THE INFLUENCE OF TEXTURED SURFACES ON THE LUBRICATION OF ARTIFICIAL JOINT PROSTHESES

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Abstract: The development of artificial joint prostheses is an especially relevant advance linked to the combined use of medical and engineering sciences. In ideal conditions a joint prosthesis should last the whole patient's life. For a younger patient, that is normally linked to using enhanced designs capable of reducing friction and wear rate, thus increasing patient's comfort and prosthesis service life. Present study concentrates on validating the use of micro-textured surfaces for improving friction and minimizing wear rate by means of increasing the (elasto) hydrodynamic lubrication range. Micro-textured surfaces have been obtained by UV-photolithography upon photosensible films and subsequent chemical etching of the uncoated surface zones. A ball-plane contact tribometer has been used to assess the friction coefficient of the different micro-textured surfaces in order to validate our approach. Significant reductions of friction coefficient have been obtained thanks to the micro-textures, what provides useful information for computer-aided design & manufacturing processes linked to the development of innovative and efficient biomimetic prostheses.

1 INTRODUCTION

Synovial joints allow the relative movement between bones of the human body. They operate in a similar way as bearings, reducing friction and wear in the contact. Typical examples of such joints are that of the hip, knees, shoulders and phalanges of the fingers. Figure 1 shows a schematic illustration (Bergmann, 2010).

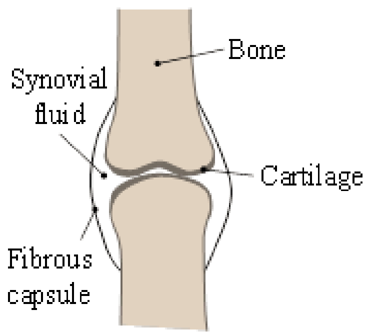

Figure 1: Outline of a synovial joint.

As shown in Figure 1, the two bones, with relative movement, are separated by a cartilage and a synovial fluid that lubricates the contact. In order to avoid the loss of lubricant, a fibrous capsule covers the joint. By means of this configuration, friction coefficients attained in the joints vary from 0.005 to 0.025, depending on the age and physical conditions of the patient (Gohar, 2008).

As time goes by, likewise in case of lesion or disease, joints can present inflammations or wear, i.e. arthritis. Therefore, characteristic consequences may arise: movement constraint, joint swelling, trembling, pain, progressive strength loss and deformity of the body part affected (Dumbleton, 1981). These symptoms can become very annoying and dramatically reduce life-quality of the sufferer.

When neither rehabilitation nor medication can mitigate the arthritis symptoms, damaged joint is generally replaced by an artificial prosthesis. Most artificial joint prostheses present two main parts, each of them placed in one of the two bones of the joint.

Relative movement is allowed between them, sometimes including an additional intermediate part for improving contact phenomena. The types of contacting materials used for prostheses are very diverse: ceramic, polymeric, metallic and their

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combinations (Pinchuk, 2006). The most usual selection is a quasi-spherical metallic element (stainless steel, Co-Cr-Mo, Co-Ni-Cr-Mo or Ti alloys, in many cases with ceramic coatings) housed in a plastic element (mainly ultra-high-molecular-weight polyethylene or UHMWPE). Prostheses must operate under very variable conditions (from static conditions to very high sliding velocities) and in such a delicate environment like the human body.

Therefore, good friction behavior and wear resistance are required with the aim of avoiding the need to substitute them, i.e. life of the prostheses is expected to be longer than that of the patient.

2 LUBRICATION IN PROSTHESES AND JOINTS

In mechanical systems three main lubrication regimes are distinguished: boundary, mixed and elasto(hydrodynamic)-EHL. The friction coefficient and wear under each regime are very different, as shown in Stribeck's curve (Figure 2).

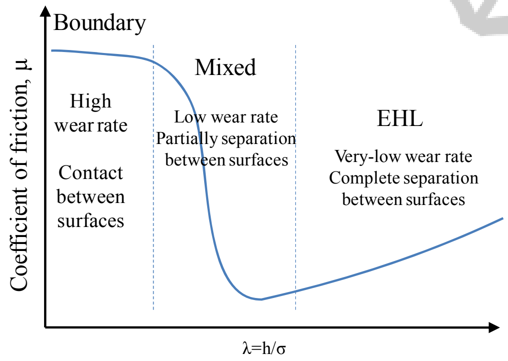

Figure 2: Different lubrication regimes in Stribeck's curve.

The differences among regimes are given by the specific film-thickness parameter (λ), which provides the relation between the lubricant film-thickness (h) and the combined roughness of both surfaces (σ), see Eq. 1. When $\lambda>3$ a complete separation between surfaces is attained and therefore EHL regime prevails. When $1<\lambda<3$ the separation is partial and mixed lubrication is assumed. Finally, when $\lambda<1$, the contact works under boundary lubrication regime (Stachowiak, 2005).

$$\lambda = \frac{h}{\sigma} \qquad (1)$$

In most working conditions, joints operate under mixed lubrication, where the separation between contacting surfaces is incomplete. Thus, low friction coefficients are obtained due to the composition of synovial fluid: including a liberation and accumulation of glycoproteins and hyaluronic acid within the cartilage interstices when the joint is submitted to pressure (Gohar, 2008).

In the case of artificial joint prostheses, the accumulation of synovial fluid is much more complex, as they are manufactured with very low surface roughness (10 – 50 nm), what stands for a specular finish on both contact surfaces. Such extremely low roughness promotes a positive increase of lubricant film thickness for low sliding velocities.

However a polished surface cannot effectively retain lubricant and important adhesion and wear problems appear at rest or at the beginning of movement, as the contact is almost dry in such conditions.

3 SURFACE MICRO-TEXTURIZATION

3.1 Expected Benefits of Micro-texturization

The main objective for introducing micro-textures on the contact surfaces of artificial joint prostheses is to fulfill the need of retaining synovial fluid at very low velocities. At the same time low surface roughness is maintained, what allows for a complete lubrication regime in such conditions.

Hence a lower friction coefficient is expected for the whole functioning range and wear rate of prostheses can be minimized and debris particle formation can also be importantly reduced (Kennedy, 2000). In addition the presence of micro-textures somehow imitates nature and promotes tissue formation and biointegration of the prostheses (Díaz Lantada, 2010).

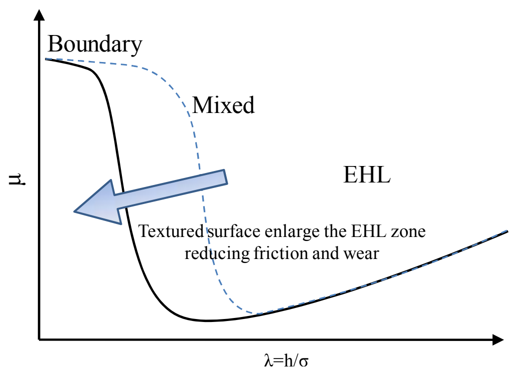

Figure 3: Improvement in Stribeck curve thanks to the use of micro-textured surfaces.

The expected effects upon Stribeck curve (as shown in Figure 2) are schematically described in Figure 3, showing a beneficial reduction of friction thanks to the presence of micro-textures (Petterson, 2003, Wakuda, 2003).

3.2 Micro-texture Design

Computer-aided design (CAD) tools have been used for the design of micro-texturization patterns, so that the characteristics of the textures could be controlled and modified in an easy way. A texturization pattern based on the repetition of circular features, with diameter (ϕ) and surface density (d) as main control parameters (see Eq. 2), has been used for our validation..

$$d(\%) = \frac{\pi\phi^2}{4l^2}\cdot 100 \qquad (2)$$

Figure 4 provides an example of one of the micro-textured surfaces obtained by following the manufacture process explained further on. Main parameters are also included (in this case ϕ = 400 µm and l = 1.12 mm).

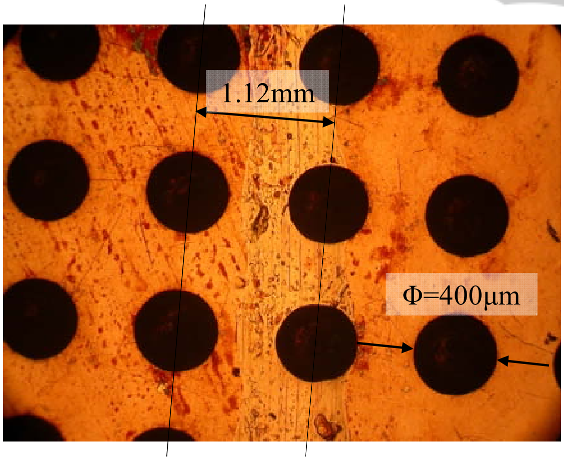

Figure 4: Final textured surface.

Feature diameter was selected using as reference the hertzian contact radius (a), Eq. 3, for a ball-plane contact (Echavarri, 2011), as a ball-plane contact tribometer was applied for analyzing the influence of micro-texturization on friction coefficient (see trials and results section).

The contact radius depends on the load (W), on the equivalent contact radius (R*) and on the reduced Young modulus (E´). In this study three different diameters have been used, one below, one similar and one above estimated contact diameter: 100, 200 and 400 µm. Surface densities of 10% and 25% have been studied in combination with the aforementioned radii.

$$p_0 = \frac{3W}{2\pi a^2} \qquad a = \sqrt[3]{\frac{3WR^*}{2E'}} \qquad (3)$$

3.3 Micro-texture Manufacture

In this work we have used copper discs as substrate material for studying the effect of micro-texturization on friction coefficient. Micro rapid prototyping technologies, in this case a combination of UV photolithography and chemical etching, have allowed us to obtain the micro-textures. In this preliminary validation we have used copper as substrate material due to its easier processability and the need of a lower etching time.

For the manufacture of the micro-textures we have followed several steps including:

- Initial preparation of the copper discs by washing out the possible surface oxides in ultrasonic cube for around 30 minutes and subsequent drying.
- Coating of the discs using Dupont Riston PM-100 photoresin.
- Exposure of the photoresin to UV light by means of a SF-100 equipment from Intelligent Micro Patterning LLC. The process is known as mask-less photolithography, as the use of programmable light filters prevents from using a physical mask.
- Development, using a Na_2CO_3 0.85% w. solution, for eliminating the uncured photoresin in those pattern zones that are going to be chemically etched
- Chemical etching introducing the disc in a $FeCl_3$ 40% w. solution for attacking the uncoated pattern zones, hence obtaining the micro-texture.
- Stripping or elimination of the remaining photoresisn.
- Washing out debris and drying.
- Final dimensional verification.

Final result of the manufacturing process is included in Figure 4, in which 400 µm has been used as diameter of the circular features and a surface density of 10% has been applied. The geometry of the micro-holes obtained is almost semi-spherical and, as results explained below show, they act as reservoirs of lubricant and promote friction reduction.

4 TRIALS AND RESULTS

Once the textures of the different probes were obtained, several trials have been carried out in a Mini Traction Machine from PCS Instruments (Lafont, 2009), simulating a ball-disc contact, using a steel ball and the micro-texturized copper discs.

Figure 5 shows the evolution of friction coefficient as a function of mean velocity (u_m), for different diameters of the circular features of the micro-textured patterns. A smooth disc without micro-texturization has been used as reference.

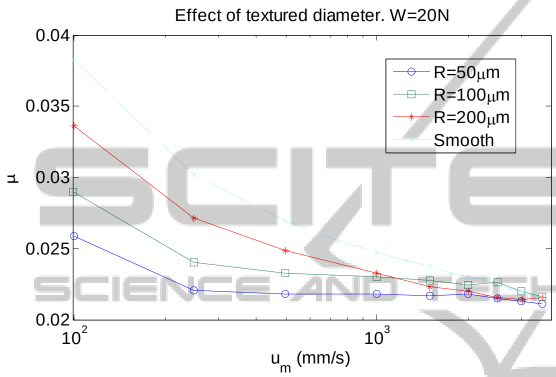

Figure 5: Friction reduction by using textured surfaces.

The friction coefficient reduction is specially noteworthy in the mixed lubrication regime (u_m<10^3mm/s). In addition smaller textures promote greater reductions of friction, specially for lower contact velocities.

5 CONCLUSIONS AND APPLICATIONS

Our results show that the use of very simple micro-textures helps to improve surface contact behavior and reduce friction coefficient in the whole mixed lubrication regime, although additional in vivo validation needs to be further researched.

Applying this methodology to the contact surfaces of artificial joint prostheses can help to obtain low surface roughnesses with micro-textures acting as reservoirs of lubricant, thus minimizing friction and improving wear behavior and prostheses service life. Such textures have also potential benefits regarding cell growth and tissue formation besides the prostheses. Future studies will be linked to the use of end materials and geometries adapted to those of the different artificial joint prostheses designs. Industrialization of the proposed process can be achieved by means of CAD-CAM technologies, in combination with advanced additive manufacturing or laser micro-mechanization.

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