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THE EVALUATION OF DIMENSIONAL AND SHAPE ACCURACY OF FRICTION PAIR ELEMENTS: BALL - CUP

Niemczewska-Wójcik Magdalena [1], *Krawczyk Marcin* [2], *Wójcik Artur* [3]

[1] Institute of Production Engineering, Cracow University of Technology, Cracow, Poland, niemczewska@mech.pk.edu.pl
[2] Laboratory of Coordinate Metrology, Cracow University of Technology, Cracow, Poland, mkrawczyk@mech.pk.edu.pl
[3] Department of Mechanical Engineering and Agrophysics, University of Agriculture in Cracow, Cracow, Poland, artur.wojcik@ur.krakow.pl

Abstract – The paper presents the principles and stages of forming a ball (metal head component) and a cup (polymeric acetabular component) constituting an artificial hip joint in the finishing process. The requirements of the standard specification ASTM F2033-12 concerning a method for measuring permissible limits of departure from roundness and roundness tolerance of examined elements were discussed. The obtained measurement results were analyzed and evaluated, on the basis of which conclusions were drawn and directions for further research were indicated.

Keywords: hip joint implant, finishing process, ASTM F2033-12, departure from roundness

1. INTRODUCTION

Articular connections play an important role in the skeletal-synovial human system. An example of such a connection is a hip joint which due to heavy loads is most susceptible to mechanical damage, deformation and pathological changes, resulting in the loss of its primary features [1,2].

Progressive aging of the population contributes to the annual increase in the number of hip replacement surgeries in which the damaged joint is replaced by its artificial counterpart – an implant (prosthesis) in Figure 1.

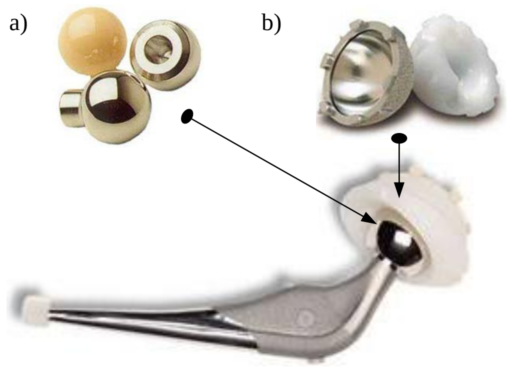


Fig. 1. Hip joint implant and its elements [3]:
a) femoral head components, b) acetabular components

This surgical procedure is called hip arthroplasty. Although lost motor functions of the hip join can be restored, post-operative complications may occur, including implant loosening. This is a major obstacle to the long-term performance of the hip implant, and thus influencing the effectiveness of arthroplasty surgery [2,4,5].

Among factors affecting the durability of prosthesis are the construction of an implant (characteristics of material as well as geometric and dynamic properties) and the human body (psyche, physiological conditions, surgical technique) [3].

What poses a major problem to the stability of joint implants is securing low frictional resistance in the ball-cup friction pair as well as minimizing wear products .

Despite the fact that many national and international research centers have been addressing the problem of implant durability, it has not been resolved to date.

Construction factors include the geometric features of the implant components, among them dimensional and shape accuracy (shape and dimensions) as well as surface quality (surface damage, waviness, and roughness) [6,7,8].

The accuracy of the formed elements of a hip joint implant with respect to shape and size plays a significant role in fitting the operating parts of an implant and its functioning.

The formation process (manufacturing) and the accompanying control (measuring) of obtained dimensional and shape parameters is subject to error [9,10]. In general terms, errors result from the interaction of the elements of the production and measurement system, such as the type of material from which the object is made, the manufacturing technology, the tool, the measuring device, measuring strategy, used software, environment, the operator, etc. [11,12,13].

There are many ways of establishing the causes of departure from dimensions and shape in the manufacturing process as well as finding out the causes of measurement errors.

Regardless of the error source, deviation from the nominal dimension (departure from roundness), determined in relevant standards, is possible.

2. MATERIALS AND METHODS

The subject of the study were elements of the friction pair of the hip joint prosthesis: ball and cup (femoral head and acetabulum). The balls were made of metal - titanium alloy (*Ti-6,5Al-1,3Si-2Zr*); whereas cups were made of polymeric material (polyethylene UHMWPE).

These types of materials met stringent requirements for materials intended to be used in medical technique with regards to joint implants.

The examined and analyzed friction pair elements (balls and cups) were labeled as follows:

- metal (titanium alloy) balls: TYT
- polymeric cups: PE

Finishing process of the metal semi-finished products was carried out on machine tools in the Institute of Superhard Materials in Kiev, Ukraine. This process consists of grinding and lapping (polishing).

Semi-finished products were subjected to grinding, first with the use of diamond abrasive grains (ASO 125/100) ranging from 125 to 100μm (Figure 2a), and then with diamond abrasive grains (ASM 3/1) ranging from 3 to 1μm (Figure 2b). Owing to this, the required size was obtained, with the head diameter equal to ø28 mm and surplus material left for the final stage of processing.

a) b)

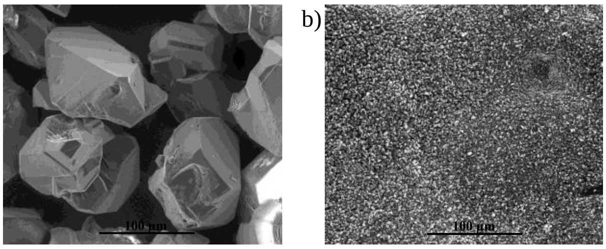


Fig. 2. Diamond tools (zoom x1000):
a) grains ASO 125/100, b) micrograins ASM 3/1

The proper function of friction pair components (such as ball-cup in hip joint implant) depends i.a. on surface topography (i.e. securing the required quality of a surface) in the manufacturing process, in particular during a finishing treatment.

The finishing process of spherical metal components (heads - balls) consisted of two stages. In both stages, discs and polishing pastes were used. The first stage was carried out using a polishing paste and a rubber blade. The second polishing stage, making up the final stage of a finishing process at the same time, was realized using a polishing paste and a disc covered with cotton. As a result, metal components (balls) with the diameter of ø28 mm, displaying the required condition of the surface layer, were obtained.

Polymeric spherical components (cups) were obtained from rods which had been cut into tabular pieces, in which holes (cups) were made subsequently in the course of a turning operation. With the view of assuring the desired work surface condition, for finishing of the inner cup, polishing with felt, with the exclusion of paste, was applied, as a result of which the polymeric components (cups) with the diameter of ø28 mm were obtained along with the required surface topography.
More details about finishing were presented in the [14].

According to the standard (ASTM F2033-12, *Standard Specification for Total Hip Prosthesis and Hip Endoprosthesis Bearing Surfaces Made of Metallic, Ceramic and Polymeric Materials* [15]), when using 5-diopter magnification the bearing surface (for femoral head as well as acetabulum) shall be free from particles, scratches, and score marks other than those arising from the finishing process. Furthermore, the spherical bearing surface of a femoral component (ball) shall have a R_a value not greater than 0.05μm and the measurements shall be taken at the location of the pole and 30° from the pole. Next, the metal or ceramic spherical bearing surface of a femoral component shall have departure from roundness of not greater than 10μm. Otherwise, the spherical bearing surface shall have a diameter equal to the nominal diameter with a tolerance of +0.0−0.2mm.

The spherical bearing surface of the acetabular component (cup) made of polymeric material shall have a diameter equal to the nominal diameter within a tolerance of +0.3−0.0mm at a temperature of 20±2°C. The cup should be oversized to the nominal within the given tolerance range. The spherical bearing surface of the polymeric acetabular component shall have a R_a value not greater than 2μm.

The obtained results, in terms of dimensional and shape accuracy as well as the surface quality of the balls and cups were compliant with the requirements of the ASTM F2033-12 standard.

Due to the complexity of research and analysis, this paper presents only the results of measurements and evaluation of dimensional and shape accuracy of the components studied.

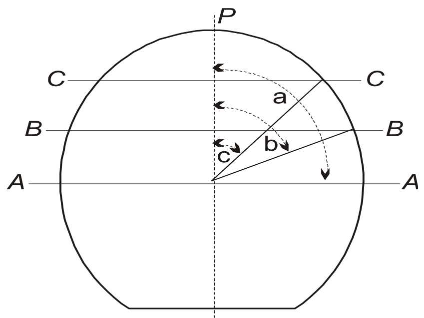
The departure from roundness was measured by using a high-accuracy three-dimensional measuring machine, the Coordinate Measuring Machine (CMM) – PMM 12106 (MPE=*0.0008+0.0025/1000*L[mm]*) - Figure 3.

Fig. 3. Coordinate Measuring Machine (CMM)

This machine has a measuring range of 1200x1000x600 [mm] and is equipped with an active scanning probe. Due to the size of the studied elements, in measurements made for the purposes of this paper, the contact tip with the diameter of 2 mm was used.

The measurement points were situated in planes marked with *A-A*, *B-B* and *C-C* as shown in Figure 4a (for femoral head - ball) and in Figure 4b (for acetabulum - cup), according to the standard ASTM F2033-12.

a)



b)

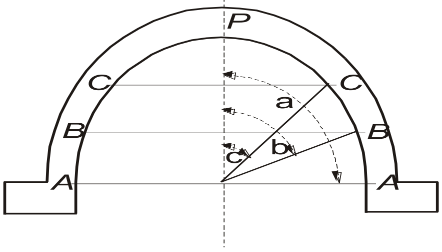


Fig. 4. Location of measurement points:
a) on the femoral head (ball), b) on the acetabulum (cup).

The departure from roundness is defined as the difference between the smaller and the larger distance measured from the centre *0*. Therefore, the measurements were carried out in the local coordinate system of the machine, having its origin in the centre *0* of the object (ball or cup) being measured. The research results from CMM were evaluated with the use of sophisticated metrological software – Quindos.

3. RESULTS AND DISCUSSION

The elements of the friction pair of hip joint prosthesis ball-cup, obtained during finishing process (Figure 5), were analysed with regards to dimensional and shape accuracy (departure from roundness and tolerance).

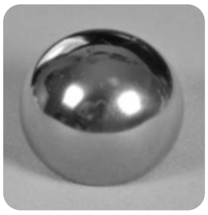
a)  b) 

Fig. 5. Samples: a) ball, b) cup

The departures from roundness concerning the artificial femoral heads (balls) and the acetabulum (cup) examined in different surface locations (planes: *A-A*, *B-B* and *C-C*) are presented in the Table 1 (for balls) and Table 2 (for cups).

Table 1. Results of measurements for balls (values)

Element	Departure from roundness *Δ* [μm]			
	1	*2*	*3*	*Mean*
TYT A-A	6,1	5,8	5,8	5,900
TYT B-B	5,0	3,8	5,0	4,600
TYT C-C	2,6	3,4	2,5	2,833

Table 2. Results of measurements for cups (values)

Element	Departure from roundness *Δ* [μm]			
	1	*2*	*3*	*Mean*
PE A-A	3,7	3,2	3,1	3,333
PE B-B	1,4	2,1	1,5	1,667
PE C-C	3,5	2,3	3,6	3,133

On the basis of the measurement results the mean value of departure from roundness for each of the planes were determined. Differences were shown in diagrams: in Figure 6, for titanium balls; and in Figure 7, for the polymeric cups.

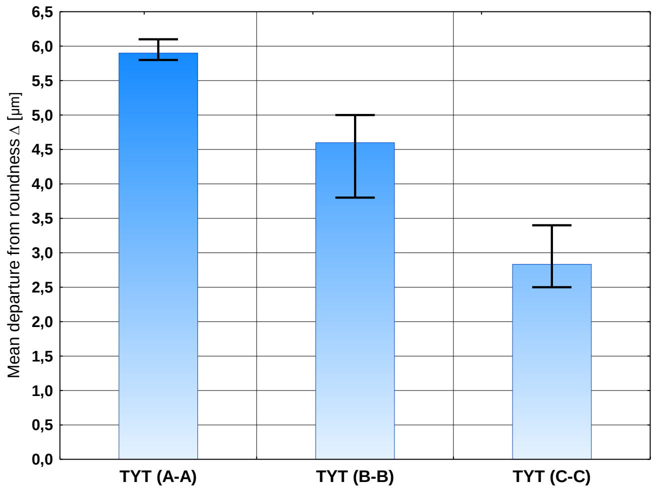


Fig. 6. The comparison of mean departure from roundness in the various measurement planes for the TYT balls

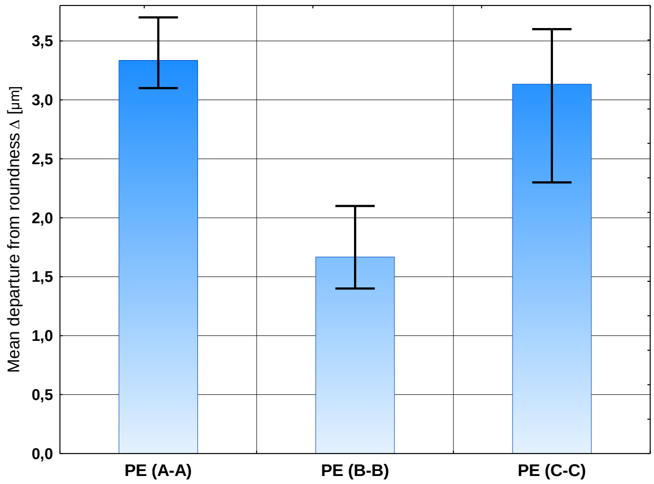


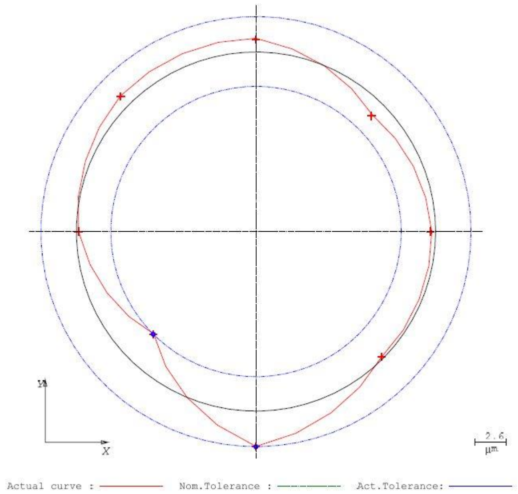
Fig. 7. The comparison of mean departure from roundness in the various measurement planes for the PE cups

The obtained results (chosen ones – Table 1 and Table 2 as well as Figures 6 and 7) showed that the specification requirements regarding balls used in conjunction with a polymeric cup ($\Delta \leq 10\mu m$) were met.

For TYT balls, the best results were obtained in the *C-C* plane, the worst in the *A-A* plane. For PE cups, the best results were obtained in the *B-B* plane, the poorest in the *A-A* plane. The dimensional tolerance is compliant with the requirements of the standard.

The measurement results of departure from roundness displayed by several planes of a selected ball (metal head component) and a cup (polymeric acetabular component) were also shown in Figure 8 (TYT no.2) and Figure 9 (PE no.2).

a)



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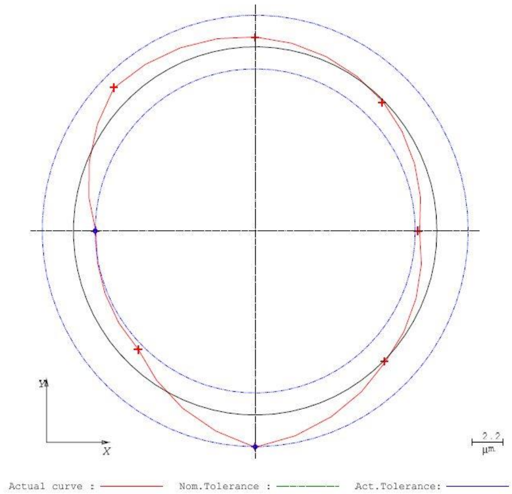


c)

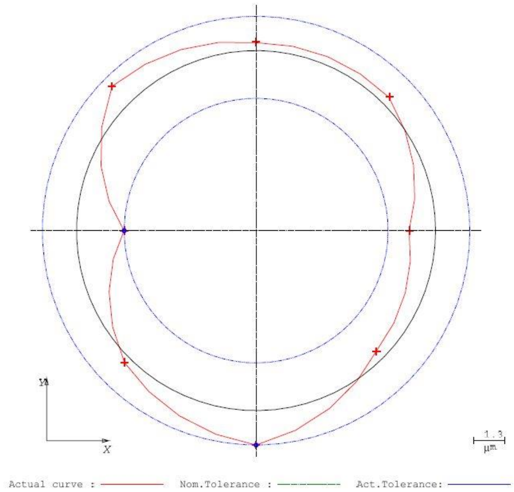
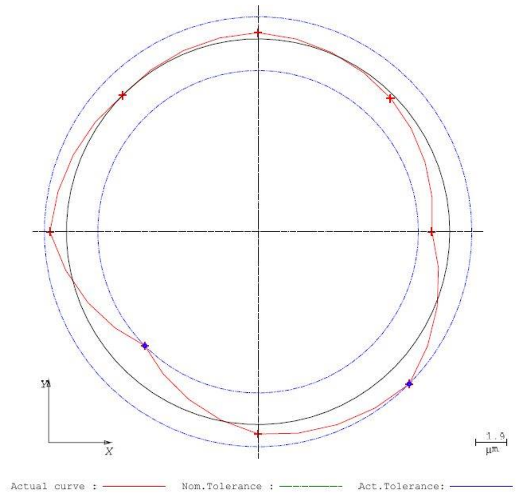


Fig. 8. Departure from roundness for metallic femoral head: a) TYT A-A plane, b) TYT B-B plane, c) TYT C-C plane

Selected measurement results of departure from roundness obtained respectively in planes *A-A*, *B-B*, and *C-C* show significant differences. However, the requirements of ASTM F2033-12 standard were met for all the studied elements.

a)



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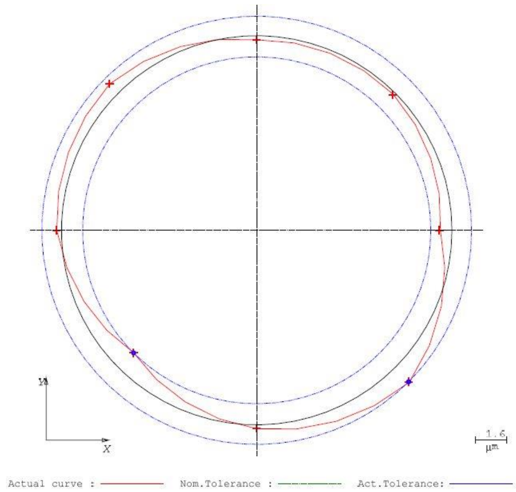

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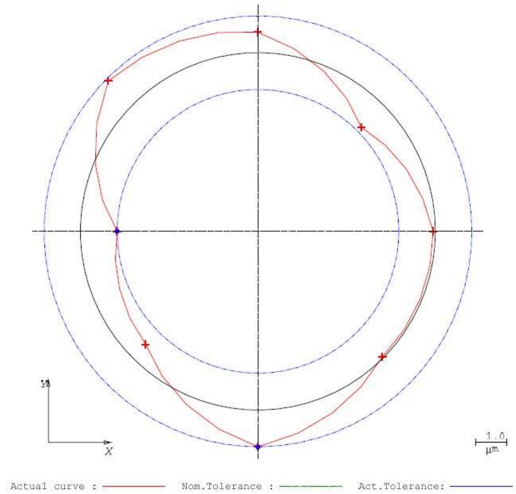

Fig. 9. Departure from roundness for polymeric acetabulum: a) PE A-A plane, b) PE B-B plane, c) PE C-C plane

It should also be remembered that in a natural hip joint the head of the femur is not a perfect sphere. In addition, an element (acetabulum-cup) which cooperates with a metal femoral head (ball) in the artificial hip joint is usually made of a soft polymeric material which is subjected to an influence of the hard metal element.

The bearing surfaces of measured cups and balls, inspected under 5-diopter magnification, were free from particles and scratches. For the TYT balls, the dimensional tolerance is compliant with the requirements of the standard. In this respect, all the measured metal femoral heads fulfilled the requirements of the standard ASTM F2033-12.

4. CONCLUSIONS

The measurement and analysis of the accuracy of the articulating elements of the ball-cup friction pair proved compliant with the requirements of the standard specification.

It seems that the deviation from shape (departure from roundness) might have resulted from the processing technology, including i.a. machine tools, machined materials, an operator of manufacturing (machining) process, a measurement device, a measurement method. These factors should be verified in further studies.

Further research will be aimed at evaluating the elements of a friction pair with regards to their durability. This will be verified with a simulator imitating human gait (in accordance with the standard ASTM F732-00 [16]). Surface topography will be taken into account as well (waviness, roughness, and surface damage). After tribological research, the examined samples will be measured with the use of 3-dimensional measuring machine. On the basis of obtained results, change in dimensional and shape accuracy, resulting from the wear mechanism to which the ball and cup are subjected, will be evaluated.

Conducting verification research will enable to draw conclusions on the production process (forming) of friction pair elements, especially on the manufacturing process of metal femoral heads (balls). Both dimensional and shape accuracy as well as the state of the working surface of an artificial femoral head component plays an important role in the durability of the hip joint implant and influences the size and the wear products of the friction pair: ball-cup (femoral head component –acetabular component).

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