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COINCIDENCE OF THE TECHNOLOGY AND THE SURFACE TOPOGRAPHY OF SPHERICAL ELEMENTS OCCURING DURING MACHINING PROCESS OF HIGH PRECISION

KOINCYDENCJA TECHNOLOGII I TOPOGRAFII POWIERZCHNI ELEMENTÓW SFERYCZNYCH KSZTAŁTOWANYCH W PROCESIE OBRÓBKI PRECYZYJNEJ

Key words:

biomaterials, precision machining, surface topography, functional properties

Słowa kluczowe:

biomateriały, obróbka precyzyjna, topografia powierzchni, potencjalne właściwości użytkowe

Abstract

The paper presents issues concerning the surface layer and the changes in surface topography with respect to spherical elements at the subsequent stages of manufacturing process. Special attention was paid to the forming of surface

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topography in precision machining processes (preliminary grinding, precision grinding, lapping with polishing).

The subjects of research and analysis were spherical elements made of a biomaterial, i.e. titanium alloy (Ti-6.5Al-1.3Si-2Zr). The surfaces of the studied components shaped during the subsequent operations of abrasive machining processes were measured using a coordinate measurement machine (CMM) and a white light interferometer (WLI).

Based on the obtained results, the changes in the surface topography of metallic spherical elements brought about during the subsequent operations of precision machining processes were assessed. In addition to this, functional properties of these surfaces were identified.

INTRODUCTION

Materials that are used for medical applications are called biomaterials. A biomaterial is any substance or a combination of natural or synthetic substances, other than drugs, which at any time can partially or totally replace a tissue, organ, or a function of the body **[L. 4**, **6**, **7**, **14**, **16]**. According to a different definition offered by [**L. 10**, **14**], it is a material possessing certain characteristics that can be used for medical purposes **[L. 6]** and out of which auxiliary body components can be manufactured for temporal or permanent use.

In broad terms, according to the authors of various papers, biomaterials exhibit the following features **[**e.g. **L. 7**, **14]**:

- Biocompatibility (in terms of semiconductor, piezoelectric, and magnetic properties), which is related to their resistance to the environment within an organism and tissue fluid, including chemical inertness, the absence of inflammatory responses and excessive tissue reaction, and the quality of not having allergic, toxic, pyrogenic, or cancer-inducing effects on an organism; and,
- A set of qualities ensuring safe, effective, and reliable load transfer between an implant, tissue, and body fluid.

An important group of biomaterials is made up by substances used for a hip joint endoprosthesis. This group encompasses metallic, polymer, and ceramic materials (inert, resorbable in the body, exhibiting controlled reactivity). Biomaterials which are intended for the components of a hip joint endoprosthesis are required to have the following specific properties **[L. 2**, **3**, **7**, **12**, **13**, **17]**: defined elasticity (elastic modulus), crack resistance, wear resistance, corrosion resistance, high mechanical properties (including good fatigue strength), biotolerance, biocompatibility, low manufacturing costs, suitable electrical properties, proper chemical composition, and fine-grained structure.

Amongst the substances which meet the mentioned requirements are monocrystalline ceramic materials (sapphire monocrystalline α-Al_2O_3), polycrystalline ceramic materials based on zirconium oxide ZrO_2 (Y-TZP), and titanium alloys TiAlSiZr (Ti-6.5Al-1.3Si-2Zr). Due to their distinctive features (such as high fatigue strength, corrosion resistance, reduced mass, and density), they belong to difficult-to-machine materials.

Positive results obtained from biomedical research open up an opportunity for adapting these materials for medical applications, i.e. for hip joint replacement, with the major focus given to the femoral head of a hip joint endoprosthesis once extensive research has been conducted.

Technological studies consist of two stages. At the first stage, a series of components is manufactured from semi-products in precision abrasive machining processes (preliminary grinding, precision grinding, lapping with polishing), which is the subject of this paper. At the following stage, tribological tests are carried out, as a result of which the operational surface layer is formed. At the both stages, the measurement and assessment of the machined surface (first stage) and the operational one (second stage) are performed. Based on the results acquired from the technological studies, information on the functionality of biomaterials intended for co-action with polymeric components in the ball-and-socket (femoral head-and-acetabular cup) configuration is gained.

MATERIALS AND METHODS

The subjects of the study were the spherical components made of biomaterials (titanium alloy Ti-6.5Al-1.3Si-2Zr) intended for the components of hip joint endoprosthesis.

The titanium alloys are characterized by the following properties **[L. 17]**:

- flexural strength σ_z [MPa]: 900
- Young's modulus E [GPa]: 114
- density [g/cm^3]: 4.43

Manufacturing– precision machining process [L. 17]

In the Institute of Production Engineering at Cracow University of Technology, a three-spindle, variable-speed machining system aimed at performing spherical elements made of difficult-to-machine materials was installed (**Fig. 1a**). This machining system was based on the body of the milling machine (FNX 30P) produced by the Factory of Precision Machine Tools AVIA S.A. The precision machining process of spherical elements was possible due to a special device designed for shaping (**Fig. 1b**) and finishing operations (**Fig. 1c**), which was equipped with a self-propelled and numerical control system.

a) b) c)

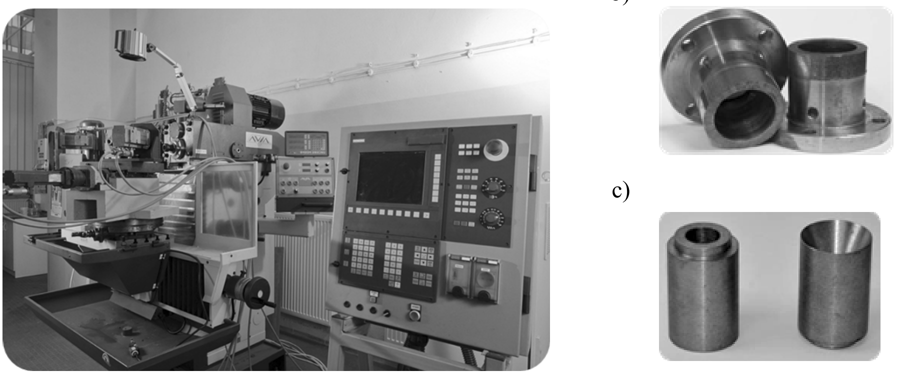


Fig. 1. Machining device (a) and diamond tools for machining operations [L.18]: shaping (b), and finishing (c)

Rys. 1. Obrabiarka (a) oraz narzędzia diamentowe do obróbki **[L. 18]**: kształtującej (b), wykończeniowej (c)

The characteristics of the machining operations related to spherical metallic elements (balls made of titanium alloy) are shown in **Tab. 1**. The machining conditions of the elements having a diameter of 28mm are provided below:

- Grinding speed [m/s] 4.1–4.7,
- Reversible rotation feed rate [cycles/min] 2–3,
- Infeed [mm/cycle]: 0.005,
- Cutting fluid, a type of coolant and lubricant to be used in precision machining centres.

Table 1. Machining operations concerning difficult-to-machine materials

Tabela 1. Etapy obróbki materiałów trudnoobrabialnych

Tool characteristics	
Stage I	• grinding wheel with an external/internal diameter of 27/19mm **Fig. 1b**, • diamond grains of different sizes ranging from 100–125 μm • organic binder
Stage II	• grinding wheel with an external/internal diameter of 30/20mm **Fig. 1c**, • diamond micrograins of different sizes ranging from 1–3 μm • organic binder.
Stage III	• polishing paste and shield (rubber or cotton one)

The size of excess material left for removal after the first operation of machining process was 0.10–0.15 µm; however, after the second operation, it ranged between 3 and 10 µm.

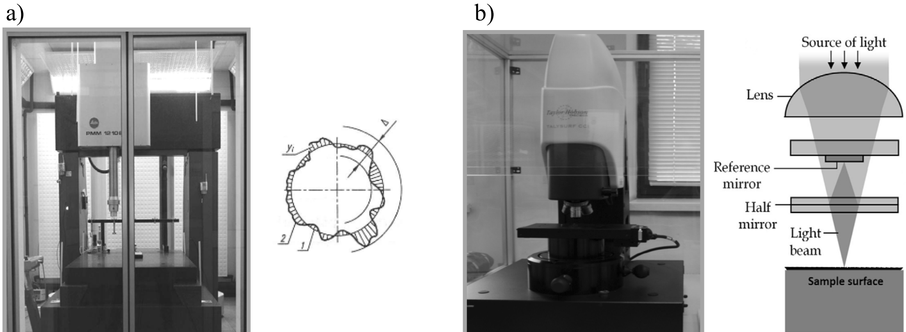
The proper function of the prosthesis (femoral head-and-acetabular cup friction pair) of a human hip joint depends, inter alia, on the surface topography formed in the course of implant manufacturing process **[L. 11**, **15]**. This especially refers to the final operation of machining, i.e. lapping and polishing at the third operation of the process.

The finishing process of the spherical elements (femoral heads, or balls) made of titanium alloy, which produced a surface layer of the balls with the desired shape, consisted of two stages: (1) lapping with the use of a polishing paste (which was prepared in the Institute for Superhard Materials of the National Academy of Sciences of Ukraine, Kiev); and, (2) polishing with the use of a rubber or cotton shield.

Measurement devices

The machines surface of the spherical elements, which resulted from precision machining processes, was measured using two devices (**Fig. 2**): a coordinate measurement machine CMM (the dimensional and shape accuracy of the elements) and a white light interferometer WLI (surface texture).

a) b)



Measuring parameters for CMM [L.8]:	**Measuring parameters for WLI**:
• readings taken in the planes *AA*, *BB*, CC	• readings taken at the pole, in the plane *CC*
• contact probe: ø5	• lens : x10 Mirou

Fig. 2. Measurement devices [L. 9]
Rys. 2. Urządzenia pomiarowe **[L. 9]**

The departure from roundness *Δ* (radial deviation from a reference circle - circularity – **Fig. 2a**) was designated in three planes (*AA*, *BB*, *CC*), and it is presented in **Fig. 3**, where *A (a)*, *B (b= 2a/3)*, *C (c= a/3)*. Parameters for the qualitative description of surface texture (**Tab. 3**) were checked by taking measurements at the location of the pole and 30^0 from the pole *P*, i.e. in the area defined by an angle between the pole *P* and the plane *CC*.

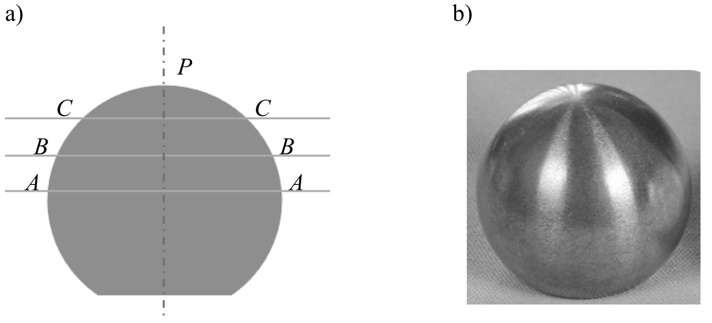


Fig. 3. Spherical element: a) location of measurement points, b) the view of the element
Rys. 3. Element sferyczny: a) lokalizacja punktów pomiarowych, b) zdjęcie

The results produced by CMM provided information on the dimensional and shape accuracy of the spherical components, which underwent changes at the subsequent operations of the machining process, i.e. grinding, lapping, and polishing; whereas the measurements carried out with the use of WLI allowed for the analysis of surface microgeometry (surface texture).

The application of two measuring devices facilitated the comprehensive analysis of the examined components, which allowed the drawing of conclusions on the machining of difficult-to-machine materials and the changes in the surface topography of spherical elements brought about in the course of the machining process.

Due to the number of conducted measurements, this paper presents only selected and representative results that are meant to illustrate the essence of the undertaken matter.

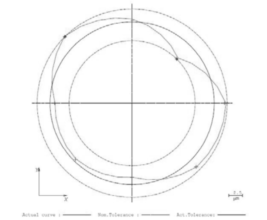
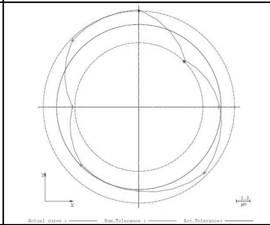
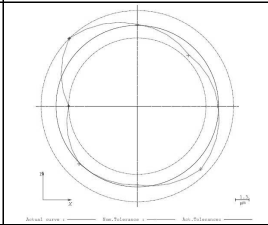
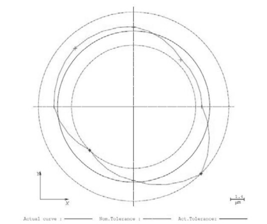
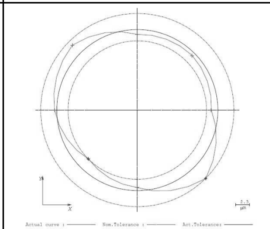
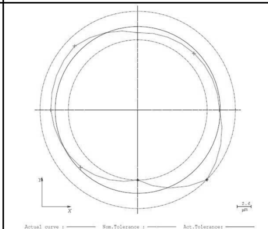
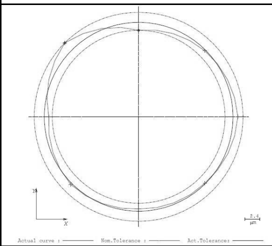
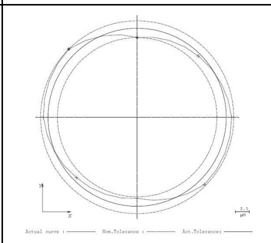
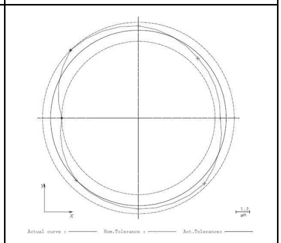
RESULTS AND DISCUSSION

The surface topography of the examined workpieces was subjected to analysis performed based on the results obtained from CMM and WLI.

Table 2 displays the results acquired from a coordinate measuring machine CMM (the measurements of the departure from roundness were taken in three different planes). **Tables 3** and **4** display the results obtained from the white light interferometer WLI.

The collected measurement results (**Tab. 2**) indicate a change in surface topography (sphericity) at the subsequent operations of the machining process, which provides evidence that the machining technology was properly adjusted to difficult-to-machine titanium alloys.

Table 2. Measurement results (CMM) – departure from roundness in planes
Tabela 2. Wyniki pomiaru (CMM) – błąd kształtu w płaszczyznach

Plane	***AA***	***BB***	***CC***
Stage I			
	Δ=5.8μm	Δ=5.0μm	Δ=2.6μm
Stage II			
	Δ=5.1μm	Δ=4.4μm	Δ=3.3μm
Stage III			
	Δ=2.9μm	Δ=2.5μm	Δ=1.7μm

The highest out-of-roundness values were observed for the plane *AA*, and the lowest values were observed for *CC*. Deviation from a reference circle was determined by a multitude of factors, such as the material from which the studied workpiece was made, the adopted manufacturing process, machining tools, the measuring machine and its accuracy, measurement strategy, software, etc. **[L. 17]**. Nevertheless, despite noticeable differences, all the measurements performed proved compliance with the guidelines of the standard ASTM F2033-12 (Δ <10 μm).

Tables 3 and **4** show the measurement results of surface topographies (surface texture) that were obtained after having derived the shape (sphericity) of the measured components. Taking into consideration the requirements imposed by the standard ASTM F2033-12 **[L. 1]** and bearing in mind that most favourable tribological conditions (assured by surface quality) which existed between the examined balls and the co-acting sockets were observed for the area between the pole *P* and the plane *CC*, the measurements of surface topography were taken at this very location. The results show the changes in surface texture occurring at the subsequent operations of machining.

Table 3. Measurement results (WLI) – surface texture and parameters
Tabela 3. Wyniki pomiaru (WLI) – tekstura powierzchni i parametry

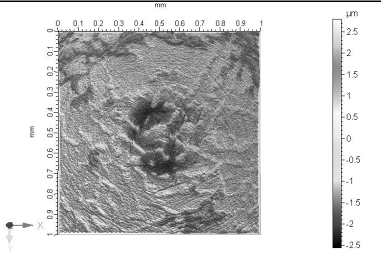
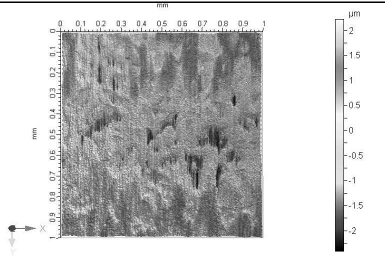
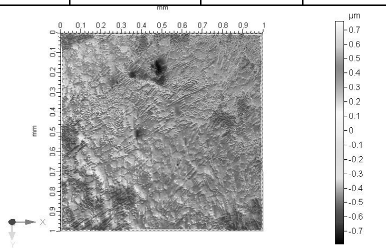
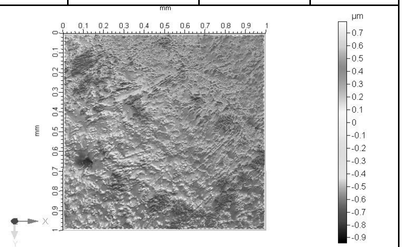
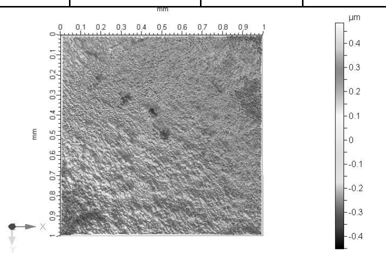
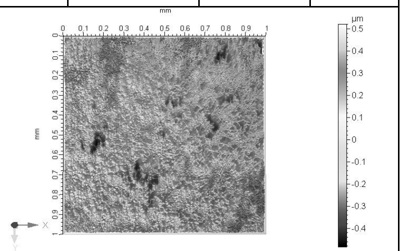
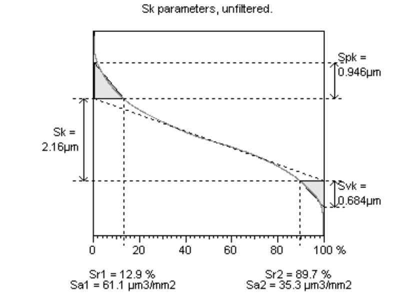
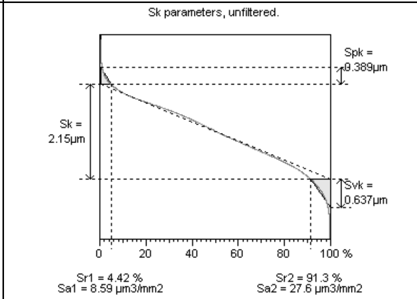
Place	***P***				***CC***			
Stage I								
	Sz [μm]	*Spd* [1/mm^2]	*Ssk* [-]	*Sku* [-]	*Sz* [μm]	*Spd* [1/mm^2]	*Ssk* [-]	*Sku* [-]
	5.35	928	0.207	2.73	4.63	898	-0.233	2.40
Stage II								
	Sz [μm]	*Spd* [1/mm^2]	*Ssk* [-]	*Sku* [-]	*Sz* [μm]	*Spd* [1/mm^2]	*Ssk* [-]	*Sku* [-]
	1.55	3393	0.047	3.16	1.73	2632	0.091	3.32
Stage III								
	Sz [μm]	*Spd* [1/mm^2]	*Ssk* [-]	*Sku* [-]	*Sz* [μm]	*Spd* [1/mm^2]	*Ssk* [-]	*Sku* [-]
	0.94	7800	0.035	3.01	1.01	5131	0.071	2.83

Table 4. Measurement results (WLI) – the graphical study of Sk parameter
Tabela 4. Wyniki pomiaru (WLI) – graficzna analiza parametrów Sk

<table>
<tr><th>Place</th><th>P</th><th>CC</th></tr>
<tr><td>Step I</td><td>
</td><td>
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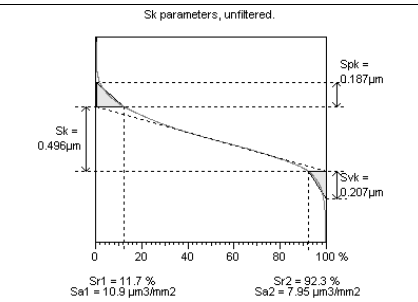
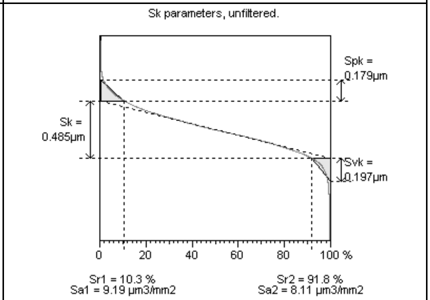
<tr><td>Step II</td><td>
</td><td>
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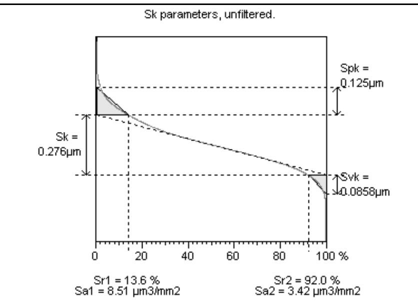
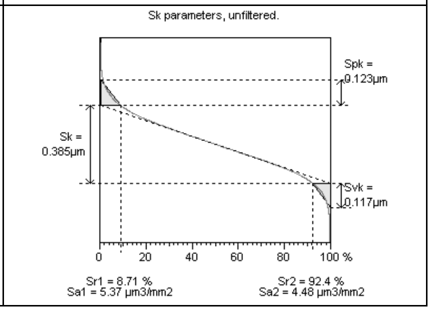
<tr><td>Step III</td><td>
</td><td>
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The changes in the surface topography was depicted in images providing qualitative information on the surface texture; whereas quantitative information about it was extracted from the values of selected roughness parameters which describe surface structure, i.e. *Sz* – the maximum height of the surface; *Sq* – the root mean square deviation of the surface; *Ssk* – the skewness of surface height distribution; *Sku* – kurtosis of the surface height distribution; *Spd* – the density of peaks.

The values of the parameters (e.g., *Sz*) indicate that the surface texture underwent considerable changes at each operation of the machining process. The largest increase in value was observed for *Spd* parameter, which means that the density of peaks constituting the bearing surface of the ball (femoral head) must have risen. This may have a powerful impact on the bearing surface of the polymeric socket being a part of the ball-and-socket friction pair constituting a hip joint endoprosthesis.

Surface inequalities observed on the metallic balls at the location of the pole *P* were evenly distributed across the surface, with fairly sharp peaks and steep slopes, which was reflected in the values of *Sku* and *Ssk* parameters. Such surface texture may influence the tribological characteristics of the ball-and-socket friction pair, since, at the early stage of co-acting, the polymeric material is being microcut from the polymeric socket and then transferred to the bearing surface of the ball as wear products.

The parameters describing the bearing area curve also provide evidence that the surface texture went through changes. With every stage, the values of *Spk*, *Sk*, and *Svk* gradually decreased, which may indicate improvement in the functional properties of the titanium alloys. The value of *Spk* parameter describing the reduced peak height of the surface indicates a decrease in peak height, which means that, during co-action, the bearing surface of the socket might have suffered less destruction resulting from microcutting the material from the articulating component. As for *Svk* parameter (reduced valley depth), its value also decreased. On the one hand, it may indicate that wear products might have been deposited in the valleys to a lesser extent. However, on the other hand, it may point to the deterioration of the functional properties of the examined surfaces, which is associated with limited storage of lubricant in these valleys. Consequently, co-action under the conditions of fluid friction gets reduced (increased risk of boundary and dry friction).

CONCLUSIONS

The results of the research, presented in this paper, which concerned the changes in the surface topography of the spherical components (made of titanium alloy: Ti-6.5Al-1.3Si-2Zr) at the subsequent operations of precision machining processes have brought about the following conclusions:

- Material properties play an important part in determining and selecting parameters for machining processes altering the surface of a manufactured component.
- The use of abrasive grains of different sizes at the subsequent operations of a machining process allow for the reduction or entire elimination of defects arising from the previous operation of machining process.
- The analysis of parameters describing surface topography obtained at the subsequent operations of machining process shows that abrasive grains exert an influence on the surface texture of metallic balls (femoral heads). Provided that the conditions of machining process are fitted with the semi-

products made of titanium alloys, the required surface quality (along with functional properties) can be ensured.

- The presented analysis of parameters and function (bearing area curve) describing the surface topography of each item in a quantitative manner seems to be sufficient at this stage of studies, since it shows the method of how the surface structure of metallic spherical components (heads of a hip joint endoprosthesis) is shaped at the subsequent operations of a precision machining process.

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Streszczenie

W pracy przedstawiono zagadnienia dotyczące warstwy wierzchniej oraz zmian topografii powierzchni elementów sferycznych podczas kolejnych etapów procesu wytwarzania. Szczególną uwagę zwrócono na kształtowanie topografii powierzchni w obróbce precyzyjnej (szlifowanie wstępne, szlifowanie precyzyjne, docieranie z polerowaniem).

Przedmiotem badań oraz analiz były elementy o zarysie sferycznym wykonane z biomateriału – stopu tytanu (Ti-6.5Al-1.3Si-2Zr). Powierzchnie elementów ukształtowane w kolejnych etapach procesu obróbki ściernej zostały zbadane z wykorzystaniem współrzędnościowej maszyny pomiarowej (*Coordinate Measurement Machine* – CMM) oraz interferometru optycznego (*White Light Intereferometry* – WLI).

Na podstawie otrzymanych wyników oceniono proces zmian topografii powierzchni metalowych elementów sferycznych podczas kolejnych etapów procesu obróbki precyzyjnej oraz określono potencjalne właściwości użytkowe tych powierzchni.