Wear 362-363 (2016) 170–178

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Assessment of a recent tribocorrosion model for wear of metal-on-metal hip joints: Comparison between model predictions and simulator results

Shoufan Cao *, Stefano Mischler

Ecole Polytechnique Fédérale de Lausanne (EPFL), Tribology and Interface Chemistry Group (SCI-STI-SM), Station 12, CH-1015 Lausanne, Switzerland

ARTICLE INFO

Article history:
Received 25 January 2016
Received in revised form
26 May 2016
Accepted 28 May 2016
Available online 3 June 2016

Keywords:
CoCrMo metal-on-metal hip joints
Wear prediction
Hip joint simulator
Tribocorrosion
Mixed lubrication

ABSTRACT

A composite running-in wear model for metal-on-metal artificial hip joints, which combines tribocorrosion and lubrication aspects, was published recently. In order to check the quality of the model prediction, wear rates from nineteen well-controlled simulator wear studies were summarized and compared to the model predicted values. The results showed that the simulator wear results correlate well with the model predicted values. By estimating the maximum wear rate, the model can be used clinically to mitigate the failure risk of metal-on-metal hip joints. Furthermore, this study demonstrates the roles of the involved crucial parameters, giving tutorial suggestions of the input parameters and output values for the wear prediction of metal-on-metal artificial hip joints.

1. Introduction

Artificial hip joints have been developed since the 1950s to replace the disabled natural joints [1,2], and to help patients recover the functionality of hip joints. The selection of the biomaterials for the components of implants (especially for the bearing surfaces) is of great importance and directly determines the performance and lifetime of implants. Considering the total hip joint replacement (THR), several materials have been used for the acetabular cup, femoral head, modular neck (if designed) and stem. Considering the head-cup bearing, employed material couplings can be divided in two main families: low friction hard-on-soft material combinations (metal-on-polymer MoP or ceramic-on-polymer CoP) and low wear hard-on-hard bearings (metal-on-metal MoM, ceramic-on-ceramic CoC or ceramic-on-metal CoM). Although both designs constitute valid solutions, specific problems have appeared.

In the low friction couplings, the soft polymer (UHMWPE) usually undergoes wear causing the release of a large amount of micrometer-size wear debris that stimulate a cascade of reaction involving macrophages and giant cells, production of biochemical mediators of inflammation, cellular recruitment and bone resorption [3], ultimately causing osteolysis and aseptic loosening of the implant. As alternatives, the hard MoM or CoC couplings exhibit much less wear than polymer. However, these couplings may release large amounts of metallic ions by contact with the corrosive body fluids as indicated by the high ions levels in blood [4] found postoperatively in patients with THR. This constitutes a potential pathological risk if those ions enter organs such as liver or spleen [5].

There is thus a clear clinical interest in minimizing the material release from artificial hip joints. This constitutes the rationale for investigating the involved material release mechanisms and for developing appropriate models correlating materials degradation to well-defined physical parameters as a prerequisite for the selection on a scientific base of improved materials and designs.

Recently, Cao et al. [6] proposed a predictive model describing the wear loss of passive CoCrMo alloys in aqueous solutions. The model considers the interaction between lubrication, wear and corrosion phenomena occurring in tribological contacts operating in aqueous solutions. This constituted the first attempt to quantitatively predict wear as a function of a combination of material, mechanical, chemical and geometrical parameters. The model is based on the assumption that the contact with the counterpart occurs at asperity junctions that plastically deform under the imposed mechanical load. This plastic deformation leads to material release by two distinct mechanisms: mechanical detachment of metallic particles and release of metallic ions by the cyclic process of exposure of bare metal to the environment followed by chemical dissolution until the passivation establishes again. The former mechanism (defined as mechanical wear) has been modeled by formalisms based on Archard's theorem [7]

* Corresponding author. Tel.: +41 21 6932948.
E-mail address: shoufan.cao@epfl.ch (S. Cao).

http://dx.doi.org/10.1016/j.wear.2016.05.025
0043-1648/

implying a proportionality between the wear rate (removed metal volume per unit time) and the product of sliding velocity and extent of plastic deformation given by the ratio of normal load to indentation hardness. The latter mechanisms (chemical wear) was described by existing models [8,9] implying the wear accelerated corrosion rate of passive metals as the product of depassivation rate, i.e. the extent of bare metal (not protected by the passive film) surface exposed to the solution by plastic deformation per unit time, and of the passivation charge density, i.e. the amount of metal that needs to be oxidized (corroded) in order to regenerate the passive film on a surface of given area. The passivation charge density can be measured in independent electrochemical tests while the depassivation rate can be derived from the sliding speed and from the width of the plastically deformed area generated at asperity contacts (which in turn depends on the ratio between normal force and indentation hardness of the metal). The presence of body fluids does not manifest itself in corrosion risk of the implant only but can also provide hydrodynamic lubrication that in principle reduces the load carried by the asperities and thus the degradation of the metal. Indeed, Dowson [10] found in a set of wear data of MoM (CoCrMo alloy) obtained in hip joint simulators an empirical correlation between running-in wear and the theoretical minimum hydrodynamic film thickness as calculated using Hamrock–Dowson formula [11]. In a recent paper, Cao et al. [6] combined the Archard's theorem, the wear accelerated corrosion model [8,9] and the Dowson's empirical equation [10] in a single mathematical composite model that predicts the extent of mechanical and chemical wear rate as a function of a series of material, mechanical and electrochemical parameters. The model is illustrated in Fig. 1.

The composite model was calibrated by a well-controlled tribocorrosion study carried out in a tribometer and used to predict other tribometer results as well as Dowson's running-in wear from hip joint simulators. Quite good correlation was found between the predicted values and experimental results.

The goal of this study is to assess Cao's model [6] by comparing model predicted wear rates with experimental results concerning self-mated CoCrMo MoM joints as tested in hip joint simulators. For this, simulator experimental studies were firstly collected from the literature and the model parameters were subsequently extracted and used to predict wear rates that were finally compared to the published experimental results.

2. Literature review

A literature review of simulator wear studies was carried out using the keywords “metal on metal”, “simulator” and “hip”. 353 publications were found in ISI Web of Science and these papers were further checked under the criteria listed here:

- The metal for the head-cup coupling was a self-mated CoCrMo alloy (biomedical standard).
- The head radius and clearance were clearly given.
- The load curve, motion type and frequency of the simulator experiments were described.
- Calf serum solutions were used as lubricant (usually with additives such as NaN3 and EDTA).
- The evolution of wear loss (volumetric or gravimetric) with testing time (cycles) was clearly given (this is necessary to calculate the wear rate and to determine the running-in period).

19 papers were found to fulfill these criteria and the results were collected in order to compare with the model predicted values. The papers covered eight types of simulators with orbital (a special type of two axis motion), two axis or three axis motions, as summarized in Table 1. All of these motions result in multidirectional movements between the head and cup. Different twin-peak load curves were applied and even for the same type of curves, different maximum values were used in different studies. The average load was calculated by averaging the load curve in one cycle. The sliding velocity is not constant during a loading cycle except in the case of orbital motion. In order to extract the necessary input values for the model, the sliding velocity was calculated by firstly determining for each specific simulator configuration the length of the sliding track using the formula given by Calonius et al. [12] and afterwards by multiplying the track length by the motion frequency. The results are shown in Table 2. The effective radius of curvature R' for each literature results was calculated from the given head radius R and clearance c_R using Eq. (1):

$$\frac{1}{R'} = \frac{1}{R} - \frac{1}{R + c_R} \quad (1)$$

Average values for the charge number n, molecular mass M and alloy density ρ as taken from the literature relative to biomedical CoCrMo alloys are 2.37, 58.55 g/mol and 8.3 g/cm^3, respectively.

Some other model parameters were not indicated in the considered publications. The application of the model requires thus

$$V_{tot} = V_{mech} + V_{chem} = k_{mech} \frac{(E')^{0.6556}}{\eta^{0.9685}} \cdot \frac{(F_n)^{1.3129}(v_s)^{0.0315}}{(R')^{1.1473} H} + k_{chem} \frac{M Q_P (E')^{0.3278}}{n F \rho \eta^{0.4843}} \cdot \frac{(F_n)^{0.6565}(v_s)^{0.5158}}{(R')^{0.5737} H^{0.5}}$$

V_{tot}	Total wear rate (mm³/s)	Q_P	Passivation charge density (mC/cm²)
V_{mech}	Mechanical wear rate (mm³/s)	M	Atomic mass (g/mol)
V_{chem}	Chemical wear rate (mm³/s)	n	Oxidation valence
k_{mech}	Proportionality factor for mechanical wear (mm$^{1.49}$)	F	Faraday’s constant (C/mol)
k_{chem}	Proportionality factor for chemical wear (mm$^{0.745}$)	ρ	Density (g/cm³)
F_n	Normal force (N)	η	Viscosity of solution (Pa·s)
H	Micro surface hardness (HV)	R'	Effective radius of curvature (mm)
v_s	Sliding velocity (mm/s)	E'	Effective Young's modulus (GPa)

Fig. 1. The equation of the composite model and the explanation of the parameters.