Fretting manifestations in total hip prosthesis

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Abstract. This paper analyses the fretting and fretting wear phenomena to the classical and modular hip prostheses. Theoretical and experimental manifestations are studied, at the interface of the femoral stem with the bone cement mantle, at the taper junction between the femoral stem and the femoral head of the prosthesis, as well as at the tapering of the femoral neck adapter's connections with the stem and the femoral head. The aim of the paper is to highlight the modularization implications of the femoral component of the Total Hip Prosthesis, especially its tribological implications (fretting wear of modular junctions, fatigue and corrosion by fretting) which can contribute to wear and increasing ion concentrations of the metal in the blood, and the possibility of the femoral shaft fracture at the femoral head junction. Theoretical approach described, allows the "Archard" law implementation to predict the fretting wear. Experimental laboratory studies focused on the analysis of the tribological phenomena occurring at the taper junctions between the femoral head and neck, as well as the neck and femoral stem, highlighting the relevant qualitative tribological aspects. For this purpose, experimental junctions were fabricated and tested on a universal MTS mechanical machine, equipped with a fatigue testing device.

1. Introduction

Modularization of total hip prostheses (THP) has started from the need to simplify the implants revision and during the years it has proven useful and reliable. This simplification was possible through the option of maintaining the femoral stem and making only a femoral head change. If the stem is to be kept under review, exposure can be improved by removing and replacing the head with a new one. Starting from the new process, this paper analyses the phenomenon of fretting and fretting wear to the classical and modular hip prostheses.

Based on the modularization reliability, many researches were made in the last years on positive effects of THP modularizations [1], [2]. It has been shown that an increase in the use of modular interfaces can have negative effects. This because, it can produce an increase of the fretting corrosion and corrosion cracking at the conical junction. In this way, corrosion products of taper junctions may contribute to the joint wear with the third body and, finally, to the joint's rejection.

Fretting corrosion can be confirmed only by revision surgery. Over the years, clinically relevant issues reported were examined but the failure mechanism could not be identified. [3] This is important

to determine whether femoral stems with modular neck will be used in the future and how patients who already have implants should be monitored.

In other researches [4], [5] it has been shown that the primary micro-movements initiated the fretting within the modular connection of taper neck. There was a continuous process of abrasion and repassivation with a subsequent cold welding to the modular titanium alloy interface. Surface cracks caused by fretting or fretting corrosion eventually lead to fatigue fracture of titanium alloy modular neck adapters. Cobalt-chromium alloy neck adapters have reduced three times the micro-movements compared to the titanium neck, especially in the case of contaminated taper connection. The incidence of fretting corrosion was also substantially lower in the case of cobalt-chromium neck. In this way, it has been showed that THP corrosion reduction seems to be related to materials combinations.

Other experimental studies [6] showed that corrosion and fretting of modular taper surfaces may be influenced by different factors, like materials combination, bending stiffness, head and neck moment arm, neck length and implantation time. For example, in vivo corrosion of hip modular taper interfaces is attributed to a mechanically assisted corrosion process. The higher diameter necks will increase their rigidity and reduce the fretting and subsequent corrosion of the taper interface, regardless of the alloy used.

Micro-movements at the stem – neck interface were investigated on a Metha (Aesculap AG) and a H-Max M prostheses [7]. Metha prostheses demonstrated a substantial number of in vivo fractures for Ti-Ti couplings, but no fractures for Ti-CoCr couplings. H-Max M prostheses with Ti-Ti couplings showed only a clinical failure. Metha's prosthesis presented a tendency towards higher micro-movements compared to H-Max M (6.5 ± 1.6 μm vs. 3.6 ± 1.5 μm). Independent to design, prostheses with Ti neck have caused significantly higher micro-movements at the interface than those with a CoCr adapter (5.1 ± 2.1 μm vs. 0.8 ± 1.6 μm). Micro-movements between the Metha prosthesis with CoCr neck and H-Max M with Ti neck were identical (2.6 ± 2.0 μm).

Models of femoral stems structured using taper junctions have shown an increase in implant rupture in the recent past. Capitanu et al. showed that the fretting in a THP results from the destruction of the passive oxide layer from the metal [8]. This leads to increased corrosion and to the residues generation, such as polymer and/ or metal oxides particles, resulting in serious dysfunctions of the hip joint.

2. Fretting between femoral stem and bone cement mantle

Fretting tests were performed on an Instron® device for fatigue testing of the cemented fixture of the THP femoral stem, installed on a MTS Bionix multiaxial dynamic servo-hydraulic testing machine. It simulates fatigue loading of a hip cemented stem during a walking cycle. The machine and the device, as well as their mode of use, are shown elsewhere [8]. Figure 1 shows photographic images of the Ti6Al4V femoral stem contact and the PMMA mantle after the fretting experiment.
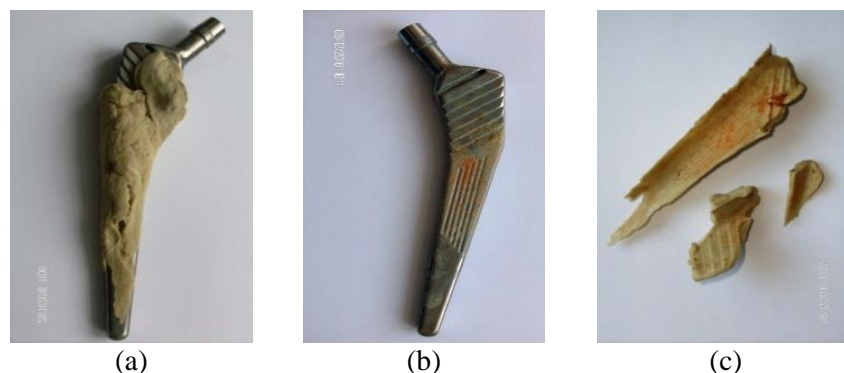

| (a) | (b) | (c) |

Figure 1. The cemented prosthesis stem (a) together with the contact sides of the cemented stem (b) and parts of the cement mantle (c) removed after 2450000 testing cycles, from the Instron® device for the fatigue test.

The presence of a visible corrosion of the femoral stem surface beneath the cement mantle and red deposits of Fe_2O_3 on the inner surface of the femoral stem (figure 1(b)), and through transfer on the inside of the PMMA mantle (figure 1(c)) were observed. These are due to fretting corrosion. For a more detailed investigation, the recovered stem and mantle were inspected further by optical microscopy.

3. Micro-movement and mechanical loading, causes of fretting in THP

An axial sinusoidal load between 230 N and 2300 N (ISO 7206-8) was applied to 1Hz for a total of 10000 cycles using the servo-hydraulic machine on which the fretting testing device was mounted, now shown in view (figure 2).
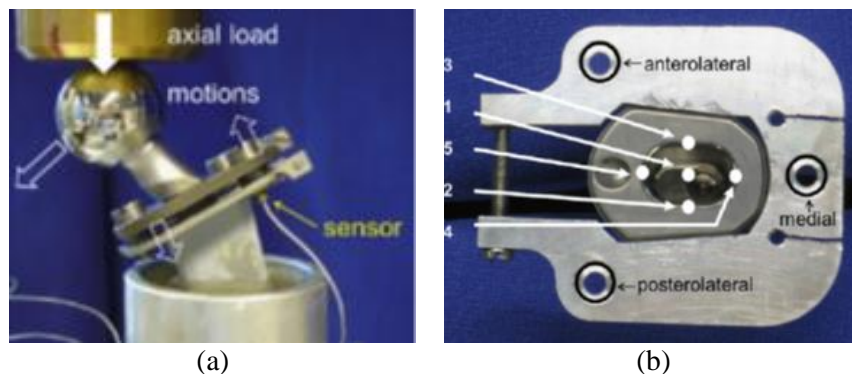

(a)   (b)

Figure 2. (a) A prosthesis mounted in the material testing machine. The servomotor was attached to an *xy* mass. The prosthesis system incorporates three eddy current sensors. Directions of motion are indicated by the light colour arrows. (b) Installation of the three eddy current sensors, with the holes of the grip screws on the sensor support and the five reference points from the mounting hole.

The micro-movements from the stem – neck interface were determined on the basis of linear displacements measured by three eddy current sensors with a 500 μm measuring range and a resolution of 500 μm – figure 2(a). This type of sensors were used due to their size and weight and to the non-contact measurement principle. The displacement in five reference points from the assembly gap was calculated from the displacements recorded by coordinate transformation – figure 2(b). For the cleanly assembled taper, the micro-movement accounted for only 27.1% / 24.9% of the displacement, while the larger part was due to elastic deformation (Co-Cr29-Mo / Ti6Al4V neck adapter). For the contaminated taper, the contribution of micro-movement was much higher (Co-Cr29-Mo: 48.1% / Ti6Al4V: 47.0%). Clear taper showed less micro-movements than the contaminated one (clean: 3.4 μm ± 2.5 μm, contaminated: 8.7 μm ± 7.41 μm, $p < 0.001$), and Co-Cr29-Mo adapters caused lower micro-movements than those of Ti6Al4V (7.8 μm ± 4.9 μm; Co-Cr-26-Mo: 7.28 μm ± 4.3 μm; $p = 0.005$).

4. Taper junctions fretting of the modular hip prosthesis

In the review published by Krishnan et al. [3] in 2013, it has been shown that any modular junction introduces the risk of micro-movement and fretting. Also, the tribological implications (fretting wear of modular junctions, fatigue and corrosion by fretting) of the THPs modularization can contribute to wear and increasing ion concentrations of the metal in blood, and to possible fracture of femoral shaft at the femoral head junction.

4.1. Theoretical approach

In the literature, there is no theoretical approach to fretting wear. This is the reason why the Archard's classic approach is applied to quantify the wear rates. It reports the amount of wear as the product between the sliding distance and the normal load. A wear coefficient is then extrapolated and it is

assumed that it determines the wear resistance of the studied material. This approach does not work when the friction coefficient is not constant. The methodology described allows the implementation of the "Archard" or "dissipated energy" law to predict the fretting wear. However, the wear energy approach is presented here as a unified prediction of a single wear energy coefficient in a wider range of strokes (from 50 μm to 1.3 mm) than Archard's law and as such has no a wide range of applications [9].

Wear energy law – equation (1) – is the basis for the calculation of the volumetric wear. In this equation the mechanical interfacial shearing is the predominant parameter for determining the wear [10]. Total volumetric wear W_v is obtained from the total accumulated local energy E, that is dissipated and a worn energy coefficient α

$$W_v = \alpha \cdot E \tag{1}$$

where

$$E = Q \cdot s \tag{2}$$

and Q is the shear traction, and s is the relative displacement of the surfaces in contact, giving

$$W_v = \alpha \cdot Q \cdot s \tag{3}$$

Dividing both members of equation (3) to the contact area, the depth of linear wear W_d can be calculated using equation (4), where τ is the shear stress of the contact surface

$$W_d = \alpha \cdot \tau \cdot s \tag{4}$$

A loading cycle over several time intervals n is necessary to be digitized to accurately model the effect of the variable load distribution on the wear over time, during the loading cycle (as it appears during driving). As such, the depth of wear for a single cycle of loading (the depth of cyclic wear W_c) can be calculated using equation (5), in which both the shear stress and the relative displacement, calculated at the end of a certain time interval, i,

$$W_c = \sum_{i=1}^{n} \alpha \cdot \tau_i \cdot s_i \tag{5}$$

The total depth of W_d wear generated in a specified total number of loading cycles N can be determined from equation (6), where j is the specific "step of analysis" which reflects the evolution of wear, β is a wear coefficient.

$$W_c = \sum_{j=1}^{(N/\beta)} \beta \sum_{i=1}^{n} \alpha \cdot \tau_i \cdot s_i \tag{6}$$

4.2. Experimental approach

In order to study the fretting of THP's modular junctions, taper and trapezoidal junctions were realized to fit the stems with which current modular prostheses were equipped. They were subjected to dynamic fatigue tests, up to 2500000 cycles, on the Instron® device [8]. The neck adapters, made of CoCr and Ti6Al4V, were used in combination with femoral heads of CoCr, Ti6Al4V and ceramics. Three of these combinations and the fretting wear images on the surfaces of these junctions, are shown in figure 3.
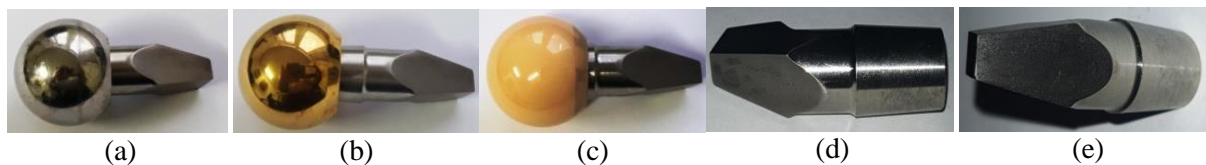

(a)	(b)	(c)	(d)	(e)

Figure 3. The femoral head – femoral neck combinations that have been tested made of CoCr (a) Ti6Al4V covered by TiN (b), ceramics (c), and taper and trapezoidal junctions of a CoCr (d) and Ti6Al4V (e) femoral neck adapter after the fretting test.

As shown in Cãpitanu et al. [8], for cemented stem prostheses, the relatively large difference between the maximum and minimum recorded friction torque and the visual observation of the prosthesis functioning through the transparent fixation support, seemed to be a sign of the fretting wear manifestation. When this difference occurred, at 2450000 cycles, testing was stopped, and the prosthesis was removed from the Instron® device and qualitatively analysed. After visual and microscopic inspection visible traces of fretting were revealed both on the taper and trapezoidal junction of the femoral neck adapters as well as on the conical holes of the femoral heads. In figure 4, there are presented images of the inner taper of the CoCr, Ti6Al4V, Ti6Al4V coated with TiN, and ceramics femoral heads, after 2450000 fretting cycles.
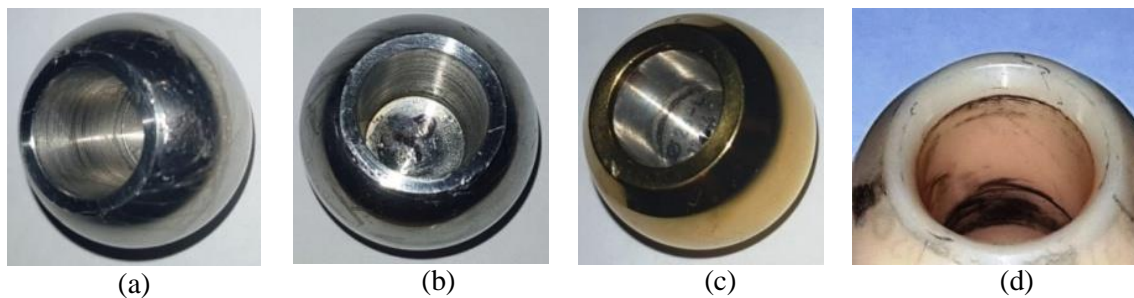

(a)　　　　　　　　(b)　　　　　　　　(c)　　　　　　　　(d)

Figure 4. The fretting and corrosion of the inner taper of the femoral heads made of Co-Cr (a), Ti6Al4V (b), Ti6Al4V coated with TiN (c) and ceramics (d), after 2450000 fretting cycles.

5. Results and discussion

Theoretically, the results of this work can be justified by the mechanistic model of tribocorrosion [11] which is known to take into account all possible mechanical and chemical interactions as follows:

$$W_{\mathrm{T}} = W_{\mathrm{m}} + \Delta W_{cw} + W_c + \Delta W_{wc} \tag{7}$$

in which W_{T} is total tribocorrosion wear, W_{m} and W_{c} are material losses due to pure mechanical wear and pure corrosive wear. The terms ΔW_{cw} and ΔW_{wc} represent the wear enhanced by corrosion and corrosion enhanced by wear, respectively.

5.1. Mechanical wear model

Mechanical wear model uses a local form of Archard's equation to calculate the wear depth. In a ball on plane configuration, the local wear depth of each point on the surface is given by:

$$\Delta h(x,y) = \frac{K}{H} \cdot P(x,y) \cdot \Delta t \cdot v \tag{8}$$

in which H, K, P, v and Δt are the hardness of the material, the Archard's dimensionless wear coefficient, the local contact pressure, the sliding speed and the time step [8] respectively.

5.2. Corrosive wear model

Corrosive wear model is based on Faraday's law and the calculation of the metal ions volume transferred to the surface and used to form the oxide [12]. The formulation used for corrosive wear is as follows:

$$V_c = \frac{QM}{nF\rho} \tag{9}$$

where V_c is the volume of metal removed by the anodic reactions. Q is the total electrical charge passed and is calculated by integrating the current over time when an excessive potential is being applied. M is the atomic mass of the metal, n is the charge for the oxidation reaction, ρ is the passive metal density, and F is Faraday's constant.

6. Conclusion

Based on the literature, it was considered that the micro-movements at the stem – neck interface were responsible for failures of modular prosthetic neck adapters observed for a number of different models. Titanium neck adapters have shown significantly larger micro-movements than CoCr neck adapters. Interfaces contaminated with fats or debris also showed significantly higher micro-movements. Because excessive micro-movements at the stem – neck interface may be involved in the implant failure process, special care must be taken to clean the interface before assembly, and generally titanium neck adapters and titanium stems should be used with caution.

Fretting and corrosion have occurred on all modular neck – stem recoveries, regardless of model. However, mixed metal couples exhibited more corrosion than homogeneous couples. This is due to the lower modulus of elasticity of the titanium alloy used for the stem, which allows for greater metal transfer and surface damage when loaded on a modular neck from CoCr alloy.

This paper shows that when the friction coefficient is not constant, it seems more relevant to consider the dissipated energy law to predict the wear fretting. By identifying the wear energy coefficients, the quantification of wear can be rationalized, and the wear resistance of the studied tribosystems can be classified. This also seems to be a convenient approach to interpret various wear mechanisms. Micro-movements associated with the modular components can also lead to fretting corrosion and consequently to the release of debris that can cause negative local tissue reactions in the human body.

7. References

[1]   Cooper H J, Della Valle C J, Berger R A, Tetreault M, Paprosky W G, Sporer S M and Jacobs J J 2012 Corrosion at the head-neck taper as a cause for adverse local tissue reactions after total hip arthroplasty *J. Bone Joint Surg. Am.* **94** 1655-61

[2]   Srinivasan A, Jung E and Levine B R 2012 Modularity of the femoral component in total hip arthroplasty *J. Am. Acad. Orthop. Surg.* **20** 214-22

[3]   Krishnan H, Krishnan S P, Blunn G, Skinner J A and Hart A J 2013 Instructional review: Hip. Modular neck femoral stems. *Bone Joint J.* **95-B** 1011-21

[4]   Hussenbocus S, Kosuge D, Solomon L B, Howie D W and Oskouei R H 2015 Head-neck taper corrosion in hip arthroplasty *BioMed Res. Int.* Article ID 758123, 9 pages

[5]   Grupp T M, Weik T, Bloemer W and Knaebel H P 2010 Modular titanium alloy neck adapter failures in hip replacement – failure mode analysis and influence of implant material. *BMC Musculoskelet Disord* **11** 3

[6]   Goldberg J R, Gilbert J L, Jacobs J J, Bauer T W, Paprosky W and Leurgans S 2002 A multicenter retrieval study of the taper interfaces of modular hip prostheses. *Clin. Orthop. Relat. Res.* **401** 149–161

[7]   Jauch S Y, Huber G, Hasche H, Sellenschloh K and Morlock M M 2014 Design parameters and the material coupling are decisive for the micromotion magnitude at the stem–neck interface of bi-modular hip implants *Med. Eng. Phys.* **36** 300–307

[8]   Capitanu L, Badita L L and Florescu V 2017 Stability loss of the cemented stem of hip prosthesis due to fretting corrosion fatigue *Tribol. Ind.* **39** 536-46

[9]   Liskiewicz T and Fouvry S. 2005 Development of a friction energy capacity approach to predict the surface coating endurance under complex oscillating sliding conditions *Tribol. Int.* **38** 69–79

[10]   English R, Ashkanfar A, Rothwell G 2015 A computational approach to fretting wear prediction at the head–stem taper junction of total hip replacements *Wear* **338** 210-20

[11]   Ghanbarzadeh A, Wilson M, Morina A, Dowson D and Neville A 2016 Development of a new mechano-chemical model in boundary lubrication *Tribol. Int.* **93** B 573-82

[12]   Ghanbarzadeh A., Salehi F M, Bryant M, Neville A 2018 A new asperity-scale mechanistic model of tribocorrosive wear: synergistic effects of mechanical wear and corrosion *J. Trib.* **141** 021601-021601-12