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Development of a fretting corrosion model for metallic interfaces using adaptive finite element analysis

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ABSTRACT

A new adaptive finite element model was successfully developed to simulate fretting corrosion at metallic interfaces. To do this, the Archard wear equation and a previously established electrochemical equation were simultaneously employed. The algorithm of this finite element approach is able to determine the volume of passive oxide layers removed from the interface and/or re-generated onto the surface; and also, material loss caused by both fretting wear and corrosion at each cycle of fretting wear in a corrosive environment. The fretting corrosion simulation method developed in this work was then used to simulate the fretting corrosion process for a CoCr/CoCr interface under a varying profile of fretting sliding and two different normal contact stresses of 250 and 500 MPa. The results showed that with increasing the normal stress, material loss caused by fretting increases; however, the material loss caused by corrosion and the oxide layer volume decrease. This new model can be employed for various fretting corrosion situations with different material combinations, interface geometries and mechanical loading and sliding profiles.

1. Introduction

Fretting corrosion (a type of mechanically assisted corrosion) is known to occur in contacting metallic components that are cyclically subjected to fretting wear in a corrosive environment. Metallic implants such as modular taper junctions of total hip replacement are an example of this failure type where mechanical loads of daily activities can induce fretting wear at the metallic interface in the presence of the corrosive body fluid. Over the process of fretting corrosion, the passive oxide layer, that plays an important role in enhancing the corrosion resistance of metallic materials, can be mechanically disrupted. Such a disruption provides a condition for the metal (or metal alloy) to lose material through the associated chemical reactions in order to re-create a new oxide layer (repassivation) and also the process of metallic dissolution [1–4]. When the passive oxide layer is abraded by a mechanical action, dissolution of the reactive metal and repassivation occur immediately in the presence of a solution, as shown in Fig. 1. New oxide films nucleate and grow such that the disrupted area is filled with a stable oxide phase of the base metal [5].

To date, attempts have been made to propose a general model for mechanically assisted corrosion to predict the behaviour of metal alloys taking into account the mechanical and electrochemical parameters. Goldberg et al. [6] used a model of surface oxide fracture and a repassivation equation, that had been previously proposed by Ambrose [7], to justify the electrochemical response of CoCrMo alloys to fracture and reformation of its oxide layer. To do this, they employed an electrochemical scratch test method in which they used a diamond pin to scratch a CoCrMo sample in a phosphate-buffered saline (PBS) medium. They developed an equation that can determine the oxide layer thickness of CoCrMo alloys.

Swaminathan et al. [8] proposed a theoretical model which incorporates both the mechanical and electrochemical parameters of fretting corrosion. They conducted experimental tests in which different combinations of Ti-6Al-4V and CoCrMo alloys were subjected to fretting wear loading in a PBS condition. In their model, they proposed a relation between the mechanical and electrochemical properties such as normal load, amplitude of sliding, surface properties, potential and current.

Due to the complexity of the fretting corrosion process, the existence of various designs for implants (in terms of geometry and size), and the limitations of physical tests, it is difficult and expensive to study fretting corrosion in metallic implants by means of *in-vitro* tests. Similar difficulties and limitations apply to other situations where fretting corrosion occurs (e.g. clamped joints [9], leaf springs [10] and ball or roller bearings [11]). Hence, finite element (FE) method could be employed as

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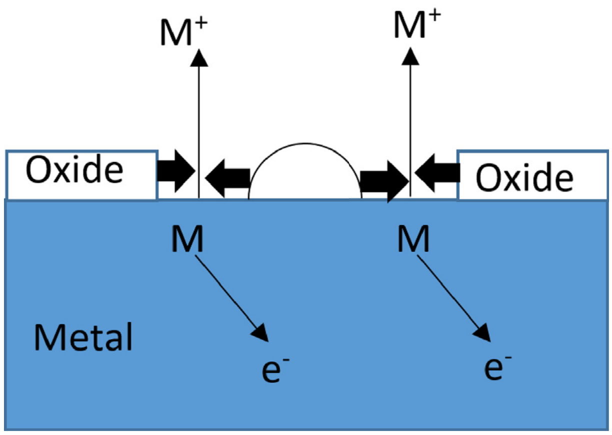

Fig. 1. Schematic of oxide layer repassivation and dissolution of metal as a consequence of mechanically assisted corrosion, adapted from Ref. [5].

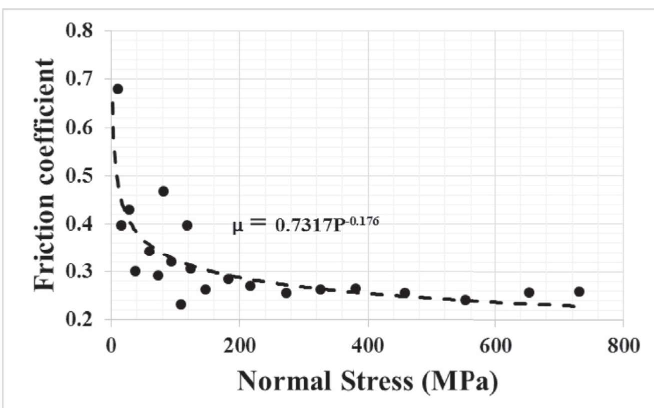

Fig. 2. Coefficient of friction between CoCr and CoCr versus normal contact stress, data from Ref. [8].

a convenient and practical way to explore complex geometries subjected to complex load cases.

In the area of modular taper junctions of hip implants, several finite element simulations have been developed to evaluate the mechanical response of the contacting components [12–14]. These studies showed that the geometric parameters such as taper angle mismatch, material combinations, and assembling load can directly affect the mechanical-related parameters such as relative micro-motions and contact stresses at the interface. These studies were limited to exploring only the contact mechanics of the interface subjected to a single loading cycle. Recently, finite element method has been used to predict the amount of material loss in a taper junction as a result of fretting wear over a few million cycles of loading [15–18]. Fallahnezhad et al. [18,19] developed a finite element fretting wear model for the contacting materials of a CoCr/CoCr head-neck taper junction in a PBS condition. They used the Archard wear equation to simulate the mechanical fretting wear process. All of these models have simulated only the mechanical fretting wear process and have neglected the effects of corrosion, in particular passivation/repassivation and consequent material loss due to corrosion.

A literature review confirms that, to date, no finite element model has been developed to simulate the fretting corrosion phenomenon in contacting surfaces of metallic materials under fretting wear loading and in a corrosive environment where passivation and repassivation repeatedly occur. In this study, therefore, a new finite element modelling method was developed to simulate the process of fretting corrosion and predict material loss due to the both mechanical fretting wear and corrosion. The equation of the oxide film regeneration (proposed by Swaminathan [8]) together with the Archard wear equation were implemented in a FE code to simulate fretting corrosion for a CoCr/CoCr material combination. This model is able to predict the amount of material loss caused by corrosion; and also, the volume of detached material caused by mechanical fretting wear. Moreover, this model is able to determine the amount of oxide layer removed from the material surface during a fretting corrosion process.

2. Methodology

The fretting corrosion process is a combination of two damaging components; mechanical wear and electrochemical corrosion. These two components are not independent processes; for instance, fretting wear can intensify corrosion (mechanically assisted corrosion). The details and procedure for developing an adaptive finite element model for this complex phenomenon applied to a CoCrMo/CoCrMo material combination are presented in the following sections.

2.1. Main equations

To model the mechanical fretting wear, Archard wear formulation was used to determine the depth of material loss over the surface (Eq. (1)).

$$\frac{V}{S} = k\frac{F_N}{H} \tag{1}$$

where V is the lost volume, S is the amplitude of sliding, k is the wear coefficient, F_N is the normal load and H is the material hardness. This equation was the core of a wear algorithm developed by McColl et al. [20] and Ding et al. [21] to model fretting wear in a pin-on-disc system. This wear equation was also used by Fallahnezhad et al. [18,19] to develop an algorithm for a two dimensional FE model of a head-neck taper junction in which the Archard equation was re-written in the form of Eq. (2):

$$h_{wear} = K.Incslip.C_{Press} \tag{2}$$

where h_{wear} is the depth of wear, K is the wear coefficient-to-hardness ratio (k/H), *Incslip* is the relative displacement of each node of the contact surface at each time increment and C_{Press} is the normal contact stress. The K ratio for the CoCr/CoCr material combination was reported as $1.68 \times 10^{-14}\,\mathrm{Pa}^{-1}$ [18]. The same equation and solution process were employed by the authors previously [18] in order to simulate the fretting wear phenomenon where the FE fretting wear model was successfully verified against existing experimental results with a good level of accuracy.

Swaminathan et al. [8] developed an equation for the re-generation of passive oxide layers (Eq. (3)) from which the oxide layer thickness can be determined. To propose and verify this equation, they conducted experimental work in which a pin-on-disc system of different materials was subjected to cyclic fretting wear, in a phosphate buffered saline (PBS) medium.

$$I_{film} = \left(\frac{\rho n F}{M_w}\right) \cdot 2\frac{V_{nom}}{\Delta}\frac{d\delta}{dt} \tag{3a}$$

$$I_{film} = 4\left(\frac{\rho n F}{M_w}\right).\frac{V_{nom}}{\Delta}\delta\nu \tag{3b}$$

where I_{film} is the oxide film formation current, ρ is the density of the oxide, M_w is the molecular weight of the oxide, n is the effective valence of the oxide, F is Faraday's constant (96,500 C/mol), V_{nom} is the nominal volume of the oxide layer, Δ is defined as the average inter-asperity distance in the sliding direction [8], δ is the amplitude of sliding and ν is the frequency of one cycle. Eq. (3b) can be used to define the current film of the fretting corrosion process for one complete cycle. The