

Equipment for the Study of Tribological Aspects of Hip Prostheses

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ABSTRACT

In this paper we present a theoretical model of friction with sliding in the presence of a lubricant for a complex, multidirectional movement for the biocompatible couple formed by polyethylene of high molecular weight – UHMWPE and titanium alloy Ti6Al4V, which is one of the couples very often used in manufacturing hip and knee prostheses. The model presupposes the existence of a preferential molecular orientation on the main sliding direction, and breaking the molecular bonds of orientation perpendicular to this direction. The model homogenizes the effects corresponding to friction of surfaces that are in contact.

A equipment for the study of tribological aspects for hip prostheses has been designed.

Keywords: plastic materials, UHMWPE, friction, prosthesis, hip, equipment.

1. Introduction

Polyethylene of ultrahigh molecular weight (UHMWPE) was used to manufacture the acetabular cup for both total prostheses of hip joints and knee joints, starting with the first half of the sixties. The high molecular weight confers upon UHMWPE superior mechanical hardness and wear resistance, as compared to the majority of biocompatible plastics.

The wear of the acetabular cup for a femoral head of 32 mm [8], [9], [10], [14] is of approximately 0,1 mm/year or 80 mm³/year which represents 30% less than the wear registered in the case of using PTFE by Charnley in the fifties [5], [6]. Knowing that the thickness of acetabular cups is of minimum 6 mm and the wear rate is of 0,1 mm/year, the conclusion is that the complete wear would be produced in 60 years. The typical components of the acetabular tibia have a minimal thickness of 6 mm at the most. For a wear rate of 0,1 mm/year, this would result in a complete wear in at least 60 years [26].

Experimental research has shown that, although total wear of the acetabular cups made of UHMWPE is very low, the microchips resulting from the wear process cause adverse reactions of the tissue, and the gradual absorption of the osseous tissue - osteolysis [1], [17]. Osteolysis leads to reducing the prosthesis resistance, patient discomfort and eventually to

revision surgery, due to which research efforts have been directed to optimizing the quality of the materials the prosthesis are made of, as well as of joint friction conditions so that eventually the percentage of the UHMWPE microchips to be very low [26].

Research on the microchips recovered from the periprosthetic tissues have shown these chips to be mostly of micron dimension or even smaller, and their form is close to spherical or hairshaped [3], [4], [7]. Quantitative analysis of the wear process for hip or knee prostheses highlights the fact that number of the hairshaped microchips is greater than the spherical ones [12], [15]. The wear mechanisms that establish the interdependence between the sizes of the parameters of the complex friction process taking place in the prosthesis on the one hand, and the form and quantity of the microchips on the other, have been proposed but the results were only of a qualitative nature [12], [15], [16].

Introducing the "multidirectional movement" between the elements of the hip prosthesis represented a main contribution to the study of the process of generating UHMWPE microchips [2], [21], [27].

Experimental research on the wear resulting from the stress applied on the elements of the prosthesis in a linear movement has shown that the medium wear degree for UHMWPE is (2-3 times) smaller than the

medium wear degree clinically determined [2], [21], [22]. In the case of applying "multidirectional movement" the results obtained from the experiments on models and those clinically determined can be compared [2], [11], [18], [22], [23], [27].

Researchers have demonstrated that the UHMWPE molecular structure has the special property that the molecules can preferentially orient towards the sliding direction of the surfaces that are in contact [21], [22], [24]. Along this direction the superficial layer roughens and the wear resistance implicitly takes greater values, whereas on a perpendicular direction it is significantly lower. Multidirectional orientation of the molecules in the case of sliding contact favoured by using transversal bonds determines a better UHMWPE wear resistance [13], [14], [19], [20], [25], by:

- increasing anisotropy degree;
- reducing the mobility of the molecular chains;
- reducing the degree of molecular orientation;
- increasing the density of chemical bonds of C-C type between the adjacent molecules which makes the separation of a molecule from another much more difficult.

This paper introduces a model that tries to reproduce the physical process of generating UHMWPE microchips based on phenomena of unbinding the inter- and intramolecular bonds. UHMWPE was considered to have a composite structure made of numerous micro-fibres oriented towards the main direction of sliding. Microchips will derive from broken fibers in the case of sliding on another direction than the main one [27].

A construction diagram is proposed for a equipment for the study of the tribological aspects for hip prostheses made of the couple of materials UHMWPE – titanium alloy Ti6Al4V, strained multidirectional in lubrication conditions.

2. Theoretical approaches

In order to analyse the wear mechanism that leads to microchips formation, we have shown in figure 1 a diagram of the contact between smooth surfaces of the UHMWPE sample (1), deformable, upon which the tangential load \vec{T} acts, and a rigid body (2) upon which the normal load \vec{N} acts.

The UHMWPE sample (1) performs an alternative rectilinear movement around the X axis, at a \vec{v} speed, whereas the rigid body (2) evolves around the Z axis, in the X - Y plane at

an angular speed $\vec{\omega}$, in the interval $(-\alpha - \alpha)$ (0° is located on the X axis).

If, for simplifying reasons, we consider the normal force to be constant, then the work of friction released during a single cycle is as follows [27]

$$\Delta L = \int_0^t (\vec{T} \cdot \vec{v}) \cdot dt = 4 \cdot \int_0^\alpha \left(\mu \cdot \vec{N} \cdot \vec{v} \cdot \frac{1}{\omega} \right) \cdot d\theta = \frac{4 \cdot \mu \cdot N \cdot v \cdot \alpha}{\omega}, \quad (1)$$

where:

- \vec{T} is the tangential force, in [N];
- \vec{N} – normal force, in [N];
- ω – angular speed, in [rad/s];
- α – maximum evolving angle around the Z axis, in [rad];
- \vec{v} – the speed vector in the rectilinear-alternative movement, in [m/s]
- μ – friction coefficient.

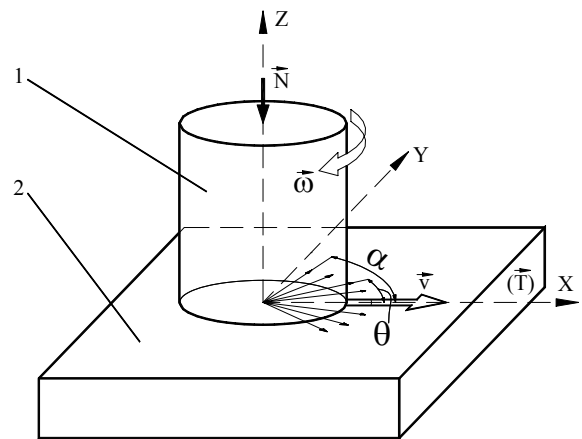


Fig. 1. Movements performed by the samples that are in contact [27]:
1 - UHMWPE sample; 2 - rigid body.

The work of friction on the secondary Y sliding direction is [27]

$$\Delta L_y = \int_0^t (T \cdot \sin \theta) \cdot (v \cdot \sin \theta) \cdot dt = 4 \cdot \int_0^\alpha \left(\mu \cdot N \cdot v \cdot \sin^2 \theta \right) \cdot \left(\frac{1}{\omega} \right) \cdot d\theta = \frac{2 \cdot \mu \cdot N \cdot v}{\omega} \cdot \left(\alpha - \frac{\sin 2\alpha}{2} \right), \quad (2)$$

and the work of friction on the principal X sliding direction is

$$\begin{aligned} \Delta L_x &= \Delta L - \Delta L_y = \\ &= \frac{2 \cdot \mu \cdot N \cdot v}{\omega} \cdot \left(\alpha + \frac{\sin 2\alpha}{2} \right) [\text{N} \cdot \text{m}]. \end{aligned} \quad (3)$$

It is considered that upon a UHMWPE fiber of l length and d width acts a force \vec{T} (fig. 2).

d – the width average in the cross-section of the UHMWPE fibers, in [mm];
 t – the time in which a movement cycle takes place, in [s].

The simplifying hypothesis is advanced, according to which ΔL_x contributes to fibers elongation and ΔL_y contributes to fibers breaking.

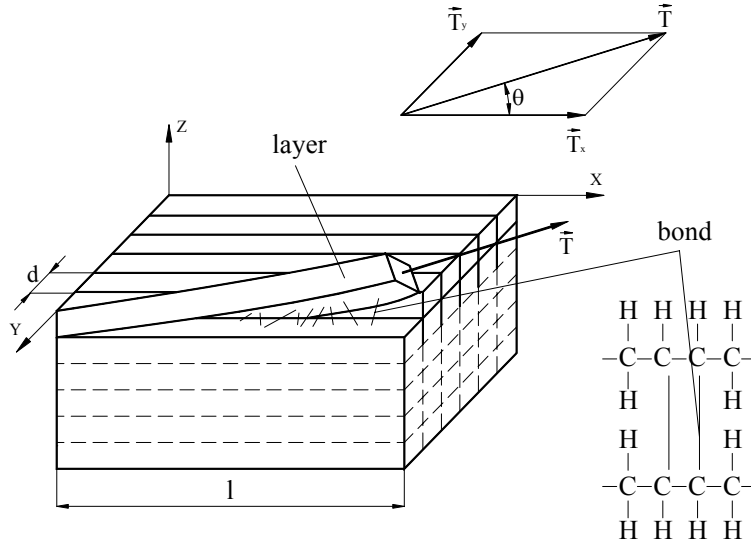


Fig. 2. The model of the UHMWPE fibers separation as a result of the action of a force \vec{T} [27]

In order that the fiber to be detached out of the basic material it must be strained for elongation in the X - Z plane and for shearing in the X - Y plane. The necessary energy for detachment is determined by using the formula [27]

$$\delta w = 2 \cdot (dl \cdot X_c \cdot \gamma_c), \quad (4)$$

where:

X_c is the density of the C-C bonds (number of bonds on an area);

γ_c – the energy of the C-C bond.

As the volume of a fibre $\delta V = l \cdot d^2$, the mechanical work necessary for producing a microchip volume unit is [27]

$$\frac{\delta w}{\delta V} = \frac{2 \cdot dl \cdot X_c \cdot \gamma_c}{l \cdot d^2} = \frac{2 \cdot X_c \cdot \gamma_c}{d}. \quad (5)$$

where:

X_c is the transversal bonds density;

γ_c – the C-C bond energy, in [J];

\vec{T} – the tangential force applied to the fibre, in [N];

l – the fiber length, in [mm];

The strain along the X axis results in fibers elongation, in reducing the cross-section so that the ΔL_y component of the mechanical work will determine the separation of the fibre selected out of the basic material.

The total volume of material transformed into ΔV microchips is determined by dividing the mechanical work that effectively leads to fibers detaching, ΔL_y , to the mechanical work necessary for producing one volume unit of microchips

$$\begin{aligned} \Delta V &= k' \cdot \frac{\Delta L_y}{(\delta w)/(\delta V)} = \\ &= k' \cdot \frac{2 \cdot \mu \cdot N \cdot v \cdot d}{\omega \cdot X_c \cdot \gamma_c} \cdot \left(\alpha - \frac{\sin 2\alpha}{2} \right) = \\ &= k' \cdot \frac{2 \cdot \mu \cdot N \cdot v \cdot d}{X_c \cdot \gamma_c} \cdot \left(\frac{\alpha}{\omega} \right) \cdot \\ &\quad \cdot \left(1 - \frac{\sin 2\alpha}{2 \cdot \alpha} \right) [\text{mm}^3/\text{ciclu}], \end{aligned} \quad (6)$$

where k' is a constant.

As $4 \cdot \alpha / \omega = t$, the relation (6) changes to

$$\Delta V = k' \cdot \frac{\mu \cdot N \cdot d(v \cdot t)}{2 \cdot X_c \cdot \gamma_c} \cdot \left(1 - \frac{\sin 2\alpha}{2 \cdot \alpha}\right) \quad (7)$$

As $(v \cdot t) = L$, where L is the average of the linear distance on which sliding with friction takes place on every movement cycle, then the relation (7) becomes

$$\Delta V = k' \cdot \frac{\mu \cdot N \cdot dL}{2 \cdot X_c \cdot \gamma_c} \cdot \left(1 - \frac{\sin 2\alpha}{2 \cdot \alpha}\right) \quad (8)$$

For $\alpha = 90^\circ$, that is for the angle in which breaking caused by transversal strains is produced, the wear factor k has a maximum value

$$k_{max} = k_{\pi/2} = k' \cdot \frac{\mu \cdot d}{2 \cdot X_c \cdot \gamma_c} \quad (11)$$

or

$$k_\alpha = k_{\pi/2} \cdot \left(1 - \frac{\sin 2\alpha}{2 \cdot \alpha}\right) \quad (12)$$

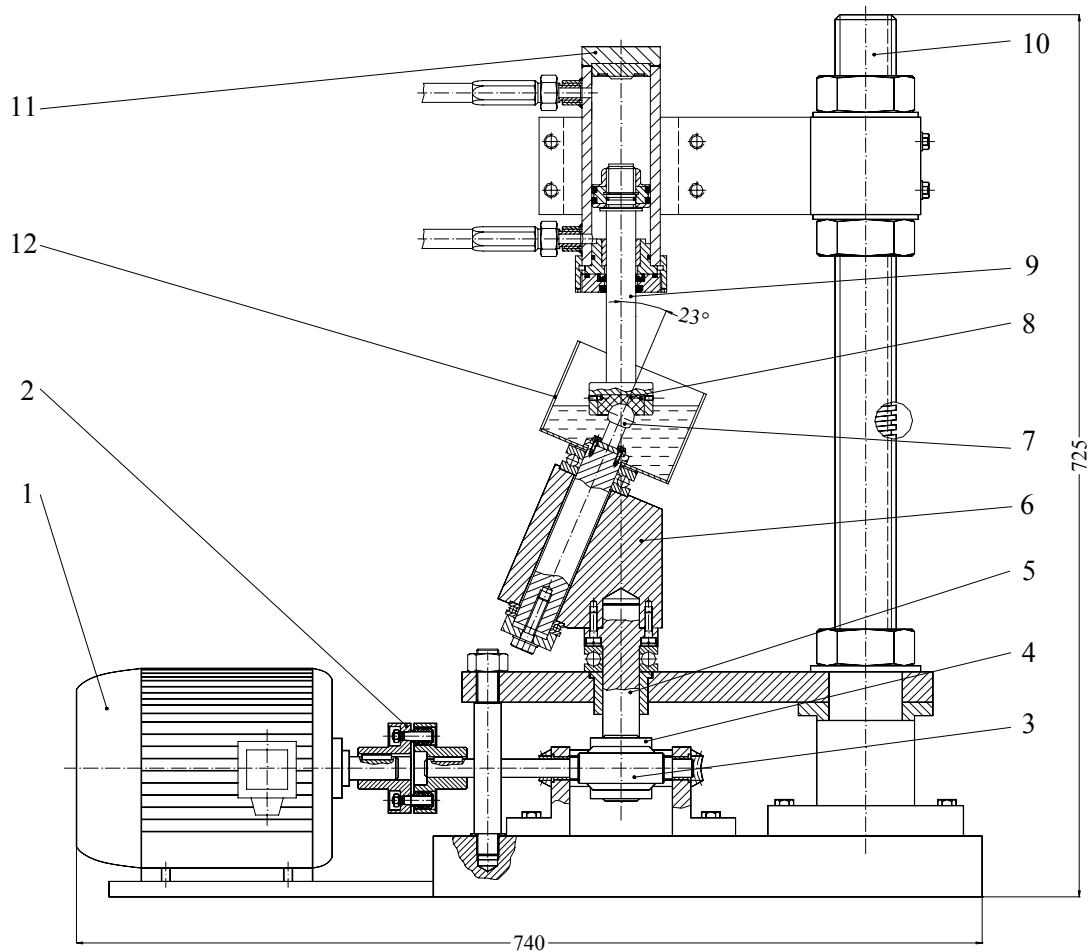


Fig. 3. Equipment for the study of tribological aspects of hip prostheses

The wear factor k is defined as

$$k = \frac{\Delta V}{P \cdot L} \quad (9)$$

that is

$$k = k' \cdot \frac{\mu \cdot d}{2 \cdot X_c \cdot \gamma_c} \cdot \left(1 - \frac{\sin 2\alpha}{2 \cdot \alpha}\right) \quad (10)$$

3. Equipment for the study of tribological aspects of hip prostheses

In figure 3 the construction diagram of a equipment for the experimental determination of the wear factor is presented.

The rotating movement is transmitted from the electric motor (1) through the elastic coupling with bolts (2), to the worm-drive (3) worm-wheel (4). The worm wheel 4 is fixed onto the shaft (5) that carries on further the

rotating movement to the body (6) on which the metallic semiprosthesis is fixed (7). The joint strain is simulated by pressing the semiprosthesis (8) and using the rod (9) acted upon by the hydraulic roller (11). The semiprotheses (7) and (8) are immersed into the lubricating fluid located into the container (12). In order to analyze the wear behaviour of the semiprotheses (7) and (8) these are disassembled by the vertical movement of the roller (11) alongside the screwed column (10).

the main idea underlining the design of the equipment for the study of the tribological aspects for hip prostheses, a equipment that we have proposed in this paper.

The equipment features a simple construction, compact and easy to use, and allows for the adaptation of the measurement equipments of the torque and of the axial force in the contact area, located within the elements of the analyzed prosthesis.

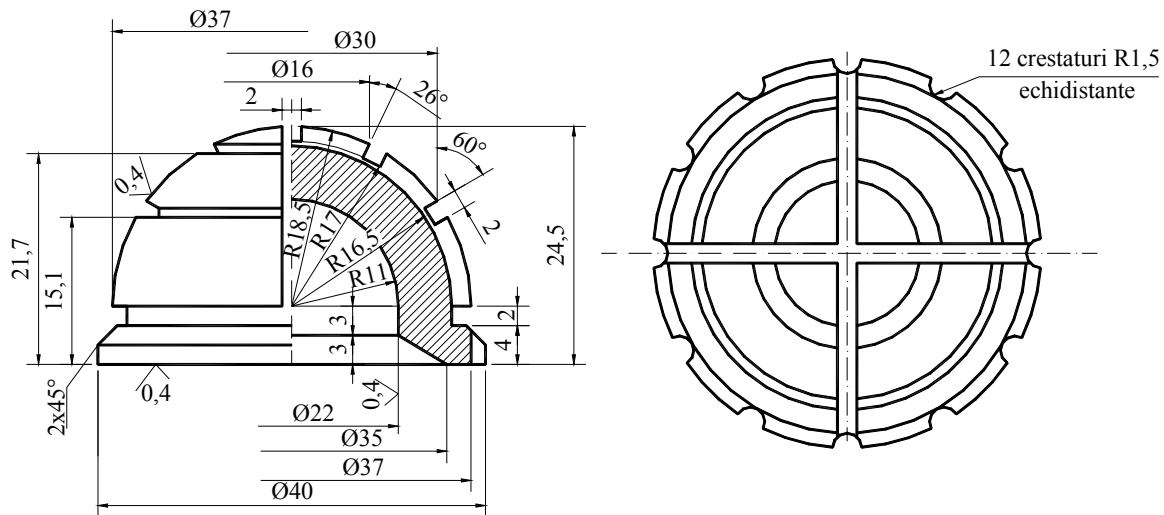


Fig. 4. Acetabular cup Ø 22

4. Experiments Planning

The equipment imagined and presented as a diagram in figure 3 works according to the following conditions:

- the analyzed couple is made of:
 - femoral head: Ti_6Al_4V ; Ø 22, 24 mm;
 - acetabular cup: UHMWPE; Ø 22, 24 mm.
- quality of the interior surface, Ø 22, 24 mm of the acetabular cup, $R_a = 0,015mm$ (fig. 4);
- the lubricant used is made of:
 - 50% deionized water;
 - 50% serum.
- testing conditions :
 - the type of the contact: sphere-plane;
 - sliding speed: $(0,0002 \div 0,2)$ m/s;
 - contact pressure: $(0,5 MPa \div 0,3 GPa)$;

The wear dimension for the couple will be determined by weighing within 3000 cycle intervals.

5. Conclusions

The theoretical model of the wear mechanism based on the existence of the work of friction on the secondary sliding direction

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Stand pentru studiul aspectelor tribologice la protezele de șold

Rezumat

În lucrare se prezintă un model teoretic al frecării cu alunecare în prezența unui lubrifiant în cazul unei mișcări complexe, multidirecționale pentru cuplul biocompatibil format de polietilena cu masă moleculară foarte mare – UHMWPE și aliajul de titan Ti6Al4V, unul dintre cuplurile des folosite în confecționarea protezelor de șold și genunchi. Modelul presupune existența unei orientări moleculare preferențiale pe direcția principală a alunecării, și ruperea lanțurilor moleculare a căror orientare este perpendiculară pe această direcție. Modelul uniformizează efectele frecării suprafețelor aflate în contact.

S-a imaginat un stand pentru studiul aspectelor tribologice la protezele de șold.

Équipement pour l'étude des aspects de tribologique des prothèses de hanche

Résumé

En cet article nous présentons un modèle théorique de frottement avec le glissement en présence d'un lubrifiant pour un mouvement complexe et orientable pour les couples biocompatibles constitués par le polyéthylène du poids - UHMWPE et un alliage titanique Ti6Al4V, qui est l'un des couples très souvent utilisés dans des prothèses de hanche et de genou de fabrication. Le modèle présuppose l'existence d'une orientation moléculaire préférentielle sur la direction coulissante principale, et casser les obligations moléculaires de la perpendiculaire d'orientation à cette direction. Le modèle homogénéise les effets correspondant au frottement des surfaces qui sont en contact. Un équipement pour l'étude des aspects tribologique pour des prothèses de hanche a été conçu.