD) model in a layer-by-layer fashion [8]. The sintering of powder is achieved by the heat of a focused laser beam. Microstructure, phase composition and mechanical and tribological properties of

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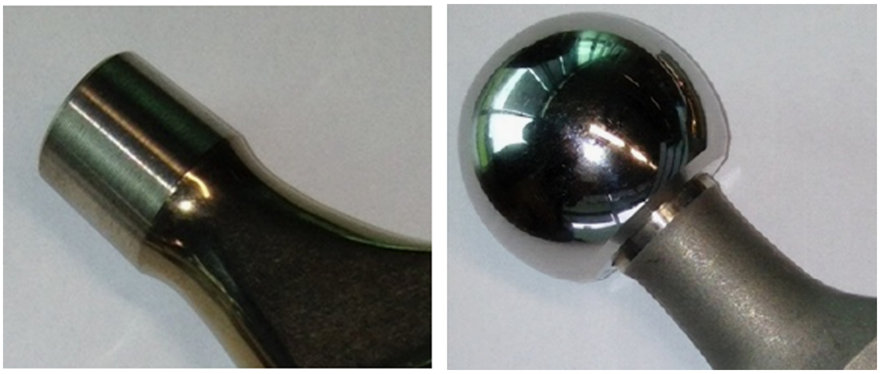

Fig. 1. Stem neck and assembled stem–head contact.

the DMLS material may differ from the same material manufactured by conventional techniques.

Numerical simulations of fretting in hip joints are very limited in the literature, but a significant amount of effort has been expended on research into fretting wear and fatigue problems for other applications. McColl et al. [10,11] developed an experimentally-validated FE based incremental method for fretting wear simulation (via material removal) based on the Archard equation and applied it to a Hertzian geometry to predict the wear-induced evolution of contact geometry and the associated effect on contact surface and sub-surface contact variables, such as contact pressure, slip and stresses. Key fretting phenomena due to material removal were predicted, such as the effect of slip amplitude on evolution of multiaxial contact stresses and multiaxial fatigue indicator parameters, such as the *SWT* parameter. More recently, Mohd Tobi et al. [12] and Zhang et al. [13] highlighted the evolution of plastic strain and the effects of incremental plasticity during fretting wear using linear and nonlinear kinematic hardening models respectively. Madge et al. [14,16] combined the Archard wear simulation method with an FE-based, multiaxial fatigue prediction to successfully predict the effect of fretting wear on fretting fatigue life, with experimental validation against Hertzian round on flat (RF) and rounded punch on flat (RPF) fretting fatigue (with substrate fatigue loading) configurations for Ti–6Al–4V. Zhang et al. [13] recently validated the energy-based wear approach [17] against the Archard approach and experimental results and also compared the fretting performance of two contrasting contact geometries (RF and RPF) (without substrate fatigue loading) and successfully captured the ratchetting phenomena under partial slip conditions for Ti–6Al–4V. A continuum damage mechanics implementation for fretting fatigue was recently developed in [18], without wear effects however.

To study fretting in hip joint implants, the detailed loading condition is required to be investigated. Duda et al. [19] developed a 3D model to improve the understanding of femoral loading by taking into account all thigh muscles, as well as body weight and contact forces at the hip, based on previous work of Brand et al. [20] and Patriarco et al. [21], for example. The study described the internal load state acting at different levels along the human femur during various phases of the gait cycle.

The development of a scientific approach for fretting life prediction in such couplings is important for new candidate materials and manufacturing methods. This paper presents a computational methodology, based on experimental testing, for prediction of fretting and wear behaviour at the head–neck contact of a hip implant. Co–28Cr–6Mo (CoCr) is adopted to represent the femoral head and two types of biological titanium alloys are adopted to represent the stem neck, namely forged Ti–6Al–4V (Ti64) and DMLS Ti–6Al–4V.

2. Test method

A pin on disk reciprocating sliding test is proposed to investigate both tribological and wear performance of the two contact arrangements: Co–28Cr–6Mo/forged Ti–6Al–4V and Co–28Cr–6Mo/DMLS Ti–6Al–4V. Fig. 2 shows the pin on disk arrangement, where a dead weight is applied on top of the arm which holds the CoCr pin, to push the pin and the Ti64 specimen in contact. A reciprocating tangential load is then applied to give a certain stroke to the arm. The pin is manufactured with a cylindrical surface and polished, as shown in Fig. 3. The test loading conditions are decided by performing a stress analysis at the stem–head contact. To reproduce the realistic stress conditions at the joint, 3D FE stress analysis of the taper-lock contact in the commercially available stem–head joint is carried out. Hertzian analytical calculation is then done to determine the design of the customized pin, e.g. the surface radius. Profilometry and SEM tests are carried out to measure the volume of the wear scars. Measurement of evolution of coefficient of friction (COF) and wear coefficient are the target aims of the tests. This work is a first step in understanding the mechanical behaviour of the taper-lock; corrosion effects, e.g. due to body fluids, will be addressed in future work.

2.1. 3D stem neck–femoral head contact simulation

The general purpose, non-linear, 3D FE code Abaqus is used here to model the global stem–head contact using 4-node linear tetrahedron mesh. Fig. 4a shows the model of the taper-lock joint with applied loading conditions and constraints. Fig. 4b shows the meshed model where the element size in the contact region is about 1 mm. Fig. 4c illustrates the loading history of the model. Initially a press fit force of 1044 N is applied at the centre of the femoral head, representing the process whereby, the surgeon uses a hammer to introduce a press fit. Ideally, a 1 kg hammer of length of 0.5 m arm, swings of 0.03 s with an angle of 90° (0.785 m) resulting in 26.1 kg m/s momentum. The impact is assumed to last for 2.5×10^{-4} s, therefore a load of 1044 N is calculated and applied. In the later steps, the peak body force of 2648.2 N is applied and released cyclically. For the axes shown in Fig. 4a, it can be divided into three directions, where $F_x=558$ N, $F_y=-294$ N, $F_z=-2572$ N. This load is based on the work of Duda et al. [19] to represent the maximum load in a gait cycle when a man (of 75 kg) is walking, in which F_z corresponds to a dynamic amplification of 3.5 times the body weight and the values of F_x