Materials Science and Engineering C 34 (2014) 69–77

Contents lists available at ScienceDirect

Materials Science and Engineering C

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

Evaluation of taper joints with combined fatigue and crevice corrosion testing: Comparison to human explanted modular prostheses

L. Reclaru [a,*], R.A. Brooks [b], M. Zuberbühler [c], P.-Y. Eschler [a], F. Constantin [a], G. Tomoaia [d]

[a] PX Group S.A., Dep R&D Corrosion and Biocompatibility Group, Bd. des Eplatures 42, CH-2304 La Chaux-de-Fonds, Switzerland
[b] Orthopaedic Research, Addenbrooke's Hospital, University of Cambridge, Box 180 Hills Road, CB2 0QQ Cambridge, United Kingdom
[c] Smith & Nephew Orthopaedics AG, Schachenalle 29, 5001 Aarau, Switzerland
[d] University of Medicine and Pharmacy Iuliu Hateganu of Cluj-Napoca, Dept. of Orthopaedics and Traumatology, Cluj-Napoca, Romania

ARTICLE INFO

Article history:
Received 6 May 2013
Received in revised form 27 August 2013
Accepted 9 October 2013
Available online 17 October 2013

Keywords:
Modular prosthesis
Fatigue corrosion
Explanted prosthesis

ABSTRACT

The requirement for revision surgery of total joint replacements is increasing and modular joint replacement implants have been developed to provide adjustable prosthetic revision systems with improved intra-operative flexibility.

An electrochemical study of the corrosion resistance of the interface between the distal and proximal modules of a modular prosthesis was performed in combination with a cyclic fatigue test. The complexity resides in the existence of interfaces between the distal part, the proximal part, and the dynamometric screw.

A new technique for evaluating the resistance to cyclic dynamic corrosion with crevice stimulation was used and the method is presented.

In addition, two components of the proximal module of explanted Ti6Al4V and Ti6Al7Nb prostheses were investigated by optical and electron microscopy.

Our results reveal that: The electrolyte penetrates into the interface between the distal and proximal modules during cyclic dynamic fatigue tests, the distal module undergoes cracking and corrosion was generated at the interface between the two models; The comparison of the explanted proximal parts with the similar prostheses evaluated following cyclic dynamic crevice corrosion testing showed that there were significant similarities indicating that this method is suitable for evaluating materials used in the fabrication of modular prostheses.

1. Introduction

Revisions of total joint prostheses such as hip and knee replacements are becoming more common. Often, revision surgery is more complicated and less predictable than primary interventions. Therefore, orthopaedic surgeons have requested a fully flexible and adjustable prosthetic revision system and more of these modular joint replacement systems with intra-operative flexibility are being developed.

Ti6Al4V and Ti6Al7Nb alloys show excellent corrosion resistance [1–6], but in the modular prostheses the combination of the mechanical process of fatigue and crevice corrosion can generate destruction of the interface between the distal and proximal modules [7].

Crevice corrosion, wear by friction and fatigue have also been described at the level of the distal–proximal junction on explanted modular prostheses of this type made from titanium alloys [7,8]. Considering the multifactorial character of crevice corrosion–fatigue–fretting, the in-vitro evaluation of a modular prosthesis is difficult [9]; the complexity of the situation with this implant resides in the existence of interfaces between the distal module, the proximal module, and the dynamometric screw in the presence of cyclic dynamic constraints.

The connection in the majority of such modular implants is designed as a taper. To achieve optimum biocompatibility, often the modular parts of these prostheses are made of titanium alloys. Unfortunately, titanium alloys are notch sensitive and tend to gall. Both of these properties are detrimental for taper joints. Therefore, control of the tendency to gall as well as the elimination of notches, either due to design or manufacturing, is crucial for the long term success of these modular connections.

In order to go a step further in investigating the safety and effectiveness of such modular prostheses, a novel technique for the evaluation of the resistance to cyclic loading under in situ conditions, the dynamic fatigue test with crevice corrosion stimulation was established.

The term cyclic (dynamic) fatigue test with stimulation of crevice corrosion covers various interrelated phenomena: crevice corrosion, fatigue and tribocorrosion. The term (static) stress corrosion with stimulation in the crevice covers two distinct phenomena: crevice corrosion and stress corrosion. In order to clarify these terms, the definitions are given below: Crevice corrosion is localised corrosion of

* Corresponding author at: PX Group S.A. Dep R&D, Bd. des Eplatures 42, CH-2304 La Chaux-de-Fonds, Switzerland. Tel.: +41 32 924 02 90; fax: +41 32 924 02 10.
E-mail address: lucien.reclaru@pxgroup.com (L. Reclaru).

0928-4931/$ – see front matter
http://dx.doi.org/10.1016/j.msec.2013.10.005

a metal surface at, or immediately adjacent to, an area that is shielded from full exposure to the environment because of close proximity between the metal and the surface of another material [11]; Fatigue corrosion is a process in which a metal fractures prematurely under conditions of simultaneous corrosion and repeated cyclic loading at lower stress levels or fewer cycles than would be required in the absence of the corrosion environment [11]; Tribocorrosion groups together all the mechanical and chemical interactions which cause the degradation of solids in relative displacement with or without contact lubricant [12] and Stress corrosion cracking results from the combined action of corrosion and a static compressive or tensile stress, the latter being applied or residual [12].

The aim of the study presented here was to compare the results of this in vitro technique with an evaluation of retrieved implants to determine whether the method reproduces failures observed in vivo.

Under dynamic mechanical load, all interfaces of the taper joint may be exposed to fretting and bearing in mind the surrounding body fluid and the crevice condition while implanted, this fretting will be amplified by corrosion and become tribo-corrosion. The first modular prosthetic system tested with this new technique is a modular revision hip stem made from either Ti6Al4V or Ti6Al7Nb alloys.

2. Materials and methods

2.1. Preparation of samples

The test samples were complete modular prostheses prepared by Plus Orthopedics AG, Fig. 1. The test was conducted on two series of these modular prostheses. The main difference between them is the alloy composition: The first series was made of Ti6Al7Nb alloy and the second of Ti6Al4V alloy. Table 1 presents the differences between the two types of modular prostheses and the experimental conditions.

For each series of prostheses, four prostheses were evaluated: 3 specimens were used in cyclic fatigue dynamic tests with stimulation of crevice corrosion and one prosthesis was used under static stress stimulation of crevice corrosion, summarised in Table 1.

2.2. Fatigue behaviour evaluation

For the fatigue tests, an LFV 10–63 kN series machine (Walter & Bai AG, Switzerland) was used and adapted for fatigue testing and research of biomedical implants (Hip Implant Prostheses according to ISO 7206-4 and 6).

A mechanical–electrochemical cell was designed especially for these tests (Plus Orthopaedics, AG), Fig. 2. It is cylindrical with a central glass tube to guide it onto the sample holder. The distal module of each prosthesis was embedded in a resin. (elastic modulus 3.8 MPa).The embedding of the tapered shape was up to 1 cm from the boundary between the distal module and the proximal module.

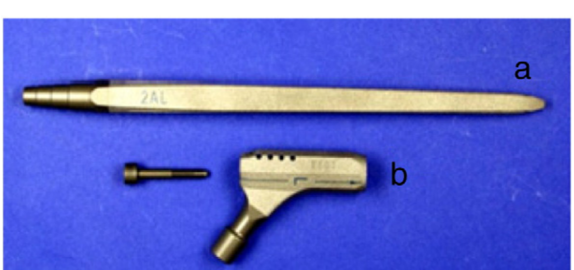

Fig. 1. Samples tested (modular prostheses): a. distal part and b. proximal part with the dynamometric screw.

Table 1
Types of modular prostheses tested and experimental conditions.

Series	Alloy	Surface	Tolerance	Code	Mechanical conditions
1st series	Ti6Al7Nb	Without specific treatment	Uniform	#1	Dynamic constraint
				#2	
				#3	
				#4	Static constraint
2nd series	Ti6Al4V	2nd type of anodizing ("Ti-anodizing")	Adapted to every level of the taper	#5	Dynamic constraint
				#6	
				#7	
				#8	Static constraint

The mechanical parameters were developed by Plus Orthopaedics AG using the following characteristics: a minimum of 0.25 kN and a maximum 3.3 kN loads, an amplitude of 1.1 mm at a frequency of 10 Hz and a control function of cyclic load (sinusoidal).

Two types of mechanical tests were conducted, one test under dynamic loading for 5 million fatigue cycles and a second test under a static force of 981 N during the equivalent time corresponding to 5 million dynamic fatigue cycles. Five million dynamic fatigue cycles correspond to approximately 5 years of walking for a person with a bodyweight of 100 kg.

The parameters of sample placement followed the requirements of the ASTM F1440 standard.

2.3. Corrosion behaviour evaluation

The potentiostatic electrochemical technique (controlled potential coulometry) adapted in accordance with the ASTM F746–87 standard [10] was used to evaluate the corrosion behaviour of the prostheses. This consists of causing an excitation of a given potential for a very short period of time and then putting on a constant potential for a given time. The steps of electrochemical measurement for one electrochemical cycle are shown in Table 2. For ten electrochemical cycles, 40 electrochemical measurements were performed at four levels: 600 mV, 650 mV, 700 mV and 750 mV. The electrochemical cycles were performed at the same time as the mechanical tests. Ten electrochemical cycles correspond to a million mechanical fatigue cycles. The test was conducted for a total of 5 million dynamic fatigue cycles.

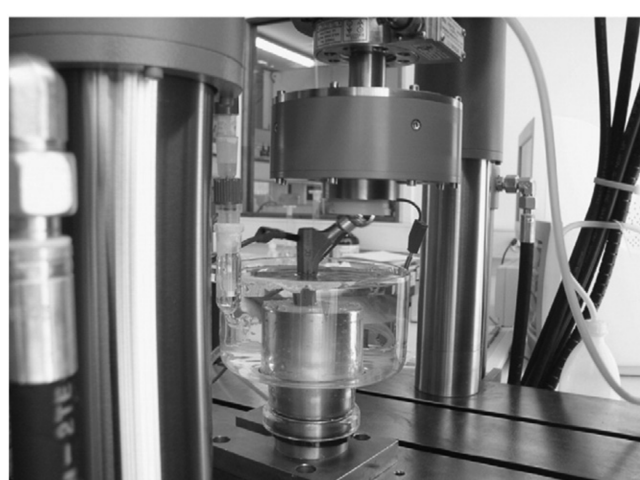

Fig. 2. Mechanical–electrochemical cell used for corrosion–fatigue tests.