Journal of KONES Powertrain and Transport, Vol. 24, No. 4 2017

ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/01.3001.0010.3160

GEOMETRICAL STRUCTURE FOR ENDOPROSTHESIS SURFACE LUBRICATION AND WEAR PROGNOSIS

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Abstract

It can be stated that over the last ten years in the European Union, the number of bone fractures caused by osteoarthritis has increased twofold. More than 100,000 hip or knee joints in total were implanted in Germany during one year. Within ten years, 5% of them have failed by aseptic loosening. The non-invasive determination of friction forces and control of their values during lubrication of cartilage cells on the superficial layer of human joint surfaces before implantation has a significant but not sufficient impact on the observation of the early abrasive wear of the cartilage joint and development of osteoporosis. From this fact was drawn the inspiration for the performed investigations related to the endoprosthesis surface parameters because knowledge of the roughness of prosthesis surfaces and friction forces and their control methods permits provision of a necessary standard deviation of the gap height and finally information about the implantation possibility. This article has been prepared based on the objective of European Project UE Grant IRSES,612593, 2013-2016 to represent the methodology and goal of the idea described in and make a wider discussion possible on this subject for further developments during the realization. To the research methods and materials used in this article realization belong: Rank Taylor Hobson-Talyscan 150 Apparatus implemented by Talymap Expert and Microsoft Excel Computer Program connected with the Mathcad 15 Professional Program and a new semi-analytical methods of probabilistic and statistic prognosis applied for theory of hydrodynamic lubrication of the curvilinear orthogonal surface and coordinates extended to the friction and wear problems of the endoprosthesis surfaces during the exploitation.

Keywords: *endoprosthesis, surface, measurements, gap height, wear, random prognosis*

1. Introduction

The increase of joint fractures number in the EU, anticipated on the grounds of the demographic development in the coming 50 years, would reach about one million. Therefore, the endoprosthesis will be transplanted even in young human age. Taking into account, the increasing necessity of artificial hip joint implantation; it is necessary to know the condition of the endoprosthesis surface. In this occasion, we must mention the aseptic slack of the endoprosthesis. Therefore, this article presents in micro-level the detailed results of measurements of the geometrical structure parameters of the cooperating head, the pivot surfaces and cement in the endoprosthesis. The results obtained are depended on the features of the prosthesis material. The prosthesis surfaces on the head and acetabulum (sleeve) are frequently made from such materials such as Vitalium, Endocast, Zircon, Polyethylene or Aluminium ceramic. The results obtained for prosthesis surface measurements, namely irregularities and unevenness, are after implantation applied to the real gap height, pressure, the load carrying capacity and the wear prognosis in an artificial human hip joint. The subject of this article it is to examine the possibility of an application of Geometrical Structure Surface parameters, to evaluate the load carrying capacity and the wear of the endoprosthesis. The problem of endoprosthesis surfaces lubrication for unsteady periodic stochastic motion has already been considered by K. Oczoś, J. Cwanek, V. C. Mow [1, 3, 4, 8]. Up to now, the random considerations and solution methods are based only on the probability of symmetric density functions of gap height changes. For example, what is considered is the classical Gauss and Pseudo-Gauss probability density function of gap height changes. Such assumed conditions denote that in each arbitrary choice period, the occurring probabilities of the gap height decreases possess the same rank as the probability values of gap height increases. The random changes of the gap height of a natural normal and pathological human hip joint or the gap height between the head and the acetabulum of the endoprosthesis are caused mainly by vibrations and the roughness of the joint surfaces. After many experimental observations, it was observed that during the arbitrarily chosen period of unsteady periodic motion of the hip joint, the probabilities of joint gap height decreases are not equal to the probabilities of gap increases. Therefore, in the present article, the asymmetric density function for the probability of gap height changes is taken into account [2, 3].

2. Measurements

The determination of the hydrodynamic lubrication of artificial Vitalium, Endocast, Zircon, Polyethylene, Aluminium ceramic endoprostheses is associated with a precise analysis of the irregularities and unevenness of the endoprosthesis cooperating surfaces, with an accuracy of less than one micrometre. The measurements of the endoprosthesis -head surfaces are performed by using a micro sensor laser installed in the Rank Taylor Hobson-Talyscan 150 Apparatus and then processed by means of the TALYMAP Expert and Microsoft Excel Computer Program. From many samples measured, the following statistical parameters have been calculated: St, Sz, Sa of surface roughness smaller than micrometre. We calculate for example: St – differences between the values of rises and deeps of head surfaces in the endoprosthesis, Sz – arithmetic mean between the values of 5 rises and 5 deeps of the head surface, Sa – standard deviation of the probability density function of the roughness distribution of artificial joint surface.

3. Head and acetabulum surfaces of artificial hip joint

The measurements of samples of the artificial hip joint surfaces of the endoprosthesis are performed by means of mechanical and laser sensors. The samples measured were made of the Endocast alloy: zircon and ceramic aluminum (see Fig. 1a and b). The samples used during the measurements and made of Vitalium or Endocast and zircon material, were either 1.25 mm long and 1.25 mm wide or 2.50 mm long and 2.50 mm wide. The samples made of ceramic aluminum were 0.988 mm long and 0.988 mm wide. In the case of Weller's artificial endoprosthesis, the metal surface of the head is coated with randomly shaped chaos scratches obtained through abrasive grain treatment [7]. The measured values of St for the metal heads of the Weller's endoprosthesis barely reach the value of 0.702 micrometre. The three dimensional (3D) structure of the surface geometry of the unused head seated onto the corundum ceramic pin is shown in Fig. 1b. On the grounds of the performed measurements, it is easy to see that the asperities of the artificial joint surfaces are smaller than those occurring in natural bone surfaces of human hip joints [7, 8].Over the entire polished surface of aluminum ceramics, micro-cavities (micro--hollows) that chaotically spread over the measuring area, can be observed. The distribution density of such micro-cavities is within the range of 10 to 120 (and even more) elements per one mm^2 depending on the type of ceramics and its firing process. The depth of micro-cavities reaches the values from 4 to 8 micrometres, measured on the area from 1 to 4 square micrometres. The occurrence of the micro-cavities on the polished ceramic surface is due to the manufacturing process of ceramic elements, which belongs to powder metallurgy field. During the process of compacting the powder and firing the ceramic elements, natural micro-pores are produced. The pores open and convert into micro-cavities during machining when successive layers of excess material are removed, also in the course of the final polishing process.

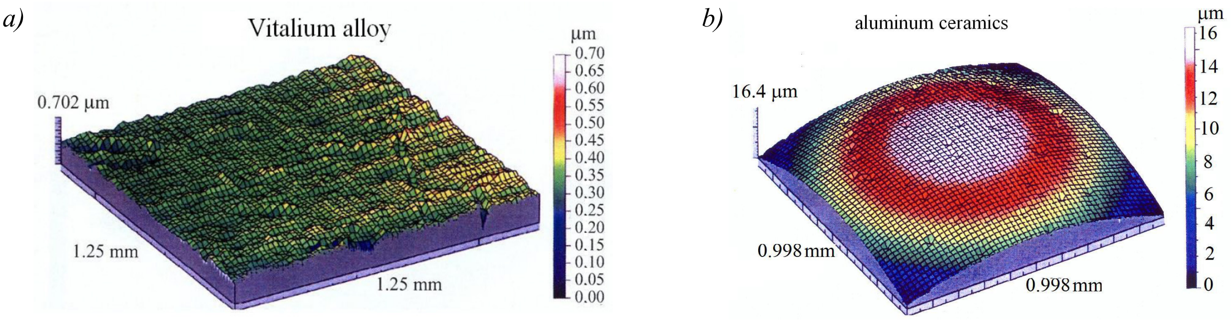

Fig. 1. a) The contour diagram of the unused surface of head of Vitalium alloy of Weller's endoprosthesis, b) the surface of the unused head of endoprosthesis made of corundum ceramic

The influence of the micro-cavities on the operational merits of ceramic heads of endoprosthesis may be considered as a positive phenomenon since they form on the smooth surface a specific network of micro-ponds, which play the role of the tanks that hold lubricating media. The roughness of the surface areas between micro-cavities is low as it maintains within the range of St – values from 0.4 to 0.8 µm [7, 8]. In the unevenness height of 16.4 µm shown, a, in Fig. 1b, apart from surface roughness, also a shape deviation from the ideal spherical surface is observed. An example of a hip joint half-endoprosthesis with a head seated onto the pin is the Francobal endoprosthesis. Its head consists of an outer metal element having a spherical form and an inner element made of polyethylene. Fig. 2 presents the geometrical structure of the surface and the vertical 2D cross-section of the unused head of a Francobal's artificial hip joint.

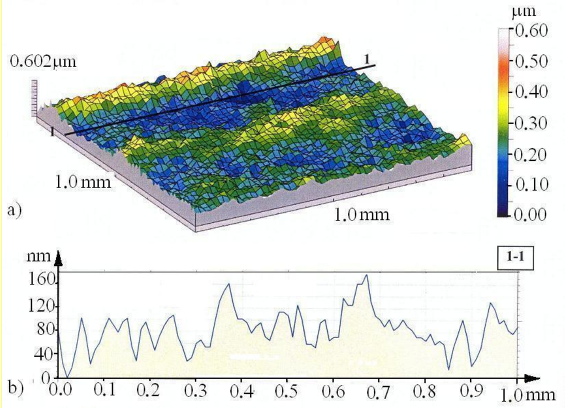

Fig. 2. Sample of a new head of endoprosthesis FRANKOBAL GL54MM: a) measured roughness of surface, b) vertical section

In the geometrical structure presented in Fig. 2, we have the following amplitude parameters: Sa = 0.0582 µm, St = 0.602 µm and Sz = 0.425 µm.

The majority of the acetabulum of hip joint endoprostheses is made of polyethylene by using the high-pressure compacting method in metal moulds. A typical image of the surface of a new and unused polyethylene acetabulum of the hip joint is shown in Fig. 3.

Based on the figures presented, it can be observed that some concentrically orientated unevenness resulting from its manufacturing process is superimposed on the basic hollow surface of the acetabulum. This phenomenon is also observed in other manufacturing processes, and it is generally known as the *technological heritage*. In the case in question, the phenomenon is characterize by the fact that the unevenness of the mould has been imprinted on the acetabulum surface [7, 8].

In Fig. 4, it can be observed that the acetabulum surface retains its anisotropic and periodic nature [7].

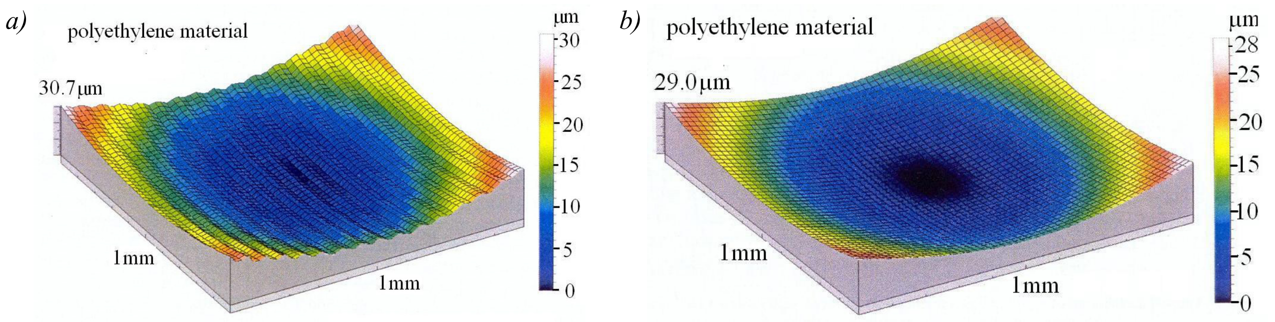

Fig. 3. Unused acetabulum of hip joint endoprosthesis: a) general view: 1 mm × 1 mm, b) separated initial spherical surface of radius R = 14.012 mm

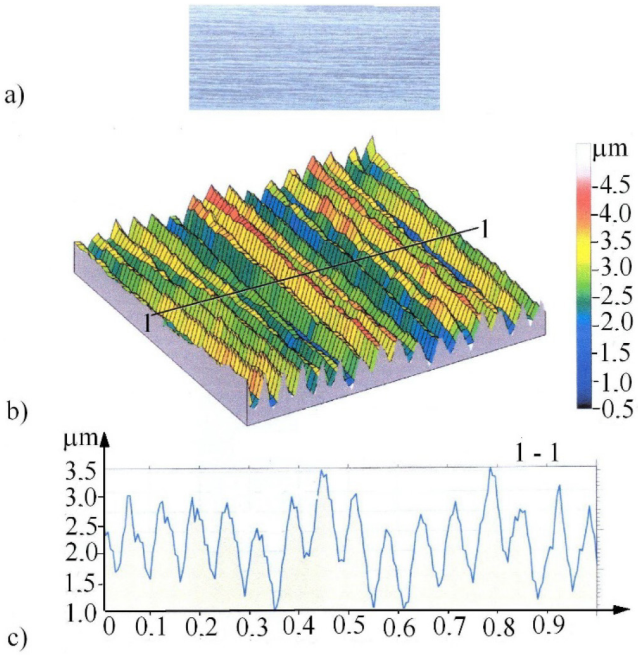

Fig. 4. Unused acetabulum of hip joint endoprosthesis: a) a view of surface roughness on 10 mm × 20 mm area, b) surface roughness on 1 mm² area, c) height of roughness characteristic cross-section profile of surface, length = 1 mm, Pt = 3.59 µm, Scale = 3.59 µm

4. Random parameters

After the abovementioned measurements of selected endoprosthesis geometry surfaces, we observe two cases, namely: the case where probabilities of increases of gap height random changes are larger f_A (smaller f_a) than the probabilities of the decreases of gap height random variations [7]. Stochastic changes of the joint gap height are determined by virtue of the main random parameters such as expectancy value and standard deviation. The abovementioned parameters are now defined. The indefinite integral of the product of the real gap height (*) and the probability density function f denotes average probability values, i.e. the expectancy stochastic value of gap height defined by [2, 6]:

$$E(*) = \int_{-\infty}^{+\infty} (*) \times f(\delta_1) d\delta_1. \tag{1}$$

Standard deviation σ, has the following form [2, [6]:

$$\sigma \equiv \sqrt{E(*)^2 - E^2(*)}. \tag{2}$$

5. Hydrodynamic pressure calculations for measured surfaces

The spherical dimensionless gap height $\varepsilon_{T1} = \varepsilon_T/\varepsilon_0$ between two co-operating endoprosthesis surfaces depends on the dimensionless variable φ in circumferential and ϑ_1 in meridian direction and time t_1, and it consists of two parts:

$$\varepsilon_{T1} = \varepsilon_{T1s}(\varphi,\vartheta_1,t_1) + \delta_1(t_1) \quad \text{for} \quad 0 < \varphi<2\pi;\ \pi/8<\vartheta_1<\pi/2, \tag{3}$$

where ε_T denotes the dimensional gap height. Symbol ε_{T1s} denotes the total dimensionless time--dependent part of the height of the thin fluid layer, without random changes, δ_1 – denotes the dimensionless stochastic corrections of gap height caused by the geometry of endoprosthesis head and acetabulum surface random changes.

The modified stochastic Reynolds equations in spherical dimensionless coordinates φ, ϑ_1 for unsteady motion determined by the Strouhal numbers takes the following form [7, 8]:

$$\frac{1}{\sin\vartheta_1}\frac{\partial}{\partial\varphi}\left[E\left(\varepsilon_{T1}^3\right)\frac{\partial p_1}{\partial\varphi}\right]+\frac{\partial}{\partial\vartheta_1}\left[E\left(\varepsilon_{T1}^3\right)\frac{\partial p_1}{\partial\vartheta_1}\sin\vartheta_1\right]=$$

$$=\left(6\frac{\partial}{\partial\varphi}+12\mathrm{Str}\frac{\partial}{\partial t_1}\right)E(\varepsilon_{T1})\sin\vartheta_1 = 6\frac{\partial}{\partial\varphi}E(\varepsilon_{T1})\sin\vartheta_1. \tag{4}$$

We denote: $p_1=p/p_0$-dimensionless pressure, $p_0=\omega\eta R^2/(\varepsilon_0)^2$, ω-angular velocity of the head, η-dimensional lubricant viscosity, ε_0-dimensional characteristic value of gap height, R-dimensional radius of the head, Str-Strouhal number, t_1-dimensionless time, φ-circumference, ϑ_1-dimensionless meridian coordinate.

The lubricant dynamic viscosity depends on [5]: We – wettability of endoprosthesis superficial surfaces in the contact with the lubricant, and p_H – power hydrogen ion concentration, BMR – Basal Metabolic Rate, BMI – Body Mass Index, joint interfacial energy, p – hydrodynamic pressure, T – temperature, t – the time of endoprosthesis exploitation.

The performed experimental measurements enable to show two dimensionless, asymmetrical f_A, f_a probability density functions for endoprosthesis gap height, versus dimensionless stochastic gap height corrections δProbability density function for gap height indicate probability values of gap height, corresponding to the dimensionless gap height corrections during the operation time. Negative (positive) gap height corrections denote decrements (increments) of relative value of gap height. Function f_A presents the case where probability values of gap height density functions are smaller for negative gap height stochastic corrections δ_1 in comparison with the probability values of density function with positive stochastic correction values δ_1. Function f_a presents the case where probability values of gap height density functions are significantly larger for negative gap height stochastic corrections δ_1 in comparison with the probability values of density function with positive stochastic correction values δ_1. Because gap height depends on wettability. We, hence the abovementioned probability density functions are depended on We. Taking into account the random asymmetrical density functions f_A, f_a obtained from the performed surface measurement results in Fig. 1-4, we can calculate by virtue of Eqs. (1-3) the following depended on We, expectancy dimensionless random values of the gap height, i.e. $E = E_A(We)$, $E = E_a(We)$ in following form:

$$\begin{aligned}
&m_{A1} \equiv E_A(\varepsilon_{T1}) = \int_{-\infty}^{+\infty}(\varepsilon_{T1s}+\delta_1)\times f_A(\delta_1)d\delta_1 = \varepsilon_{T1s}+0.25,\\
&m_{a1} \equiv E_a(\varepsilon_{T1}) = \int_{-\infty}^{+\infty}(\varepsilon_{T1s}+\delta_1)\times f_a(\delta_1)d\delta_1 = \varepsilon_{T1s}-0.25;\\
&E_{A1}(*)^3 \equiv E_A\left(\varepsilon_{T1}^3\right)= \int_{-\infty}^{+\infty}(\varepsilon_{T1s}+\delta_1)^3\times f_A(\delta_1)d\delta_1 = (\varepsilon_{T1s}+0.25)^3+3\sigma_{A1}^2(\varepsilon_{T1s}+0.25),\\
&E_{a1}(*)^3 \equiv E_a\left(\varepsilon_{T1}^3\right)= \int_{-\infty}^{+\infty}(\varepsilon_{T1s}+\delta_1)^3\times f_a(\delta_1)d\delta_1 = +(\varepsilon_{T1s}-0.25)^3+3\sigma_{a1}^2(\varepsilon_{T1s}-0{,}25),
\end{aligned} \tag{5}$$

where $\sigma_{A1} \approx \sigma_{a1} = 0.38188$. To obtain a dimensional value of the standard deviation σ_A, σ_a we must multiply σ_{A1}, σ_{a1} by the characteristic dimensional value of gap height $\varepsilon_0 = 10\cdot10^{-6}$ m. In this case, the dimensional standard deviation equals 3.81837 micrometres. It follows from the measurements that the standard deviation value attains about 4.0 micrometres for the considered endoprosthesis.

6. Numerical example

Between endoprosthesis surfaces, the dimensional gap height ε_T has an average value of 70 μm. At first, we neglect random changes, i.e. $\delta = 0$. Dimensionless gap height Eq. (3) has the value: $\varepsilon_{T1} = \varepsilon_T/\varepsilon_0 = 7$. Taking into account the random changes of endoprosthesis surfaces i.e. $\delta \neq 0$, hence accordingly with Eqs. 5, we calculate the dimensionless m_{A1}, m_{a1} and dimensional m_A, m_a expectancy values of the gap height for two cases of asymmetric density functions f_A, f_a (see Fig. 5) respectively:

$$\begin{gathered} m_{A1} = 7.00 + 0.25 = 7.25,\ \ m_A = m_{A1}\cdot\varepsilon_0 = 72.50\ \mu\text{m}, \\ m_{a1} = 7.00 - 0.25 = 6.75,\ ma = m_{a1}\cdot\varepsilon_0 = 67.50\ \mu\text{m}. \end{gathered} \tag{6}$$

Expectancy values of cubed gap height accordingly with Eqs. 5 are as follows:

$$\begin{gathered} E_{A1}(*)^3 = (7.25)^3 + 3\times(0.3818)^2\times7.25 = 384.2486,\ \ E_A(*)^3 = E_{A1}\times(\varepsilon_0)^3 = 384248.6\ \mu\text{m}^3, \\ E_{a1}(*)^3 = (6.75)^3 + 3\times(0.3818)^2\times6.75 = 310.4987,\ \ E_a(*)^3 = E_{a1}\times(\varepsilon_0)^3 = 310498.7\ \mu\text{m}^3. \end{gathered} \tag{7}$$

To obtain pressure p, we put the obtained values Eqs. (5-7) into a modified Reynolds equation Eq. (4). The expectancy value m of the gap height for two asymmetrical density functions f_A, f_a obtained from the measurements is estimated in the interval:

$$67.50\ \mu\text{m} = m_a \leq m \leq m_A = 72.50\ \mu\text{m}. \tag{8}$$

Taking into account dimensional standard deviations $\sigma_A \approx \sigma_a = 3.81837$ μm, the dimensional expectancy values m_A, m_a of the gap height are estimated in the following intervals [2]:

$$\begin{gathered} 68.69\ \mu\text{m} = m_A - \sigma_A \leq m_A \leq m_A + \sigma_A = 76.31\ \mu\text{m}, \\ 63.69\ \mu\text{m} = m_a - \sigma_a \leq m_a \leq m_a + \sigma_a = 71.31\ \mu\text{m}. \end{gathered} \tag{9}$$

7. Corollaries and conclusions

Based on the analysis of the geometrical structures of the surfaces of boneheads and the acetabulum of artificial hip joints, the following conclusions can be drawn:

1. On the basis of the friction theory it is favourable to join, as a friction pair, the endoprosthesis head of randomly variable non-directed surface and the acetabulum of directed anisotropic surface.
2. Joining the acetabulum surface of a large value of lubricant that maintains its ability and the head surface made of aluminium ceramics of a high value of concentration of micro-ponds, we may create favourable conditions for boundary lubrication over the friction region of cooperating surfaces.
3. It follows from the calculations from Eqs. (4-9) that the gap height increments and decrements caused by the surface roughness and fatigue, abrasive and corrosive wear of endoprosthesis surfaces attain about 13%.
4. By virtue of the intervals of the expectancy gap height values Eqs. (5-8), we demonstrated that the differences between the load carrying capacity for hydrodynamic unsteady pressure with random effects for pressure calculated from Eq. (4) for $\sigma \neq 0, \delta \neq 0$ and load carrying capacity without stochastic effects (i.e. for $\sigma = 0$, $\delta = 0$), attain about 20 percent.

5. The lubrication and load carrying capacity determination for the human hip endoprosthesis, considered without a random analysis of the gap height between two cooperating surfaces that have not been worn out is incorrect and gives large inaccuracies.

Acknowledgements

This research project has been supported by the European Project UE Grant under contract number UE Grant IRSES, 612593, 2013-2016.

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