EXPERIMENTAL DETERMINATION OF THE WEAR OF TOTAL ENDOPROSTHESIS POLYETHYLENE CUP USING HOLOGRAPHIC INTERFEROMETRY

Martin Houfek*, Vladimír Fuis*, Zdeněk Florian*

This article deals with determining the size of linear wear of acetabulum of total hip endoprosthesis by experimental modelling. The creation of an experimental sample and the equipment to simulate human walking are described in detail. The greatest attention is paid to the method for determining the topography of polyethylene cup and measuring of the loss of polyethylene during the simulation of walking. Holographic interferometry was selected to determine the loss of polyethylene cup on the basis of extensive analysis. Further parts of the article focus on first experience with the application of this method, results and other possibilities.

Keywords : *holographic interferometry, total endoprosthesis acetabular cup, measurement of wear*

1. Introduction

One of the problems of contemporary total endoprostheses (TEP) is their limited lifespan, which is around 15 years. Modern times pose higher and higher demands on humans, which is negatively reflected in the application of TEPs at an earlier age, and young patients with this diagnosis appear. Therefore, the effort of doctors, technicians and manufacturers is to design, manufacture and apply TEPs with higher durability. The cause of a limited life of total hip endoprosthesis is the wear of polyethylene acetabular cup. It is claimed in [1] that implants with polyethylene wear rates up to 0.05 mm/year have a very low frequency of periprosthetic osteolysis and loosening, while implants with wear rates greater than 0.3 mm/year have a significantly higher risk of developing osteolysis. All the circumstances related to the emergence and propagation of periprosthetic osteolysis have not been clarified adequately, therefore the effort to create a TEP with a minimum production of particles is of undeniable importance. The quantity of wear particles is closely related to the surgical technique, TEP design and behaviour of the patient. TEP design can affect the amount of wear particles in different ways. One of them is undoubtedly improving the quality of polyethylene, or selection of other contact materials for acetabular cup and femoral head. The second is adjustment of pressure distribution between the head and the cup. Adverse effects of wear particles can be reduced by preventing or reducing of particles entering the space between the bone tissue and the cup, or the bone tissue and the TEP stem. This issue is dealt with in article [6], which describes the creation of biologically active interface between the implant and the bone tissue. Such interfaces can be created by implants with hydroxyapatite-based surfaces. Synthetic hydroxyapatite has osteoconductive properties, which means that it

* Ing. M. Houfek, Ph.D., Ing. V. Fuis, Ph.D., Ing. Z. Florian, CSc., Faculty of Mechanical Engineering, University of Technology in Brno

supports the ingrowth of osteoprogenitor cells into a suitably modified implant surface, thereby preventing the ingress of wear particles.

Reducing the head diameter has a significant effect on the change in the distribution of contact pressures. Without mechanical analysis, it is difficult to say whether the effect is positive or negative. Reducing the head diameter, even when reducing its area, may mean increased contact pressure, and thus increased wear. The above mentioned mechanical analysis must include determination of contact pressure between the head and the cup and the experimental determination of wear under these conditions, where the method for determining the wear must be very sensitive.

2. Description of the problem situation

Solution of deformation and stress of the hip joint or the hip joint with applied TEP is a complex task of human biomechanics, which can be solved today due to the development of computational techniques and numerical methods of continuum mechanics. The same applies to the contact pressure between the TEP head and cup. In order to predict the amount of wear particles on the basis of mechanical quantities determined by this solution, it is necessary to determine the wear experimentally – for a certain calculated course and size of contact pressure. Although the number of wear particles is large, their volumetric or mass quantity is small (due to their microscopic size). Therefore, the TEP aseptic loosening, as a result of polyethylene granuloma, occurs only after several years. This time is short in terms of TEP life, but long for experimental determination of wear. Therefore, the demands on the experimental method to determine the wear are extreme. The consequence of these facts is that despite the existence of a number of methods to determine the wear, the subject of further research and development is new efficient methods based on different principles. Optical methods belong to the most effective of them. Holographic interferometry is an optical method applied in the topography of solids, so it was also used to measure the linear wear of polyethylene cup of total endoprosthesis.

3. Description of the experimental measuring chain

The entire assembly is placed on a rigid base plate that is suspended on pneumatic cylinders. This measure is very important due to environmental influences that can bring adverse effects in the measurement, such as vibrations. These effects are eliminated with pneumatic cylinders. A helium-neon laser that is firmly attached to the base plate was used for the coherent and monochromatic light source. Another part of the measuring chain is a system of mirrors that is used for easier handling of luminous flux. The mirrors change direction, or deflect the luminous flux and point it to the places where its effect is required. To create a hologram, the beam must be bifurcated. This is carried out by a double refractor. The light is polarized while passing through this divider. So we get waves which are perpendicular to each other. Since this effect, which has a negative impact on the interference, occurs, it is necessary to include another element in the system, in order to remedy this problem. A half-wave plate, where the plane of polarization is rotated by 90°, must be included in the run of beams, which is polarized in parallel with the plane of incidence. Further elements in the optical path are lenses. The lenses are used to extend the divergence and collimation. The beams are modified only in the last step when the beam passes through a spatial filter and enters the surveyed object. Lenses with a small focal length are suitable for this adjustment of beams. In this case, we used a connection to condense the beam of rays. Further elements in the optical path are objective lenses in the spatial filter with a small focal length, serving as filters for unwanted collimation. Since solid particles adhere to the surface of optical devices, it is necessary to perform optical filtering of beams through the focal pinhole diaphragm, which is located in the spatial filter. The diaphragm aperture is inserted into the focal plane of the lens, which causes the release of only one maximum. The last element of the optical path is a holographic glass plate coated with a special emulsion. A holographic record is made on the holographic plate when the beam passes through all the optical elements described above, at the correct configuration of settings of these elements. Using these optical devices, we can put together a measurement chain providing high-quality holographic records.

4. Principle and evaluation of the size of material loss

The method for evaluating the material loss is realized by means of holographic recording. To obtain a hologram, two beams are necessary – the reference beam and the object beam. After recording and developing the hologram in a chemical solution, it is necessary to place the hologram precisely on the original place of recording. The object is then illuminated by a beam again and so-called reconstruction is performed. The reference beam serves now as a reconstruction beam. The object beam produces interference on the holographic plate, making monochrome stripes of given width, corresponding to the given shift of material surface. Quantitatively, the formation and position of the stripes is given by description of the reconstruction wave according to [3].

The condition for creating dark stripes is given by :

$$\Phi_{\mathrm{S}} - \Phi'_{\mathrm{S}} = \pi\,(2\,m+1)\ , \tag{1}$$

where Φ_{S} is the original topology, Φ'_{S} is the topology after a given number of cycles, m is an integer.

Reflection wave interference will be used to determine the size of loss. Path difference will be equal to twice the distance between the surfaces Δ and therefore it holds :

$$\Delta = \frac{1}{2}\,\frac{\lambda}{2\pi}\,(\Phi_{\mathrm{S}} - \Phi'_{\mathrm{S}}) = \frac{\lambda}{2\pi}\,(2\,m+1)\,\frac{\lambda}{2}\ , \tag{2}$$

where λ is the wavelength of the laser.

5. Creating a model

The basic problem defined in the introduction and the following chapter is solved partly in the submitted paper. An important part of the solution is to determine the level of the model of the problem being solved. Of course, it would be ideal to perform measurements on a specific patient, which is impossible for many reasons. As it is the first model related to the identification of polyethylene acetabulum wear at our workplace, a simple model involving the mechanical interaction between the acetabulum and the head of total hip endoprosthesis was created. The basic characteristics of this model have already been defined at the design, construction and production of load equipment simulating human walking. Force interaction between the cup and the head of the hip joint was determined on the basis of experience in computing solutions of various hip connections at the level of resulting contact forces. In this way, the value of the resulting contact force between the head and the cup was determined to be 2400 N for a person weighing 80 kg, and the direction of this force is deflected from the vertical by 17°. Human walking is simulated using two independent rotations. One expresses adduction associated with the movement of human in the frontal plane, the second expresses the flexion with extension of the lower limb in the sagittal plane. The sizes of these movements are based on the literature [2] and own measurements. The size of adduction is ±5° and the size of flexion with extension is ±25°. Figure 1 shows a scheme of the load machine. The flexion with extension is simulated by a vertically positioned motor on the rotor of which a ceramic head of hip TEP is placed. Adduction is simulated by a horizontally positioned motor the shaft of which is connected to a dish for TEP cup application. At first measurements the direction of the carrier of final contact force was identical to the axis of the vertically positioned motor.

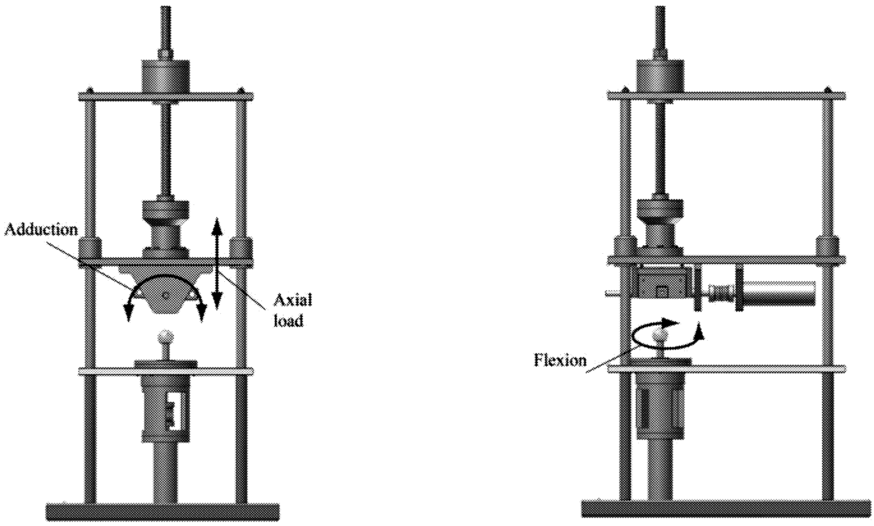

Fig.1: Scheme of the load machine

6. Mechanical properties of polyethylene

The mechanical properties of polyethylene depend primarily on the method of production. From this perspective, low-pressure polyethylene, the structure of which is more regular than in other methods of production, appeared to be most convenient and with better mechanical properties. Its main advantages include ease of processing, biocompatibility, low moisture absorption and high impact value. Currently, ultra-high molecular weight polyethylene (UHMWPE) is mostly used, as its characteristics and practical use proved most advantageous. It is characterized by high elongation and resistance to biological corrosion. A big asset of polyethylene is its ability to absorb impact stress. This advantage is used for acetabular cup, where impacts are produced due to the function. 'Creep' is characteristic for polyethylene. This effect occurs at a time delay. This means that deformations occur under constant load. Table 1 shows some of the mechanical properties of polyethylene. The disadvantage is the need for sterilization of polyethylene. Sterilization is performed by irradiation with gamma rays in a nitrogen atmosphere. Ultra-high molecular weight polyethylene is achieved by irradiation with electron beams at heating process that creates cross links. The result is a structure that is highly resistant to abrasion. The polyethylene of brand names Sulene-PE and Durasul is used for biomechanical implants.

Material	Density [kg/m^3]	Yield strength [MPa]	Breaking strength [MPa]	Elongation at failure [%]	Impact value [kJ/mm^2]
Sulene-PE	927–944	min–21	min–35	min–300	min–180
Durasul	927–944	min–19	min–27	min–250	min–30

Tab.1: Mechanical properties of polyethylene

7. Presentation and analysis of measurement results

Using optical holographic methods, we are able to locate the wear size and places where is this wears.The analysis of the wear of material was carried out on a designated network of Fig. 2, in the radius of 2 and 6 mm. Table 2 is an example of setting the holographic device and calculating the length of exposure. Fig. 3 shows an example power load acetabulum arthroplasty. After each stage of loading were made records with holographic interferential stripes example in Fig. 4. The holographic image to assess the size of the wear (2) and results are presented for illustration in Fig. 5. After all stages of loading and wear evaluation chart is construct polyethylene total wear Fig. 6.

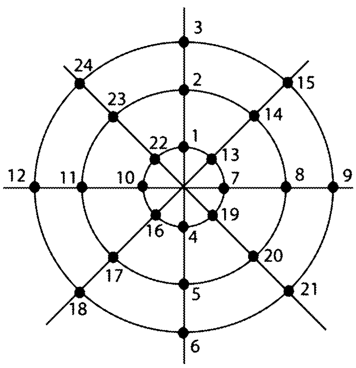

Fig.2: Marked measuring points on the TEP cup

Measurement of beam energy			
	Marking	Measured value	Unit
Image	I_{O}	1.63	μW/cm^2
Reference	I_{R}	4.50	
Measured total beam	I_{C}	6.82	
Beam ratio			
$\frac{I_{\mathrm{R}}}{I_{\mathrm{O}}} = 2.76$			
Calculation of exposure time			
$t = \frac{I_{\mathrm{P}}}{2\,I_{\mathrm{c}}} = \frac{65}{2 \times 6.82} = 4.76$			s
Actual exposure time	5		

Tab.2: Mechanical properties of polyethylene

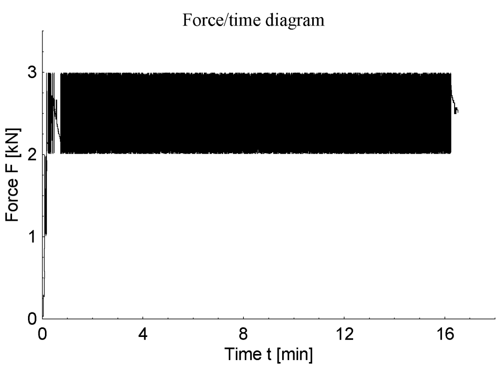

Fig.3: Force/time diagram

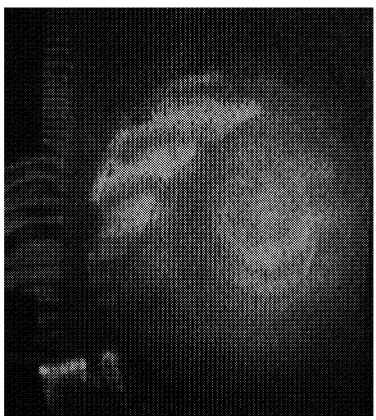

Fig.4: Image with interference stripes

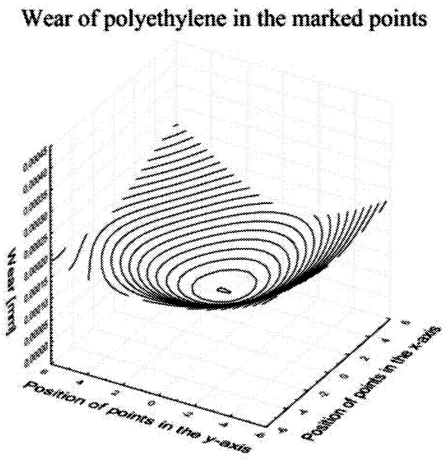

Fig.5: Wear of polyethylene in the marked points

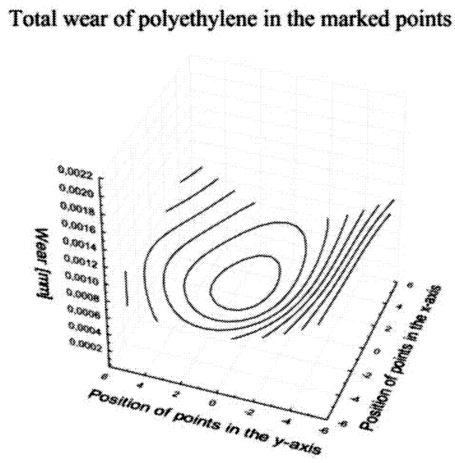

Fig.6: Total loss of polyethylene in the marked points

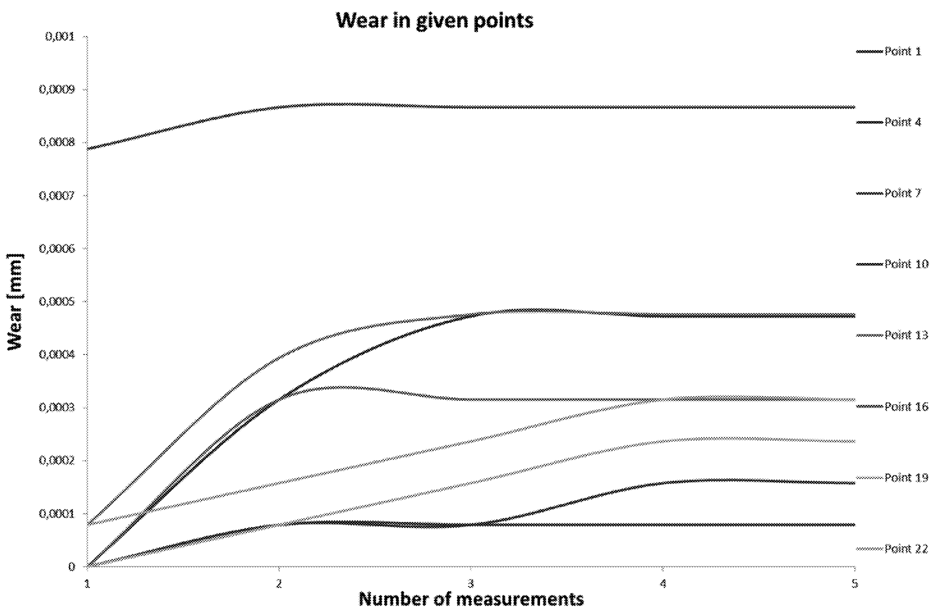

Fig.7: The size of wear after five loaded cycles the radius R2

8. Conclusion

The wear of polyethylene described in this article is measured using the holographic optical method. The linear loss of polyethylene of the hip TEP acetabulum is calculated from the change in topology of individual surfaces (between the given measurements). A network of points was created on the acetabulum, in which the material loss and the total loss were evaluated after 500 and 2500 load cycles simulating human walking, respectively. The total loss of polyethylene in the analyzed area is in the range of $\langle 0.000079, 0.001520\rangle$ mm. The analysis implies that there is no significant loss of polyethylene on the cup circular areas with the radius of 2 mm after 1500 cycles, see Fig. 7. The probable cause of this

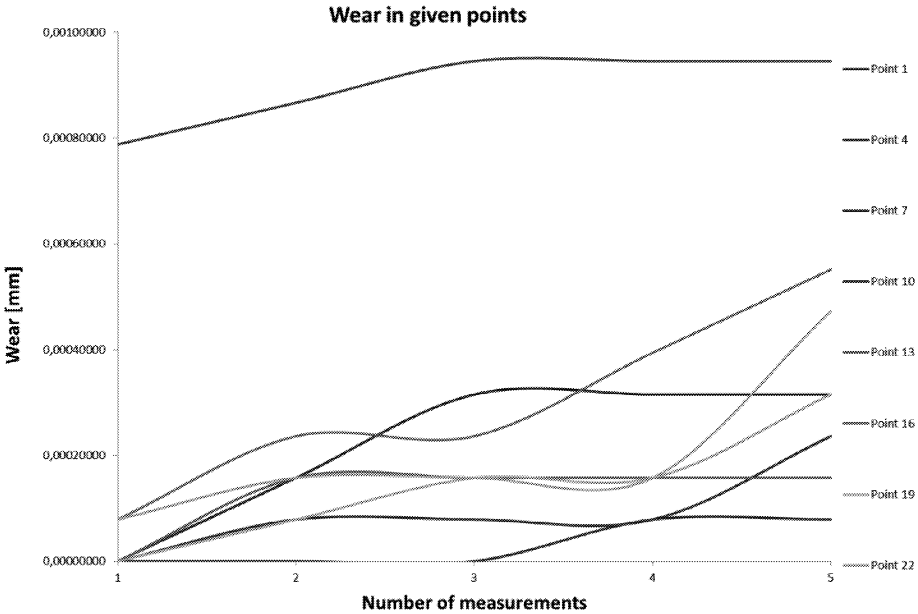

Fig.8: The size of wear after five loaded cycles the radius R6

phenomenon is that the femoral head and the acetabular cup were mounted with clearance, so the contact is the most frequent near the centre and the contact area increases with increasing wear. A different situation is in the radius of 6 mm, see Fig. 8, where the loss of material is increasing with an increasing number of load cycles. It may be concluded that the used method of holographic interferometry is a suitable tool for identifying small material losses that cannot be identified with a sufficient precision by another method (e.g. weighing).

Acknowledgments

This study was suppoted by the project The Ministry of Education, Youth and Sports of the Czech Republic, research plan MSM 0021630518 'Simulation modeling of mechatronic systems' and project FSI-S-11-12 'Complex analyses of biomechanic problems'.

Literatura

[1] Gallo J., Havránek V., Zapletalová J., Mandát D.: Measurement of Wear of Hip TEP Polyethylene Cup with a Universal Measuring Microscope, Acta Chirurgiae Orthopaedicae Et Traumatologiae Čechosl., 73, 2006, p. 28–33
[2] Čihák R.: Anatomie 1, Avicenum, Prague, 1987
[3] Baláš J., Szabó V.: Holographic Interferometry in Experimental Mechanics, Bratislava 1986
[4] Miler M.: Holography (Theoretical and Experimental Elements and Its Use), Prague 1974
[5] Baudyš A.: Technical Optics, Skriptum ČVUT, Prague 1996
[6] d'Antonio J.A., Dietrich M.: Bioceramics and Alternative Bearings in Joint Arthroplasty, Washington DC, 2005

Received in editor's office: July 19, 2011
Approved for publishing: October 18, 2011