Implications of the fretting phenomenon on the stability of the total hip prosthesis - A review

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ABSTRACT

The paper presents a review of three of the studies undertaken by the authors regarding the implications of the fretting phenomenon that can manifest in a total hip prosthesis, on its stability. Experimental investigations have been made on Ti6Al4V / UHMWPE prostheses with cemented stem. Failure to fix the cemented stem of the prosthesis occurred at 2450000 cycles, after which visual inspection was done and photographic recordings were made. Two different conditions were considered for the normal force $N$ between the contact surfaces: constant or proportional to the axial force $P$. Determination of the stresses induced in the fretting process required the preliminary characterization of the relationship between the friction force $F$ and the axial force $P$ produced during the loading cycles. Hereafter, experimental studies were carried out to detect the early stage when fretting wear of the Ti-6Al-4V alloy, used for the hip prostheses, appears. Wear is a critical aspect for estimating the fretting fatigue. It was taken into account the unanimous finding that the surface roughness of the testing sample has a significant influence on the occurrence and evolution of the fretting scar. Studies were realized on samples of special shape presented in this paper.

Keywords: hip implant, fretting corrosion, fretting fatigue, PMMA, Ti6Al4V

1. INTRODUCTION

Fretting refers to the friction process involving low amplitude displacements, more precisely, displacements with a total amplitude less than the width of the contact between two components. In recent years, several studies have focused on understanding this phenomenon, and, of course, on finding solutions to prevent and / or avoid it. Fatigue design of some components in these domains, without taking into account the effect of fretting, will certainly lead to the premature and unexpected failure in many applications [1].

Fretting corrosion is a degradation phenomenon of the contact in an aqueous environment. It is one of the most critical problems in the design of total hip prostheses, since it occurs at the contact surface between the femoral stem and the bone cement [2].

Fretting in a total hip prosthesis is due to the destruction of the passive oxide layer from the metal, thus leading to the intensification of corrosion and to the generation of residues, such as polymer particles and metal oxides [3] that results in serious dysfunctions of the hip prosthetic joint.

Cyclical loading due to human walking, as well as differences between the mechanical properties of the femoral stem and of the bone cement, give rise to loss of the contact between the two materials. This leads to secondary effects, such as degradation and cracking of the cement. Debris, including metallic oxides and ions, penetrate into the bone tissues through cracks and finally induce inflammation of the bone tissues. Currently, the most used materials for the manufacture of the femoral stems are cobalt-chromium alloys, titanium alloys or austenitic stainless steels (SS 316L). The bone cement, such as poly (methyl methacrylate), is introduced into the spongy and cortical bones. Deterioration by fretting corrosion between SS 316L and poly (methyl methacrylate) was investigated experimentally, under similar conditions to those found at the interface between a femoral stem and the bone cement in a real prosthesis [4].

Interfacial energy dissipated and wear volume after 2,000,000 cycles were measured. It has been shown that the wear volume can be expressed as a function of dissipated interfacial energy. It was found that the wear volume of PMMA is linearly correlated with the cumulative dissipated energy, [3]. Fretting may be referred to as material's deterioration caused by small oscillatory movements between the bodies in contact. This can result in surfaces damage and dimensional changes. There can be also observed a remarkable decrease of the useful life in the presence of bulk effort. Surface degradation is defined as fretting wear, while the crack development can be termed fretting fatigue. To estimate
the life of fretting fatigue, the problems of the complete process are usually divided into two phases: crack initiation and crack propagation.

The level of fretting damage is determined by the amplitude of the relative sliding between the femoral stem and the bone cement [6, 7]. If the sliding amplitude is so small that some parts of the contact remain adherent, and others slide over the other opposite surface, the cracks are generated predominantly near the edges of the contact (fretting fatigue). If the sliding amplitude is large enough to allow all the parts of a surface to slide over the other surface, wear (loss of material) occurs across the entire contact surface (fretting wear).

Similar findings were also presented for Ti6Al4V alloy femoral stem [8]. In the human body, the Ti6Al4V alloy is immersed in a physiological solution having a high sodium chloride concentration (~ 0.2 M) at a temperature of 38 °C. Because of the significant difference in mechanical properties (especially Young's module, with a ratio of 90 between Ti6Al4V and PMMA), shielding effort is taking place. This physical phenomenon can be explained by the fact that the metallic materials and the polymers do not exhibit the same deformation under the applied stress, thus leading to the unsoldering between the metal and the cement. Therefore, adhesion between metal and polymer is lost after a short period of human walking. This unsoldering involves the fretting (friction under low displacements) and subsequent friction between materials that enter in contact. Subsequently, the materials (Ti6Al4V and bone cement) are subjected to low displacements, friction loading in a corrosive environment, resulting in fretting corrosion. Consequently, the wear occurs between the bone cement and the Ti6Al4V alloy. It involves the generation of debris (corrosion products), which often cause inflammations or reactions, ending with aseptic loss of implants fixation and need replacement.

Giannakopoulos et al., [9] have stated that the problem of fretting can be approached as a problem of simple fatigue subjected to localized concentration of stress. They developed an analytical model for fretting fatigue at a corner of a rounded mandrel in contact with a substrate and made an analogy with the initiation of the fatigue crack at the notch of a tip. Fretting fatigue is a type of multi-axial fatigue with a disproportionate load, thus introducing multiaxial stress fields and severe stress gradients. Therefore, multiaxial criteria are used to define the failure. Various multiaxial criteria have been developed in the past that use critical deterioration parameters along with various methods to define the estimated life. Generally, the stress and deformation components combined with the material constants are totally assimilated to the limit of fatigue resistance by inversion stretching / torsion, or by the Manson-Coffin and Basquin relationship, Nesládek et al., [10]. Therefore, it allows the estimated lifetime to be calculated according to the fretting fatigue scenario.

In the case of total modular hip prostheses, the fretting also manifests at the conical junction between the femoral head and the stem [11]. There are evidences in the specialized literature of some experimental researches on fretting in THR [12, 13], but there is only a limited number of studies on the numerical simulation of this type of wear (Zhang et al., [14] 2013, Elkins et al., [15]). It is obvious that more researches are needed to help inhibiting the effects of corrosion. However, the works presented here focus exclusively on the fretting wear as being the main mechanism that causes damage at the conical junction head – stem in the THR. The methodology described in [15] allows the application of the "Archard" or of the "Dissipated Energy" wear law to predict the fretting wear.

C. Montebello et al., [16], described a new method of modeling the stress gradient effect in fretting fatigue. The analysis of the mechanical fields near the edges of the contact allows extraction of the un-localized intensity factors that take into account the evolution of the stress gradient. For this purpose, the kinetic field around the ends of the contact is divided into a sum of multiple terms, each expressed as a product between the un-localized intensity factors, \( I_1 \), \( I_2 \), \( I_3 \), dependent on the macroscopic loadings applicable to the mechanical assembly, to the reference spatial fields, \( d_c \), \( d_p \), \( d_f \), depending on the local geometry of the workpiece. This description is obtained by non-intrusive post-processing of the FE calculation and is designed to be easily implemented in the industrial context. By using the macroscopic load as an input, the procedure consists in calculating a set of un-local stress intensity factors that represent an indicator of the severity of the stress field near the edges of the contact. This description has two main advantages. Firstly, the un-local stress intensity factors are independent of the geometry used. Secondly, the procedure is easy to apply to the FE model on industrial scale.

J. Domínguez (1998) [17] analyzes the cyclical variation of the friction forces and of the contact forces during the fretting fatigue tests. The friction forces and the forces involved in the partial sliding and the amplitude of the small slidings between the contact surfaces are examined globally. L. Capitanu et al., [19] presented the case of breaking a stem of a cementless stem prosthesis as a result of induced efforts, superimposed on a defect in the manufacture in the femoral stem. Also, L. Capitanu et al. [20], presented their studies on the friction and contact stress analysis during fretting fatigue, and its influence on the loss of stability of the cemented stem of the hip prosthesis due to fretting corrosion. Experimental investigations have been made on Ti6Al4V/ UHMWPE prostheses with cemented stem, following the fretting manifestations at the interface of the bone cement mantle PMMA (polymethylmethacrilate) Simplex P type, with the femoral stem (Ti6Al4V). Studies have been made under stress and biological motion 3D conditions. An Instron device was used for fatigue testing of the cemented fixation of the hip prosthesis stem, this being installed on a MTS Bionix triaxial dynamic testing servo-hydraulic machine. However, because of the shape with notches of the stem, it was not possible to directly identify the occurrence or initiation of some fretting cracks. This is
why studies continued on the same MTS Bionix triaxial dynamic testing machine, using Ti6Al4V traction samples, modified to study theoretically (L. Capitanu et al. [19, 20], F.J. Schoen and A.S. Hoffman [21]) and experimentally (L. Capitanu et al. [19]) the initiation and evolution of fretting scar.

In the experimental conditions used, the fretting contact between the pad and the sample was a punctiform contact, which produced a fretting wear scar (L. Capitanu et al., [22]. The incipient fretting scar evolved rapidly, even during the short time considered (maximum 30 minutes). From the determinations of the in-time evolution of the fretting wear resulted that under the experimental conditions used (short testing time), it was found that in the case of the shortest experiment (5 min) the fretting wear scar is visible. The profiles and the photomicrographs of topographies of the studied initial surfaces and of those obtained after short contact periods by fretting were recorded and analyzed. Simultaneously the friction coefficient was measured. Samples with roughness of $R_a = 0.075 \, \mu m$ ($t = 3 \, s$) and $R_a = 0.19 \, \mu m$ and $R_a = 0.045 \, \mu m$ were tested.

The recording of fretting scars allowed the calculation of the volume of material worn by fretting and correlation with the friction coefficient value recorded during each test. It was found the existence of a minimum of the wear curve resulting for the roughness $R_a = 0.045 \, \mu m$ of the Ti6Al4V alloy surface.

These suggest that the growth of the fretting cracks appears to be trans-granular, and this observation suggests that the cracks growth may be influenced by the crystallographic structure of the stem material. This observation is consistent with the studies of D.B. Garcia and A.F. Grandt Jr. [22].

2. MATERIALS AND TESTING EXPERIMENTAL TECHNIQUES

2.1 Materials

Typically, 316L austenitic stainless steel has been used previously for the manufacture of total hip prostheses, and now the titanium alloy Ti-6Al-4V and cobalt-chromium alloys are used. These are used due to their mechanical properties and good biocompatibility (Buciumeanu et al., 2009). In this study, contact of the Ti6Al4V alloy stem, of which chemical composition is shown in Table 1 and the PMMA bone cement, type Simplex P was used and analyzed. PMMA is an optically transparent thermoplastic material.

| Table 1: Chemical composition of the Ti6Al4V alloy (w/w) |
|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Element         | Compos.        | Al (max)       | O (max)        | N (max)        | V (max)        | Fe (max)       | N (max)        |
| Compos.         | 5.50-6.75      | 0.020          | 0.05           | 3.50-4.50      | 0.40           | 0.015          | 0.10           |
| Ti              |                |                |                |                | 0.40           |                |                |
| Other (max)     |                | 0.40           |                |                |                |                |                |
| Bal.            |                |                |                |                |                |                |                |

At room temperature, it is a rough and brittle material. Its mechanical strength, Table 2, is much lower than that of the Ti6Al4V

| Table 2: Mechanical properties of the tested materials |
|-----------------|----------------|----------------|----------------|----------------|
| Material        | Poisson coefficient ($\nu$) | Young’s modulus ($E$) [MPa] | Yield strength ($\sigma_y$) [MPa] | Tensile strength ($\sigma_t$) [MPa] |
| Ti-6Al-4V        | 0.29           | 119            | 825            | 895            |
| PMMA (Simplex P) | 0.39           | 2.5            | 65             | 75             |

2.2 Experimental device

Fretting fatigue tests were performed on an Instron® device for fatigue testing of the cemented fixation of the femoral stem of the total hip prosthesis – Figures 1(a) and (b), installed on a MTS Bionix multiaxial dynamic testing servo-hydraulic machine Figure 1(c), equipped with a hip implants testing system. Instron® fatigue testing device for the bone cement fixation of femoral stem of the total hip prosthesis was specifically designed to meet the requirements of ISO 7206-4.
Figure 1 (a) Instron® fatigue testing device for the bone cement fixation of femoral stem of the total hip prosthesis, (b) Instron® testing device scheme for prosthetic stem fatigue fixture and (c) MTS Bionix multiaxial dynamic testing servohydraulic machine, equipped with system for testing the hip implants

It simulates the fatigue loading of a cemented hip stem during a walking cycle. The device consists of a support made of a composite femoral model from Sawbones® transparent plastic with an intermedullar channel, in which the stem is cemented, mounted in a sealed saline chamber, a low friction loading head incorporating a bearing with low friction and an adapter for fitting at the charging cell of the system - Figure 1 (b). The sealed saline chamber contains a high concentration sodium chloride solution (~ 0.2 M) at a temperature of 38 °C. It was chosen to use the intramumeedullar channel section to fix the stem to the physiological position. The assembly has a temperature regulator and a recirculation pump for in vivo testing. The flexible support for the prosthetic stem allows to be used a wide variety of hip geometries, offset angles, embedding materials and depths. The device applies compressive, flexural and torsional stresses to meet the requirements of ISO 7206-4. Compression loading through the loading head causes the femoral stem specimen to be subjected to some loads and frequencies as are specified in ISO 7206-8. The test ends either when the sample does not fail after 2,000,000 cycles, or when a certain number of preset cycles have been reached. In the case of this research, the test was stopped at 2,450,000 cycles when signs of destructive manifestation of fretting occurred. The testing fluid medium used was NaCl mixed with distilled water, and the test frequency was 10 Hz. MTS Bionix multiaxial dynamic testing servo-hydraulic machine – Figure 1(c) allows the triaxial testing of hip orthopedic implants and from a tribological point of view [18].

The MTS Bionix system for implants testing is equipped with three rotary motors for the Inner-Outer Rotation (IOR) movement; for the Flexion-Extension (FE) movement and for the Abduction-Adduction (AA) movement and with three displacement transducers, one for (AA) movement, an angular displacement transducer for FE and an angular displacement transducer for IOR. In addition, the MTS Bionix system has a torque transducer, with two Wheatstone bridges, one for (AA) movement, an angular displacement transducer for FE and the other for measuring the torque. The torque transducer is resistive and is coupled to a 662 20 h-04 current converter to process the signals received from each Wheatstone bridge. The testing machine allowed to be set the number of cycles, the normal force size on the joint implant (force F that has a pulsating shape), the lower and upper limits of the angular displacement of each rotation, as well as the movement law for each type of rotation, according to ISO 14242-3. Appropriate matching of the sample was checked before the test. It was adjusted to a value of 210 bar of the pump pressure. After adjustments of the command response, the output values for each axis (axial, torsion, FE, AA, IOR) were reduced to zero.

Finally, experimental studies were conducted to detect the early stage in which the fretting wear of the Ti-6Al-4V alloy used for hip prostheses appears. Wear is a critical aspect for estimating the fretting fatigue. Studies were realized on samples of special shape, in order to be able to study the influence of in contact surfaces roughness on the durability to fretting. Fretting pads with roughnesses $R_a$ of the contact surface of 0.015 μm and 0.045 μm and Ti-6Al-4V samples with roughnesses $R_a = 0.045$ μm, $R_a = 0.075$ μm and $R_a = 0.19$ μm were used. Trial times of 3 seconds, 30 seconds, 1 minute, and 5 minutes were selected to capture the moment of the fretting scar appearance, long before it eventually trigger the fretting cracking. Simultaneously with the fretting wear of the surface, the friction coefficient was also measured. From the determinations of the in-time evolution of fretting wear, it resulted that, under the experimental conditions used, the minimum wear takes place at a certain value of the roughness and not at the minimum roughness. Surprisingly, the minimum friction coefficient does not coincide with the minimum fretting wear. The experimental and theoretical findings are presented in the following section.
3. EXPERIMENTAL RESULTS AND DISCUSSION

This section refers to the results of the four approaches made and analyzed in this study:
1. Stability loss of the hip prosthesis stem due to the fretting corrosion;
2. Analysis of the friction and contact stress during the fretting fatigue;
3. Influence of the roughness on the initiation of the fretting fatigue scar of the Ti-6Al-4V alloy.
4. Manifestation of the fretting at the conical junction of the femoral head with the prosthesis stem.

3.1 Stability loss of the hip prosthesis stem due to the fretting corrosion

Following the experimental tests performed on MTS Bionix system, variations in time of the vertical contact force (in blue) and time variation of the torsional torque (in red) of the cemented stem and of the cementless stem (L. Capitanu et al., 2017a). These recordings are made at 2,450,000 cycles, when the friction moment range limits have become wider and more variable. This was considered to be a sign that the friction between the femoral head and acetabular cup became larger, obviously not because of wear, because the wear occurs after millions of cycles, but because of the contact loss between the Ti6Al4V alloy femoral stem and the mantle of bone cement PMMA – Simplex P. To illustrate this, Figures 2 and 3 show three records for each tested stem: cemented and cementless. Figure 2 shows the graph of the vertical contact force (in blue) and the torsional torque (in red) for the cemented prosthesis.

![Graph](a)

![Graph](b)
Figure 2 In time graph of vertical contact force (blue) and of the friction torque (in red), at the cementless stem testing.

Figure 3 shows the graph of the vertical contact force (in blue) and the torsional torque (in red) as a function of time in testing the cementless stem of the hip implant. In these graphs, the minimum and maximum values of the represented sizes variation can be seen. These values are marked on the x-axis with points A and B.
Based of the graphs presented, Tables 3 and 4 summarize the values of friction torque recorded and of the calculated mean friction coefficient in testing of the cemented stem of the hip prosthesis, compared to testing the cementless hip implant, at 2450000 cycles.

**Table 3**: Values of friction torque and calculated friction coefficient for cementless stem

<table>
<thead>
<tr>
<th>Graph</th>
<th>Point</th>
<th>W (kN)</th>
<th>M (kNmm)</th>
<th>( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig. 2 (a)</td>
<td>A</td>
<td>0.3</td>
<td>0.1</td>
<td>0.0238</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>3</td>
<td>0.3</td>
<td>0.0072</td>
</tr>
<tr>
<td>Fig. 2 (b)</td>
<td>A</td>
<td>0.3</td>
<td>0.05</td>
<td>0.0119</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>3</td>
<td>0.6</td>
<td>0.0143</td>
</tr>
<tr>
<td>Fig. 2 (c)</td>
<td>A</td>
<td>0.3</td>
<td>0.1</td>
<td>0.0238</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>3</td>
<td>0.3</td>
<td>0.0072</td>
</tr>
</tbody>
</table>

The average value of the mean friction coefficient: 0.0147

**Table 4**: Values of friction torque and calculated friction coefficient for cemented stem

<table>
<thead>
<tr>
<th>Graph</th>
<th>Point</th>
<th>W (kN)</th>
<th>M (kNmm)</th>
<th>( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig. 3 (a)</td>
<td>A</td>
<td>0.3</td>
<td>0.1</td>
<td>0.0238</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>3</td>
<td>0.7</td>
<td>0.0167</td>
</tr>
<tr>
<td>Fig. 3 (b)</td>
<td>A</td>
<td>0.3</td>
<td>0.1</td>
<td>0.0238</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>3</td>
<td>0.5</td>
<td>0.0119</td>
</tr>
<tr>
<td>Fig. 3 (c)</td>
<td>A</td>
<td>0.3</td>
<td>0.1</td>
<td>0.0715</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>3</td>
<td>0.5</td>
<td>0.036</td>
</tr>
</tbody>
</table>

The average value of the mean friction coefficient: 0.0253

Since the friction moment in a spherical joint (the femoral head – acetabular cup joint) is given by the relation \( M_f = \mu RF \), where \( R \) is the radius of the femoral head \((R = 0.014 \text{ m})\) and \( F \) is the normal force whose maximum and minimum values were set on the Instron testing machine at 3 kN and 0.3 kN respectively, the calculation of the friction coefficient was made by dividing \( M_f \) at the product between the femoral head radius \( R \) and the normal force \( F \). It appears that when testing the cementless stem, the average value of the friction coefficient \((\mu = 0.0147)\) is lower than the one of the cemented implant \((\mu = 0.0253)\). The relatively high difference between the maximum and minimum value of torsional torque, and the visual observation of prosthesis functioning through the transparent support of its fixation, can be a sign of the fretting wear manifestation, so that the testing was stopped when these differences occurred, i.e. at 2450000 cycles. Afterwards, the prosthesis was removed from the Instron® device for the fatigue testing of the cemented fixation of the femoral stem. Stem prosthesis was very easily extracted from the composite bone support, after some left-right movements, together with a big part of the PMMA cement mantle. PMMA Cement – Simplex P mantle was carefully removed from the femoral stem to keep its integrity as far as possible. The stem and PMMA mantle were then inspected and photographed separately, optically and microscopically. It has been found that there is an obvious corrosion of the surface of the femoral stem beneath the cement mantle and reddish deposits from
tribocorrosion remnants on the surface of the femoral stem and through transfer on the inner side of the PMMA mantle. These are probably due to corrosion by fretting.

Figure 4 shows images of the cemented prosthesis stem together with a part of the cement mantle extracted after 2,450,000 cycles from the Instron® device for fatigue testing of the cemented fixation (a), the stem of the prosthesis after removal of the cement mantle (b) and parts of the cement mantle after its removal from the prosthesis stem (c).

For a more detailed investigation, the recovered stem and mantle were inspected further by optical microscopy. The microscopic inspection of the Ti6Al4V stem and of the inside of the cement mantle was performed hoping to identify specific cracks by fretting fatigue. Inspecting proved to be very difficult because of the shape with notches of the femoral stem and in the replica of the inner surface of the PMMA mantle. In this situation, only a CELESTON® # 44302 Mini Handheld Digital Microscope could be used with 15-30x magnification. Despite all these difficult conditions, very interesting images of the femoral stem surface after the fretting experiment, which are presented elsewhere (L. Capianu et al., 2017) were recorded. The recorded images have highlighted the existence of some obvious cracks on the surface of the stem, as well as a thin interface of acrylic PMMA bone cement remained on its surface. These suggest that the growth of the fretting cracks appears to be trans-granular, and this observation suggests that the cracks growth may be influenced by the crystallographic structure of the stem material. This observation is consistent with the studies of D.B. Garcia and A.F. Grandt Jr., 2005.

The above presented an analysis based on those published in the speciality literature, of the friction and contact stresses occurring during the fretting fatigue.

### 3.2 Analysis of the friction and contact stresses during the fretting fatigue

M. Buciumeanu et al., 2009, proposed a modification of the Smith-Watson-Topper (SWT) and Morrow parameters for prediction of life at fretting fatigue to take account of deterioration by wear. It is proposed that, in addition to the main stresses involved in the fretting contact (axial, normal and tangential stresses), a new parameter, the stress concentration factor, $K_t$, due to the “effect of the fretting scar” should be considered. The modified Morrow parameter has been shown to provide good predictions of the sustainability at fretting fatigue, but more accurate predictions with the SWT parameter have been obtained. J. Geringer and D.D. Macdonald [5], investigated experimentally the fretting corrosion of the AISI 316L SS couple against poly (methyl methacrylate) under small displacements. The wear observed on stainless steel was modeled using the Point Defect Model (PDM). The originality of this approach in the PDM application to fretting corrosion is the use of a modified ratio of the barrier layer dissolution in the case of cyclic wear. D.B. Garcia and A.F. Grandt Jr., [23] analyzed the surfaces of Ti-6Al-4V samples fracture produced during fretting fatigue experiments controlled in laboratory to provide evidences regarding the physical nature of fretting, and of the fretting fatigue cracks. Each fracture surface was analyzed by optical microscopy and electronic scanning to locate and record the fretting cracks. The fracture by fretting has been described as somewhat smooth and inexpressive. H.A. Fadag et al., [24] analyzed the behavior of crack growth in fretting fatigue conditions through a finite element sub-modeling method to estimate the duration of crack propagation in Ti-6Al-4V alloy samples. They analyzed two contact geometries, cylinder-on-flat and flat-on-flat. The calculated durations of cracks propagation were combined with the results of an experimental study in which the fatigue total life was measured. The numerical-experimental
combined approach showed the duration of cracks initiation. The life of cracks propagation increased as the cyclic effort applied in the material mass increased, in a similar manner for both contact geometries.

S.H. Teoh [25] presented a review of biomaterials fatigue, showing that the real mechanisms in vivo are complex and involve the hostile environment in the body. Fatigue breakage and wear are commonly reported in orthopedic applications, such as hip joint prostheses. Because it is not possible to avoid the failure, recent work has focused on predictive tools to allow for more accurate anticipation, so as to avoid catastrophic failure in vivo. He presented a review of the fatigue breakdown problems of metallic, polymeric and ceramic implant materials on recent testing techniques and discussed the future development of biomaterials resistant to breakage and wear.

Yongqing Fu (2000) [26] discussed the application of several types of advanced surface modification methods to mitigate the fretting damage such as physical and chemical vapor deposition (PVD and CVD), ion implantation, laser treatment and plasma nitriding, etc. Some coatings are effective for attenuating the fretting wear, while others are more effective in fretting fatigue conditions. The effects of surface modification methods on resistance to fretting are explained with the help of fretting maps. A coating method has been proposed to select the most appropriate surface treatments or coatings to minimize the probability of fretting damage. Jaime Dominguez (1998) [17] conducted a systematic, theoretical and experimental investigation of behavior at fretting fatigue of the Ti-6Al-4V alloy, both under annealing conditions after fretting, and solution-treated and over-aged. He used a ball-on-flat device for fretting fatigue that facilitated a real-time control and monitorization of all relevant parameters such as contact geometry, contact loadings (normal and tangential) and bulk effort.

L. Capitanu et al., [18-20], conducted an analysis of the cyclical variations of the friction forces and of the contact stresses during fretting fatigue, highlighting the influence of mechanical and surface factors on fretting fatigue. They have shown that stress analyzes in solid state mechanics involve a particular structure with a given geometry made for a particular material whose elastic properties are known (Young’s modulus and Poisson’s coefficient). The structure is externally stressed by forces and / or moments and is connected in some form with the environment. The objective of an effort analysis is to determine the stress and forces fields in the structure to see if the structure gives rise to excessive deformatons or stresses that can cause mechanical failure. The effort analysis can be done either numerically or by mathematical solutions. In the first case a simulated computer model is used, for example the finite element method. The stress analysis can be done either numerically or by mathematical solutions. In the first case a simulated computer model is used, for example the finite element method. In the second case, the solution is obtained by explicit mathematical formulas. These close shapes solutions are only available for particular structures, with regular shapes, such as prismatic bars and beams. Forces acting on the surface of a structure can be determined experimentally either directly from measurements or indirectly using a laboratory model. The stresses state of the prosthesis state is fully described by six effort components. All in all, this effort state is known as an effort tensor. Although the components may vary with the specific coordinates system chosen, the effort state remains the same. In other words, the effort state along an object does not depend on a specific coordinates system chosen. It depends only on load, geometry and material properties. The simplest representation of the effort state is in the main coordinates system and by three main components of the normal effort. Bone/ prostheses structures often require information about the “interface” loadings where the different materials are connected. These interfaces are not always aligned with the external coordinate system, nor do they generally align with the main directions of loading [20]. For this purpose, a local coordinate system can be introduced relative to the point of interest, against which the normal interface and the shear loads are expressed. The three loading representation methods (coordinates, main stresses and at interface) are illustrated in Figure 5 (a), for a two-dimensional example, in which a presents the main stresses (σ₁, σ₂) in the principal direction α, relative to the x - y coordinate system; (b) the effort components (σx, σy and τ) in the x – y coordinates system; (c) the effort components (σx and τ) normal and parallel to a chosen surface, for example an interface with a β - orientation with respect to the y -axis. Figure 5(b) shows the distribution of the stretching and compression stresses, and Figure 5(c) illustrates shear stresses at the stem / cement interface for a cemented THA stem simulated by a FE model.
The limit stress (or elastic limit) of a material is typically measured by uniaxial compression and traction tests or shear tests on simple geometries material samples. The question is how to link a calculated 2D or 3D state of effort, characterized by six components, to those resulting from the uniaxial tests, in the idea of estimating the probability of failure. For this purpose, it is necessary to calculate an equivalent (or actual) effort by using a particular resistance criterion. For example, the von Mises resistance criterion assumes that the material will yield (plastic deformation) when the distortion energy will increase for a certain value. The von Mises effort can be calculated from the equation:

\[ \sigma_m = \sqrt{\left(\frac{1}{2}(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2\right)^2} \tag{1} \]

where \( \sigma_1, \sigma_2, \) and \( \sigma_3 \) are the main stresses at the point of interest in the material.

These values of von Mises equivalent stress can be simply compared with the failure requests values obtained from samples of the same material, tested in the laboratory for stretching or uniaxial compression to estimate the probability of failure. They give reasonable predictions for isotropic materials. For elastic anisotropic materials (such as bone) or for viscoelastic materials, they are less satisfactory. However, they are often used for these materials.

Deformation energy density also represents the deformation state of a material but was not directly related to a failure criterion. This quantity can be calculated using the following formula:

\[ U = \frac{1}{2}(\varepsilon_1\sigma_1 + \varepsilon_2\sigma_2 + \varepsilon_3\sigma_3) \tag{2} \]

where \( \varepsilon_1, \varepsilon_2, \varepsilon_3, \sigma_1, \sigma_2, \) and \( \sigma_3 \) are the specific deformations and the main stresses, respectively.

This formula is valid only for isotropic materials, where the directions of the main forces and of the main stresses are parallel. The function of the deformation energy density is commonly used to formulate the constitutive equations of nonlinear elasticity. It is also used in the theory of adaptive bone remodeling on request (F.J. Schoen and A.S. Hoffman [21]).

Dominguez (1998) [17] used a fretting testing device involving the application of fluctuating axial loads on specimens previously loaded to compression by contact elements. The elements are joined by a counterpressure bridge that maintains a fixed distance between them, or by a supporting structure (Figure 6).
Determination of the stresses produced by the fretting process requires to establish the relationship between the forces $F$ and $P$ during the loading cycles ($P$ being the axial force to which the sample is subjected, and $F$ is the friction force resulting from the movement that appears due to the action of the axial force $P$). Two different conditions for the normal force $N$, between the contact surfaces: constant or proportional to $P$, were taken into consideration. The limit values of the friction force $F$ ($F_{\text{max}}$ and $F_{\text{min}}$) and the change of their phase and for $P$ were determined under different loading conditions, as well as their potential effects on fatigue damage. Dominguez hypothesized the presence of a $P_c$ limit of the load, independent of $N$, beyond which sliding occurs, provided that $N$ is proportional to $P$. This would mean that beyond a limit value of the normal $N$ load, an increase in it will not produce any increase in $F$. A hypothesis accepted almost unanimously (Fadag et al., 2005 [24]) assumes that if at a constant normal force $N$, the amplitude of the cyclic charge $P$ increases gradually, then the amplitude of force $F$ increases, up to a maximum value at which occurs the sliding. Beyond this point, increasing the amplitude of the axial load does not increase $F$, and if it exists, it will decrease slightly. If the previous hypothesis is assumed to be true, then the $F$ force amplitude diagrams according to $P$ at different apertures of the bridge and at different normal forces $N$ indicate that the slide starts at approximately constant $F/N$ ratio values. That is, the value of the friction coefficient $\mu$ at the beginning of the sliding is approximately constant and independent of $N$ and $P$. This contradicts the hypothesis that there is that $P_c$ load mentioned above. If the assumption made is supported or not for the flat, cylindrical and spherical contact surfaces, it is more correct to assume that the sliding will occur when $F$ is equal to $\mu N$, $\mu$ being $N$ and $P$ dependent.

In the case where $N$ is proportional to $P$ ($N = \eta P$, with $\eta$ constant), the friction forces change by the effect of loading cycles $P$ in a sample with fretting contact with a bridge and a point (Figure 6). For a $P$ load, which grew from zero, it was concluded that if sliding does or does not occur, it depends on the relationship between $\eta$ and $\mu$. Figure 6 shows two points A and B (one on each surface), located in the area that begins to slide just before the start of the global slide. In the hypothesis of a linear behavior before the global slide, the displacement of point A ($A\delta_A$) in response to a $\Delta P$ increment of the force increase, can be expressed as

$$\delta_A = C \cdot \Delta P$$  

(3)

where $C$ is the conformation of the sample – pad couple, and $\Delta P$ is an incremental increase of the axial load that does not produce a global sliding.

The contact surfaces shall be subjected to a friction force $F \leq \mu N$ and the displacement of the B point may be expressed as

$$\Delta \delta_B = D \cdot \Delta F$$  

(4)

where $D$ is the compliance of the fretting bridge.

Previous equations are used below to analyze two different cases of $P$ load changes, namely, monotonous increase from zero, and the application of a cyclic load with the start of the loading sequence from zero.

### 3.2.1 Monotonous increase from zero

In the absence of sliding, $A\delta_B$ will be identical to $A\delta_A$ so that Eqs. (5) and (6) will lead to

$$\Delta F = \frac{C}{D} \cdot \Delta P$$  

(5)
where \( C/D \) can be experimentally determined during the loading process, before the sliding begins.

In the presence of sliding, the \( \Delta \delta_A \) will be higher than \( \Delta \delta_B \). If this occurs, the changes of \( F \) and \( \delta_B \) can be expressed as

\[
\Delta F = \mu \eta \Delta F \tag{6}
\]

\[
\Delta \delta_B = D \mu \eta \Delta P = k \Delta P \tag{7}
\]

where \( k/D \) can be experimentally determined as the ratio of \( \Delta F \) and \( \Delta P \) during sliding.

The displacement of \( A \) during sliding will be given by

\[
\Delta \delta_B > \Delta P \tag{8}
\]

because the friction force, which opposes to \( P \) and therefore the displacement of the point \( A \), will be smaller than in the absence of the sliding, in which case Eq. (5) will be supported.

He analyzed the monotonous increase from zero. If \( P \) increases from zero, global sliding will occur if

\[
\frac{C}{D} > \mu \eta \tag{9}
\]

namely if

\[
\frac{C}{k} > 1 \tag{10}
\]

If \( C/k < 1 \), then no sliding will occur while the load increases from zero. When \( C/D \) exceeds \( \mu \eta \), in which case \( \Delta F \) will be given by Eq. (8), and the sliding will occur throughout the whole incremental increase range of the load, and when \( C/D \) is smaller, no sliding will occur at any moment and \( \Delta F \) will be given by Eq. (5).

### 3.2.2 Cycling loading

If \( C/k < 1 \), \( i \) being the time of the first increase of loading from \( P = 0 \), there is no sliding. Also, assuming that the minimum number of subsequent cycles will always be greater than zero, no sliding is observed during unloading. When \( C/k > 1 \), a load will cause the friction forces to evolve according to the axial force \( P \), \( P_{\text{max}} = P \), being obtained by

\[
F_{\text{max}} = F_N = \mu \eta P_{\text{max}} \tag{11}
\]

During unloading, the sliding will occur if the variation is of the type

\[
- \mu \eta P_{\text{min}} > \mu \eta P_{\text{max}} - \frac{C}{D} (P_{\text{max}} - P_{\text{min}}) \tag{12}
\]

which can be written as

\[
C \Delta P > k (P_{\text{max}} + P_{\text{min}}) \tag{13}
\]

or

\[
\frac{1 - R_p}{1 + R_p} > \frac{k}{C} \tag{14}
\]

Typically, many fretting fatigue tests are performed involving friction bridges subjected to a constant normal force \( N \). Under these loading conditions and provided that no global sliding occurs at any time, the friction forces \( F \) will not be in phase with the \( P \) loads applied on the sample. But even if the friction force \( F \) and the axial force \( P \) are in phase, the stresses that occur near the contact surfaces will be out of phase.
As a result, in the case of spherical contact between two elements of the same material, the effort changes are examined at different points of the contact surface and in its vicinity. Before that, a brief description of the process used to calculate the effort is included. The analysis is based on the results of contact pressure distribution on spherical surfaces, at normal loads and transverse loads, in the presence of global sliding and partial sliding. The result is the evolution of the tangential traction distribution on the contact, at different laws of variation of the friction force \( F \) and the normal force \( N \). When two spherical surfaces are in contact under a normal force \( N \) (Figure 6) they are subjected to a tangential force \( F < \mu N \) in the BA area, which has the ring shape on the contact area.

The \( A_{B-B} \) central area is an area where the surfaces will not slide,

\[
A_{B-B} = \frac{b}{a} \left( 1 - \frac{F}{\mu N} \right)^{\frac{1}{3}}
\]

and where the tangential traction forces can be represented by the equations

\[
\tau_1 = \frac{3 \mu N}{2 \pi a^3} (a^2 - \rho^2)\sqrt[3]{\frac{a^2}{(a^2 - \rho^2)}} = \mu \sigma_{xy} ; \quad b \leq \rho < a
\]

\[
\tau_2 = \frac{3 \mu N}{2 \pi a^3} \left[ (a^2 - \rho^2)\sqrt{\frac{a^2}{(a^2 - \rho^2)}} - (b^2 - \rho^2)\sqrt{\frac{b^2}{(b^2 - \rho^2)}} \right] ; \quad \rho \leq b
\]

### 3.3 Influence of the roughness on the initiation of the fretting fatigue scar of the Ti-6Al-4V alloy

Fretting is a phenomenon where at the interface there is a complex interaction between wear, corrosion and fatigue. Thus, this phenomenon involves many aspects of contact mechanics, multiaxial fatigue, tribology, and materials science. Directly or indirectly, the damage produced by fretting fatigue is caused by several factors and variables such as the relative displacement amplitude, the normal load, the tangential and axial loads, the nature of the material, the friction coefficient, the cyclic frequency, the temperature and the environment, as well as material factors such as roughness and hardness. All these factors are interdependent variables that influence this phenomenon.

Using the specimen and pad geometries, which are shown in Figure 7, fatigue fretting tests were performed which could surprise the occurrence of fretting scar, in the precursor stage of initiation and propagation of the fretting crack. Test sample – Figure 7(a) has a special shape, with two flat opposite faces, milled, in the middle of the sample, rectified and polished. A cylindrical seat (A) with diameter of 10.1 mm and depth of 2.5 mm was practiced in the middle of these faces. In this seat the fretting sample was introduced – Figure 7(b). This was done to study the influence of the surfaces roughness in contact (pad – sample) on durability to fretting. The spherical head of the pads Figure 7(c) was polished up to a roughness of 0.05 μm. Prior to testing, the samples surfaces and pads surfaces were ultrasonically cleaned in alcohol.

![Figure 7: Geometry of the specimen, sample and fretting test pad.](image)

Test sample – Figure 7(a) has a special shape, with two flat opposite faces, milled, in the middle of the sample, rectified and polished. A cylindrical seat (A) with diameter of 10.1 mm and depth of 2.5 mm was practiced in the middle of these faces. In this seat the fretting sample was introduced– Figure 7(b). This was done to study the influence of the surfaces roughness in contact (pad – sample) on durability to fretting. The spherical head of the pads Figure 7(c) was polished up to a roughness of 0.05 μm. Prior to testing, the samples surfaces and pads surfaces were ultrasonically cleaned in alcohol.

Figure 8 schematically shows the configuration of the sample-pad test in the case of fretting fatigue tests.
The two pads were pressed perpendicular to the flat faces of the sample by a pair of compression springs, which are loaded with adjustable screws. Also, two vertical compression springs acting on the pad are used to apply the pre-tangential loading (to avoid the pads’ movement). In the cylindrical seats of the specimen, the fretting samples were inserted. This was done in order to study the roughness influence of surfaces in contact, about the durability at fretting. Several pads and fretting samples were produced, which were finished at the roughnesses of $R_a = 0.015 \text{ μm}$ with profile A1 and surface image A2, respectively $R_a = 0.045 \text{ μm}$ (A3-A4), $R_a = 0.075 \text{ μm}$ (A5-A6) and $R_a = 0.19 \text{ μm}$ (A7-A8) shown in Figure 9.

Under static conditions, the compressive stresses due to contact point, $p_{\text{max}}$ and $p_{\text{med}}$ (maximum and average contact pressure) are given by:

$$p_{\text{max}}^3 = 1.5PE^2 / \pi a^2 \left(1-\mu^2\right)^2$$ (18)

$$p_{\text{med}} = \frac{P}{\pi a^2}$$ (19)

while the radius $a$ of the circular contact surface is:

$$a^3 = 1.5\left(1-\mu^2\right)P \frac{r}{E}$$ (20)

where $P$ is the load; $a$ is radius of the contact surface and $r$ the radius of the spherical head of the fretting pad. For coupling components made of steel, the values of the previous equations become:

$$p_{\text{max}} \approx 5800\sqrt{P}$$ (21)
Further details on the finishing of the specimen friction surfaces are given in (L. Capitanu et al., 2017a and L. Capitanu et al., 2017b).

After the super-finishing stage, the four different mentioned roughness values were obtained ($R_a = 0.015 \, \mu m$, $R_a = 0.045 \, \mu m$, $R_a = 0.075 \, \mu m$ and $R_a = 0.190 \, \mu m$) for Ti-6Al-4V samples surfaces. Surfaces roughness was determined using a profilometer with parametric transducer and graphical recording, Perth-O-Meter.

The tool allows not only the recording of surface profiles, but also the determination of the $R_a$ and $r.m.s$ values, defined as:

$$R_a = \frac{1}{l} \int_0^l y \, dx$$

(24)

$$r \cdot m \cdot s = \sqrt{\frac{1}{l} \int_0^l y^2 \, dx}$$

(25)

The tests mainly followed the evolution of the fretting scar according to the normal load applied under different roughness conditions of the surface and normal loading, but at constant tangential loading. Details about the tests performed under lubrication conditions with SBF (simulated body fluid) from Hyclone Inc., USA, were presented in L. Capitanu et al., 2017c).

To observe in good condition the wear of the fixed surface according to the roughness of the coupling, the following solution was used: the coupling asperities were concentrated on one of the surfaces, especially the mobile one. The fixed surface has always had the minimum achievable roughness, i.e. approximately $R_a \approx 0.015 \, \mu m$. As it is known, the composite roughness of the coupling, expressed by standard deviations, $\sigma$ is $\sigma^2 = \sigma_1^2 + \sigma_2^2$, where $\sigma_1$, $\sigma_2$ represent the standard deviations of the two surfaces.

If one of the surfaces has a much smaller roughness, i.e. $\sigma_1 \ll \sigma_2$, then $\sigma \approx \sigma_1$. Thus it is possible to study the influence of roughness on wear, even by changing the roughness of a single surface. In these conditions and under a load $P = 30 \, N$, the relative velocity $u = 1.74 \, m/s$ and at the temperature $\theta = 50 \, ^{\circ}C$ of the lubricant volume, the evolution of the surface wear was determined in function of time, for the roughness of the specimen surface mentioned above.

3.3.1 Evolution of the contact surface state in fretting conditions

The consequence of fretting is the fretting scar that forms in the area of the contact between pad and sample and which can evolve from initiating the fretting scar, appearance and propagation in time of the fretting crack, until the break of the sample. The initiation phase takes almost 80% of the coupling’s runtime. To estimate the reproducibility of the results, some fretting wear scars obtained under the above-mentioned conditions (at time $t = 5 \, min$) are selectively presented in Figure 10.

![A9](image1.png)

![A11](image2.png)

![A13](image3.png)
Figure 10 Central transversal profile and image of fretting wear scar. $R_a = 0.015 \mu m$, $t = 5$ min.

The scar volume for the three experimental determinations is: 1057 specimen: $V = 8.50 \times 10^{-5}$ mm$^3$; 1058 specimen: $V = 6.11 \times 10^{-5}$ mm$^3$; 1059 specimen: $V = 4.00 \times 10^{-5}$ mm$^3$, resulting an average volume $\bar{V} = 6.2 \times 10^{-5}$ mm$^3$. For wear measurements, a deviation of 2.5% is completely satisfactory.

Figure 11 shows the evolution of the wear depending on time, for the roughness $R_a = 0.045 \mu m$ of the pad. Trial times of 3 s, 30 s, 1 min and 5 min were selected, each realized with a new coupling.

For the roughness $R_a = 0.045 \mu m$, the evolution of wear versus time was determined with the same pad, the total fretting time on the scar being divided in intervals of 1 minute (A17), 3 minutes (A19), 5 minutes (A21) or 10 minutes (A23). This solution was chosen to also monitor the change of the pad surface state. In Figure 12 is shown the transversal profile and the image of the fretting wear scar for the sample with $R_a = 0.045 \mu m$, $t = 5$ min (sample 703); $R_a = 0.045 \mu m$, $t = 5$ min, but with the buffer from the previous determination (total operating time $t = 10$ min, sample 704); $R_a = 0.045 \mu m$, $t = 5$ min, with the pad from the previous test (total operating time $t = 20$ min, sample 705).
Figure 12 Profile and image of wear scar for samples with $R_a = 0.045\ \mu m$, $t = 5\ \text{min.}$ (sample 703); $R_a = 0.045\ \mu m$, $t = 5\ \text{min.}$, but the fretting pad from the previous determination (total running in time $t = 10\ \text{min.}$ (sample 704); $R_a = 0.045\ \mu m$, $t = 5\ \text{min.}$, but the pad from the previous determination - total running time $t = 20\ \text{min.}$ (sample 705).

The evolution of fretting wear depending on time for different roughnesses is presented in the double-logarithmic diagram in Figure 13.

By increasing the operating time from 5 minutes to 30 minutes, the wear increases by only about 10%. It is worth noting the rapid reduction of the wear velocity over time, excepting the surface with roughness $R_a = 0.045\ \mu m$. In the first 3 seconds, here produces between 25% and 50% of the wear in 30 minutes. This evolution of the wear is explained by the surfaces running, which leads to a change in the lubrication regime (in the first few seconds of operation). This observation allows the use of the wear value at $t = 5\ \text{min}$ as a representative quantity for the used operating conditions. During this operation period, the values scattering is small. In the case of surfaces with $R_a = 0.045\ \mu m$, the wear is so low that during the entire period of time used, the lubrication conditions remain roughly unchanged.

The evolution of the fretting wear function of time, for roughness $R_a = 0.075\ \mu m$ (samples 829, 830 and 832) is shown in Figure 14.
Different roughnesses used have caused not only a difference of the volume of the wear scar, but also, of its appearance (wear type). In the case of the surfaces with $R_a = 0.015 \, \mu m$, $R_a = 0.075 \, \mu m$ and $R_a = 0.19 \, \mu m$ at $t = 3 \, s$, the wear is of adhesive type (metallic shape with pronounced scratches). In the case of surfaces with $R_a = 0.045 \, \mu m$, the fretting wear is predominantly oxidative. While the fretting wear velocity is reduced due to surface conformation, the surfaces with $R_a = 0.015 \, \mu m$, $R_a = 0.075 \, \mu m$ and $R_a = 0.19 \, \mu m$ also undergo in oxidative wear regime. The evolution of the fretting wear scar function of time, for roughness $R_a = 0.19 \, \mu m$ (samples 835, 849, 836, 837 and 850) is shown in Figure 15.
Figure 15 Fretting wear evolution function of time, for roughness $R_a = 0.19 \, \mu m$ (samples 835, 849, 836, 837 and 850).

For the roughnesses $R_a = 0.015 \, \mu m$, $R_a = 0.075 \, \mu m$ and $R_a = 0.19 \, \mu m$, the results obtained for the volume of the worn material are in accordance with the contact deformation, determined by the parameter of the lubricant film $h_{min} / \sigma$. An influence of the running-in was observed for surfaces with roughness $R_a = 0.045 \, \mu m$. After the first 5 minutes of operation, the entire contact surface is covered with oxide. The scar obtained after another 5 minutes, with the same pad, has a special shape, the oxidative wear area is limited to half of the loaded surface (samples 835 - A52 and 849 - A54).

Figure 16 shows the central profile and the image of the fretting wear scar from the surface with $R_a = 0.15 \, \mu m$, $t = 30$ min, sample 997 (new pad).

Figure 16 Central transversal profile and image of wear scar, $R_a = 0.15 \, \mu m$, $t = 30$ min., sample 997, (new pad).
Next, Figure 17 shows the effect of the running-in on the fretting wear behaviour of the surface with $R_a = 0.15 \mu m$ (sample 998), with the same pad as in the previous test, $R_a = 0.015 \mu m$.

![Figure 17](image)

**Figure 17** The effect of running-in on the fretting wear behaviour of the surface with $R_a = 0.015 \mu m$, $t = 5 \text{ min}$, sample 998. The bush from previous determination was used.

Under the experimental conditions of Figures 16 and 17, it is clearly observed the start of the stretching of the fretting scars (from top to bottom, A62 and A64), as well as the typical W-shape of the cross-section profile of the scar, form noted in many of the papers published in the field (Dominguez, 1998, L. Capitanu et al, 2017 c).

Different roughnesses used have caused not only a difference between the values of the fretting worn volume, but also of the wear scar appearance (type of wear). In the case of surfaces with $R_a = 0.015 \mu m$, $R_a = 0.075 \mu m$ ($t = 3 \text{ s}$) and $R_a = 0.19 \mu m$ ($t = 3 \text{ s}$), the wear is of adhesive type (metallic shape with pronounced notches). In the case of surfaces with $R_a = 0.045 \mu m$, the predominant type of wear is the oxidative one. While the wear velocity is reduced as a result of the surface conformation, surfaces with $R_a = 0.075 \mu m$ and $R_a = 0.19 \mu m$ also function under oxidative wear regime.

In the case of super-finished surfaces with $R_a = 0.015 \mu m$ no favorable influence of the running-in is observed. For the surfaces with roughnesses of $R_a = 0.045 \mu m$, a favorable influence of the running-in was observed (Figure 18).
3.3.2 Influence of the initial roughness of the sample on the fretting wear and friction coefficient

The minimum value of the surface wear should coincide with the minimum value of the surface roughness. A large number of wear measurements were performed on the four roughnesses: \( R_a = 0.015 \, \mu m; \) \( R_a = 0.045 \, \mu m; \) \( R_a = 0.075 \, \mu m \) and \( R_a = 0.19 \, \mu m. \) Simultaneously with the production of fretting scars on the surface of Ti-6Al-4V alloy samples, the coefficient of friction was also measured. The average values of the volume of fretting scar (worn material) and of the friction coefficient for the four roughnesses are:

\[
R_a = 0.015 \, \mu m \rightarrow V_u = 7.0 \times 10^{-5} \, mm^3 \rightarrow \mu = 0.038;
\]
\[
R_a = 0.045 \, \mu m \rightarrow V_u = 7.0 \times 10^{-6} \, mm^3 \rightarrow \mu = 0.050;
\]
\[
R_a = 0.075 \, \mu m \rightarrow V_u = 3.7 \times 10^{-5} \, mm^3 \rightarrow \mu = 0.058;
\]
\[
R_a = 0.190 \, \mu m \rightarrow V_u = 1.0 \times 10^{-4} \, mm^3 \rightarrow \mu = 0.078.
\]

The effect of the running-in on the fretting wear behavior of the surface was also analyzed. This was done by using the same pad for several successive tests. In Figure 19 are shown representative images of the running-in effect on the fretting wear behavior of the surface – with the pad from the previous determination, for three of the four roughnesses (samples 1077 – A76, 1065 – A80 and 1067 – A82).
The existence of an optimal roughness could be explained either by an effect on the lubricant film or by a change in the mechanical properties of the surface. In this case, at the optimum roughness, the reduction of the $h / \sigma$ ratio is compensated by increasing the wear resistance of the surfaces.

3.4 Manifestation of the fretting at the conical junction of the femoral head with the prosthesis stem trunion

As specified in Section 1, in the case of modular total hip prostheses, the fretting also manifests in the conical junction between the femoral head and the femoral stem trunion. The methodology described in Duisabeau et al., 2004, and Kim et al., 2013, allows the implementation of Archard's wear law or "dissipated energy" 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 races (from 50 mm to 1.3 mm) than in Archard's law, and it does not has a wide application field. Wear energy law Eq. (26) is the basis for the calculation of the volumetric wear, where the interfacial shearing work is the predominant parameter for the wear determination. It shows that the total volumetric wear $W_v$ is obtained from the product of the total local accumulated dissipated energy $E$ and a wear energy coefficient $\alpha$, as follow:

$$W_v = \alpha E$$  \hspace{1cm} (26)

where

$$E = Qs$$  \hspace{1cm} (27)

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

$$W_v = \alpha Qs$$  \hspace{1cm} (28)

Dividing both sides of Eq. (28) by the contact area, the depth of linear wear $W_d$ can be calculated using Eq. (29), where $\tau$ is the shear stress of the contact surface

$$W_d = \alpha \tau s$$  \hspace{1cm} (29)

The process used for the numerical implementation of this wear law is first of all to determine the depth of wear of contact surfaces generated on components of a single loading cycle. Subsequently, if the components will be, as usual, the object of millions of loading cycles during their lifetime, this one-cycle wear depth is multiplied by a $\beta$ - wear scaling factor so that to realize an analysis that gives the scar that is obtained within an acceptable time period. The "wear scaling" factor represents a certain number of loading cycles (eg, $10^5$) and its value depends on how accurately the evolution of wear is calculated and how it evolves over time. After measuring the wear depth, the contact surfaces geometry of the components is then modified to reflect the wear that would have occurred during $\beta$ cycles. Calculated wear can only be applied to one or both components in equal or unequal proportions, depending on the combinations of the materials in contact. The process is then repeated using the updated geometry up to a specified number of loading cycles that have been applied, or until a pre-determined wear depth has been reached.
To accurately model the effect of wear on the variable loading distribution over time during a loading cycle (as it appears during the walking), it is necessary to mesh a loading cycle in a number of time intervals, \( n \). As such, the wear depth for a single loading cycle (\( W_c \) cyclic wear depth) can be calculated using Eq. (30), in which \( \alpha \) and \( \beta \) are the shear stress of the surface and the relative displacement, respectively, calculated at the end of a specific time interval \( i \).

\[
W_c = \sum_{i=1}^{n} \alpha \tau_i s_i
\]  

(30)

The total wear depth \( W_d \), generated in a specified total number of loading cycles \( N \), can be determined from Eq. (31), where \( j \) represents the specific "analysis stage", reflecting the evolution of wear.

\[
W_c = \sum_{j=1}^{N} \beta \sum_{i=1}^{n} \alpha \tau_i s_i
\]  

(31)

The accuracy and effectiveness of this approach depends on many factors, not at least on the magnitude of the used wear energy coefficient \( \alpha \). In addition, the number of time intervals \( i \) used to discretize the loading cycle, as well as the size of the "wear scaling factor" \( \beta \) require a careful analysis of their influence on the accuracy and runtime of the analysis.

The authors detailed a little bit about the problem of fretting at the conical junction of the femoral head – femoral head, because this appearance is very obvious on the conical junction of the femoral stems recovered from the recovery surgery, but they will not return to it in this paper.

4. CONCLUSION

This paper was designed to provide a picture of the complexity of fretting phenomena commonly manifested in hip total prostheses, is a review based on four papers published on the phenomenon of fretting, as follows:

- Stability loss of the hip prosthesis stem due to the fretting corrosion;
- Analysis of the friction and contact stress during the fretting fatigue;
- Influence of the roughness on the initiation of the fretting fatigue scar of the Ti-6Al-4V alloy.
- Manifestation of the fretting at the conical junction of the femoral head with the prosthesis stem.

Reitering on the analysis of friction and contact stress analysis during the fretting fatigue [18], the following conclusions are obtained.

(a) Depending on the special geometry under fretting and predominant load levels, the external and friction loads can be out of phase. This phase change was analyzed for the case when normal force \( N \) is proportional to axial force \( P \) and was obtained the F/N ratio, as a function of model conformity and the fretting bridge.

(b) During a loading cycle of the friction forces, out of phase not only uploads change, but also the efforts \( \tau_{zx} \) and \( \sigma_{xy} \) in points on the contact area and even close to the bottom, even when the loads are in phase. The change can be quite significant, depending on the point considered and the loading parameters.

(c) It has been verified that with the spherical contact under low amplitude, at the global slipping associated with the axial loads applied to the specimen, the effort cycles amplitude depends on the slipping amplitude relative to the size of the contact area. The field of von Mises equivalent effort will shorten the increase of relative cyclical movement.

(d) As a result, determining the fatigue life of an item under fretting, requires not only the knowledge of minimum and maximum efforts produced by each type of load involved (normal to surface, of friction, axial), but also of the way in which exchanges between them. This process involves the simulation of a loading process cycle and determination of the effort behavior during that cycle.

Reitering to the trunion fretting and wear of the stem of total hip prosthesis and its influence on the prosthesis stability, was briefly presented the fretting and wear produced during the functioning of the total hip prosthesis at the conical junction of the femoral head fixation on the femoral stem spindle. The two stages of femoral head fitting on the femoral stem spindle (impact and elastic relaxation), as well as the evolution of the fretting phenomenon during a loading cycle, and the slow relative movement of the femoral head, have been highlighted. The qualitative findings confirmed the results in specialized literature obtained by FEM of the nodal sliding. Although this problem is reported very little in literature, it is very important, constituting a "hidden enemy" of the stability of the total hip prostheses. This study encompasses the image of the fretting phenomenon that occurs between the cement mantle and the femoral stem of the cemented hip prosthesis.

References


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