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The surface topography of a metallic femoral head and its influence on the wear mechanism of a polymeric acetabulum

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ABSTRACT

The wear mechanisms of friction components depend on conditions of articulation, material properties and surface topography of the co-acting parts. Therefore, it is important to examine these determinants in order to improve the durability of a friction pair. With the view of securing the longer life of articulating surfaces, a metallic femoral head used in conjunction with a polymeric acetabulum was subject to research. The components of the friction pair were prepared in accordance with the standard specification ASTM F2033-12. From the precision machining process of metallic femoral heads, two different kinds of surface topography (defined by Ra parameter: $Ra(A) < Ra(B)$) were obtained. The tribological research was performed with a testing machine simulating the kinematic movements and the working conditions of a natural joint (friction pair: ball-and-socket) in the Ringer's solution. The measurements of the surface topography (machined and worn surfaces) were conducted using the following measuring devices: coordinate measuring machine, white light interference microscopy and scanning electron microscopy. Based on the analysis results, the influence of the surface topography of the metallic ball upon tribological characteristics was determined. The wear mechanisms of the polymeric socket resulted from a number of phenomena, including plastic deformation, abrasive wear, fatigue and adhesion.

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1. Introduction

In the human osteoarticular system, the important role is played by synovial joints, among them the hip joint. Due to heavy loads that it carries during movement, it is exposed to destruction, deformation, mechanical damage and pathological changes [1,2]. When the hip joint loses its primary functions, at first pharmacological and relieving treatments are applied. If these methods are of no avail, surgical treatment becomes a necessity. Arthroplasty counts amongst most common hip joint reconstruction surgeries. It is based on

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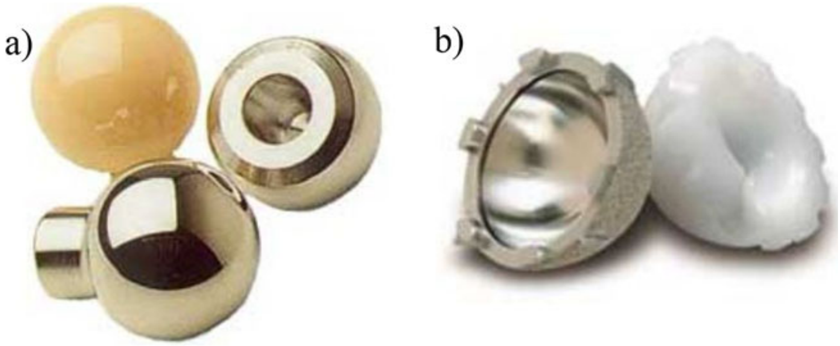

Fig. 1 – Hip joint prosthesis components [7]: (a) femoral heads and (b) acetabulum.

replacement of a natural hip joint with an artificial equivalent called endoprosthesis, which helps restore the lost motor function to the joint. The durability of the prosthesis ranges from 7 to 12 years, depending on the way it is exploited [3–6]. Due to relatively short use of prosthesis and the necessity for replacing it, solutions that would ensure its longest possible operation are looked for.

It is important to constantly seek for better materials and construction solutions with regard to prosthesis components (Fig. 1), which in turn requires a lot of research to be carried out, not only from the biomedical but also technological point of view.

Technological research encompasses, among others, measurement and analysis of the surface topography obtained during the manufacturing process (machined surface MS) and the surface topography obtained from tribological test (worn surface WS), i.e. shape, waviness, roughness and surface defects [8–11]. On the basis of the results obtained from technological research, it is possible to evaluate the accuracy of dimensions and shape, the quality of the machined surface [4,12–16] and the influence they have on the functioning [17,18] of the ball-and-socket prosthesis.

The dimensions (tolerances), the shape, the surface quality of hip replacement parts (femoral head and acetabulum) as well as the method of their measurement are specified in ASTM F2033-12 2012 *Standard Specification for Total Hip Prosthesis and Hip Endoprosthesis Bearing Surfaces Made of Metallic, Ceramic and Polymeric Materials*.

Sphericity (radial deviation of roundness Δ – circularity) of artificial femoral heads should be designated in planes marked with AA, BB, CC, which is indicated in Fig. 2a; the acetabulum – according to Fig. 2b. The requirements relating to the surface roughness (defined by Ra parameter – arithmetic mean deviation of the roughness profile) should be checked by performing measurements in the planes marked with AA (a), BB ($b = 2a/3$), CC ($c = a/3$) and pole P, which is indicated in Fig. 2a and b.

According to the standard ASTM F2033-12, firstly, when using 5-diopter magnification, the bearing surfaces should be free from particles and scratches other than those arising from the machining process (finishing process). Secondly, the bearing surfaces of metallic femoral heads of total hip joint prostheses used in conjunction with a polymeric acetabulum should have a Ra value of not greater than 0.05 μm, while the departure from roundness Δ shall not exceed 10 μm.

The spherical bearing surface of the acetabulum shall have a Ra value not greater than 2 μm and the bearing surface of the polymeric acetabulum shall be free from particles, scratches, and score marks other than those arising from the finishing process.

The standards generally provide the value of Ra parameter as a guideline for preparation of objects in the manufacturing process. It should be noted that the Ra parameter is only an average arithmetic deviation of the roughness profile, and therefore it does not reflect the surface characteristics thoroughly. Hence, in the standards (ASTM F2033-12) it is recommended that other profile parameters, more sensitive to local peaks or valleys, should be taken into consideration while analyzing surface texture. It is commonly known that the assessment of the surface topography based exclusively on 2D

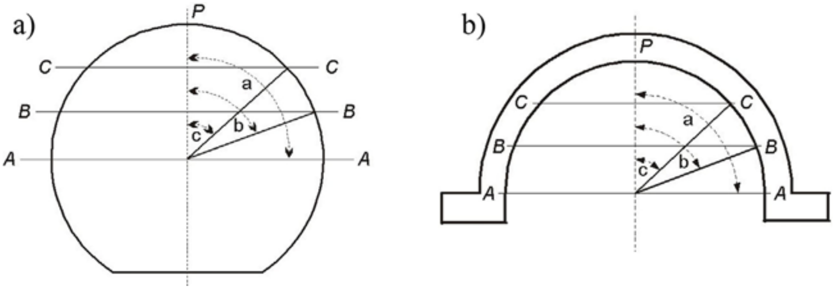

Fig. 2 – Locations of measurement points of total hip joint prosthesis (ASTM F2033-12): (a) for femoral head and (b) for acetabulum.

parameters (profile) is not satisfactory since it refers only to a single profile [9–11,14,15]. Hence, the evaluation of the surface texture should take into account 3D parameters (surface). Currently, there are dozens of parameters describing a surface in a quantitative way. Drawing on the available results of studies, several parameters were chosen, on the basis of which the evaluation of the surface texture of the components, obtained from the machining process (machined surface MS) and through tribological investigations (worn surface WS), was made. In addition, it is suggested that the images of the examined surfaces should be viewed by using a scanning electron microscopy SEM. This will enable a complete analysis of the surfaces of the tested components to be made and meaningful conclusions to be drawn.

2. Materials and methods

The subject of the research and analysis were the following material pairs: metal (titanium alloy Ti-6,5Al-1,3Si-2Zr) – polymer (Ultra-High-Molecular-Weight Polyethylene: UHMWPE). These materials meet stringent requirements imposed on materials (biomaterials) that are intended for medical devices [19].

Fig. 3 presents the main stages of technological studies for biomaterials.

The first stage (Manufacture of co-acting components) relates to the manufacturing process, in particular to the forming of the surfaces of components made of materials exhibiting special properties (difficult-to-machine materials) and used for special purposes (medical devices).

The aim of this part of research is working out of the steps and conditions (parameters) of finishing process and preparing of components which meet the requirements of the standards.

Metallic semi-finished products were subjected to precision machining operations which comprised three stages of abrasive machining: (1) preliminary grinding with a grinding wheel composed of abrasive synthetic diamond grains (granulation of 125/100 μm) on the metallic binder; (2) precision grinding with abrasive synthetic diamond micropowder (granulation of 3/1 μm) on the polymeric binder, which produced the required form and dimensions; (3) lapping with an abrasive Poliflex® tool on the rubber binder (the outcome of which was type B surface topography – ball B) and polishing with an abrasive Poliflex® paste using felt flap wheels (resulting in type A surface topography – ball A), which created the required surface quality [20].

Polymeric semi-finished products (discs cut from one-meter long bars) were subjected to turning process to obtain the required form and dimensions (the diameter of the working part equal to 28 mm). Then, the working surfaces of the polymeric sockets underwent a sequence of polishing with felt until the desired surface finish was received.

After completion of machining process, all the workpieces were cleaned in an ultrasonic cleaner to remove debris from the studied surfaces.

An important part of the verification of the adopted finishing process are the studies of the machined surface (MS); therefore, the second stage of research (Studies of machined surface MS) puts emphasis on them. The aim of research at this point is to identify the relationship between the parameters of finishing process and potential functional properties of machined surface topography. To achieve this aim, three research devices were used.

Departure from roundness of the socket (acetabulum) and ball (femoral head) was measured using the high-accuracy three-dimensional measuring machine Leitz PMM 12106 Coordinate Measuring Machine (CMM). The surface texture analysis was based on the results obtained using the dual beam high-resolution Scanning Electron Microscopy FEI Quanta 3D FEGSEM integrated with the Energy Dispersive Spectroscopy system (SEM/EDS) and the Taylor Hobson White Light Interference microscopy (WLI).

The research conducted on the stereometric aspects of the topography of the machined surface (MS) along with analysis

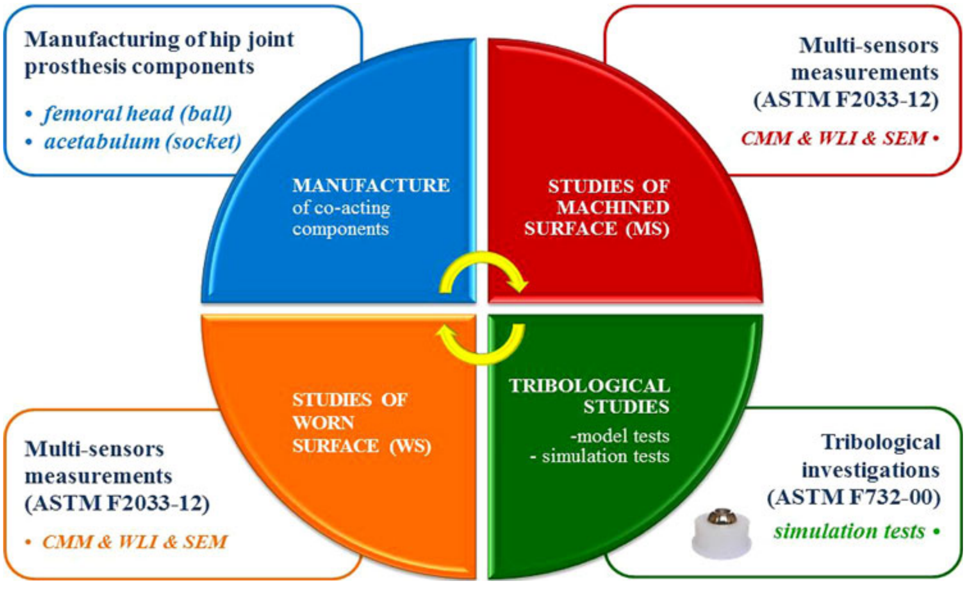

Fig. 3 – The scheme of technological studies for biomaterials.

of the results allows to assess the state of the surface formed in the manufacturing process, and above all, to determine the potential functional properties of the machined surface, which should be verified in the next step; this leads to the third stage of the studies, i.e. Tribological studies (machined surface MS converted into worn surface WS), the aim of which is to identify the relationship between potential properties of the machined surface and obtained tribological characteristics.

The tribological studies of the biomaterials generally consist of two stages (a full description is provided in ASTM F732-00 2006 *Standard Test Method for Wear Testing of Polymeric Materials Used in Total Joint Prostheses* and [21]): (1) model tribological tests which are performed on simple, pin-on-plate samples, involving reciprocating motion; (2) simulation tribological tests performed on samples whose shapes and dimensions simulate a real hip joint.

The goal of the first stage of tribological studies is to select a friction pair exhibiting the best tribological characteristics, i.e. the lowest friction coefficient and the least wear intensity of a polymeric component. Model tests are time-consuming (single test takes about 11.5 days); still, they take less time than simulation tests (about 30 days).

The both stages of tribological studies were conducted in surrounding Ringer's solution (which is equivalent to physiological fluid).

The standard (ASTM F2033-12) give maximum value of *Ra* roughness parameter, but does not specify the minimum value. Therefore, during the model tribological tests three different surface textures of metallic plates were studied; the surface texture of metallic plates were characterized by *Ra* parameter, as per the following relation: $0.025\ \mu m < Ra(A) < Ra(B) < Ra(C) < 0.055\ \mu m$. Based on the results obtained from model tribological tests, two out of three surface textures of metallic plates showing the best tribological characteristics were chosen, *Ra*(A) and *Ra*(C).

The paper presents the second part of the tribological tests conducted on the basis of the results received from the model tribological tests. Thus, in the paper, descriptions and results concern only the simulation tribological tests.

In order to verify the chosen combinations which received satisfactory results during comparative model studies (pin-on-plate friction pair) of biomaterials, in the second stage of tribological studies, the components were subjected to tests on a simulator (Fig. 4a and b), as it was described in the first stage of technological studies. The components of the ball-and-socket friction pair (Fig. 4c) reflected a real hip artificial joint.

During the tests, the ball moved in an oscillating (rotating-reversible) movement around its axis within the socket and in swing motion against the socket axis. The signals from the sensors, such as loading force, friction torque, and the temperature of lubricant, were measured and recorded, and the amount of performed cycles was counted. The tests were performed at the parameters presented in Table 1.

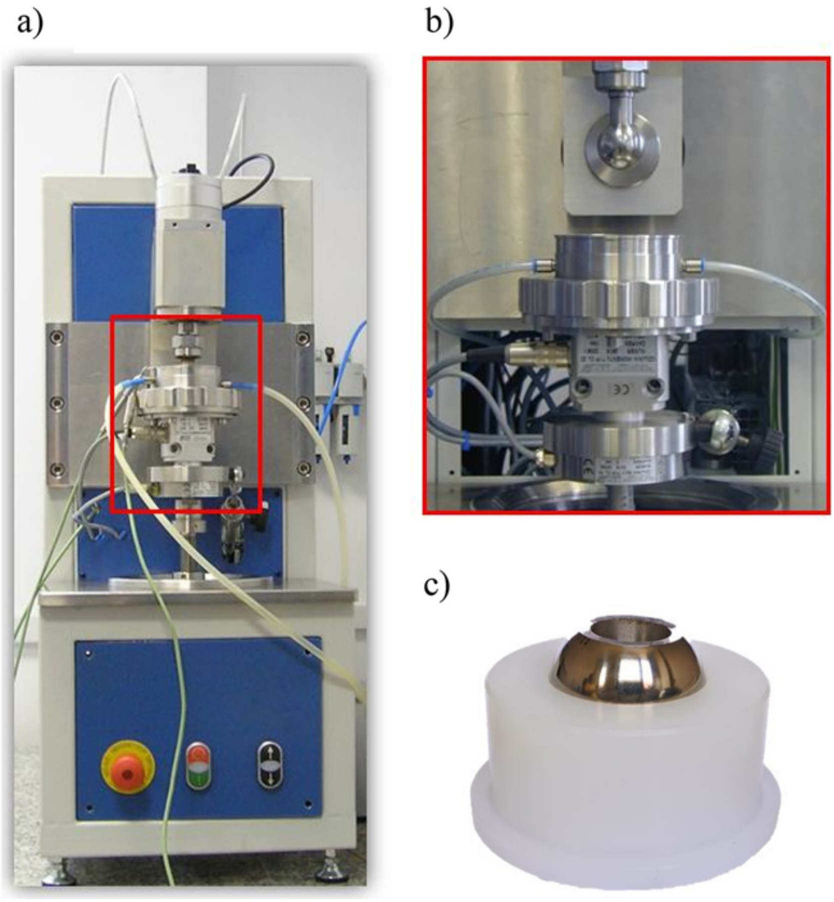

Fig. 4 – Research stand: (a) testing machine, (b) the main part of the testing machine and (c) friction pair components.

Table 1 – Parameters of simulation tribological tests.

Parameter	Value
• Range of rotating-reversible motion	$-65 \div 65^\circ$
• Range of pendulum motion	$-25 \div 25^\circ$
• Rotation frequency	0.5 Hz
• Number of cycles	10^6
• Lubricant temperature	36.6 ± 0.5 °C

The load changed cyclically during the tests of the analyzed combinations (ISO 14242-1: Implants for Surgery-Wear of Total Hip Joint Prostheses-Part 1: Loading and Displacement Parameters for Wear-Testing Machines and Corresponding Environmental Conditions for Tests), similarly to a natural human hip joint during movement – Fig. 5.

The results obtained from simulation tribological tests (focusing on the tribological characteristics such as friction torque, wear intensity) should be referred to the testing conditions, among others, associated materials, the shape and dimensions of friction components as well as surface topography (stereometry). Additionally, the wear mechanisms as well as the wear products of the investigated components should be identified, which was the subject of the fourth stage of studies (Studies of worn surface WS).

The aim of the research at this point is to find the relationship between the properties of the machined surface (MS), the tribological characteristics (friction torque and wear intensity) and properties of the worn surface (WS) as well as indicating the wear mechanisms of the friction pairs components.

After each 250,000 cycles, the simulation tribological test was stopped, the friction pair dismantled, and the surfaces of the friction pair components were studied, in compliance with the guidelines of the standard ASTM F2033-12, as it is described in the section entitled *Introduction*. In the paper, the example results of studies and analysis (after one million cycles) for sockets and balls were presented.

The worn surface (WS) topography of the metallic balls (femoral heads) used in conjunction with the polymeric socket (acetabulum), was investigated and analyzed using three research devices (CMM, WLI and SEM/EDS) and specialist software (Quindos for CMM and TalyMap Platinum v.6 for WLI).

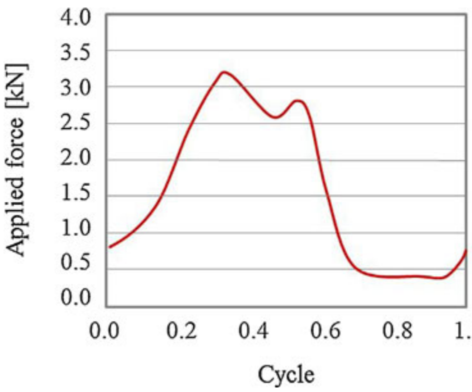

Fig. 5 – The load change of the prosthesis during a single cycle [22].

The liquid between the co-acting surfaces, apart from fulfilling its primary purpose (ensuring fluid friction, reducing the occurrence of scuffing, etc.), played an important role in transporting the wear products. For this reason, after simulation tribological tests, the analytical studies of the chemical composition of the lubricant from the friction zone were carried out using SEM/EDS. Based on this analysis, the wear products derived from the contact zone of friction components were identified.

The results obtained using the CMM and WLI were used in the second stage of research to check whether the tested components were performed correctly in respect to the accuracy of dimensions, shape and surface texture (departure from roundness, roughness); in the fourth stage of research, the change of surface topography was checked and the tracks and mechanisms of wear were assessed. The results obtained from SEM/EDS facilitated the visualization of the surface topography of the studied components – its real images – and allowed for checking, in analytical studies, the chemical composition of the wear products appearing on the metallic parts and in the lubricant filtered out from the friction zone.

On this basis, it was found that the surface topography of the balls had influence on friction (friction torque) and wear (wear tracks, wear products, and wear mechanisms) with respect to the examined material combinations.

The analysis resulted in conclusions, on the basis of which further studies are planned in search for new materials and technologies.

3. Results and discussion

Fig. 6 presents the characteristics of the surface topography of the polymeric socket obtained using the CMM (departure from roundness), WLI (surface texture after shape removal – sphericity) as well as showing the images of the surface obtained with the use of SEM.

The surface images of the socket interior, obtained from SEM and WLI, exhibited characteristic marks evenly distributed across the examined surface, resulting from the finishing process. Departure from roundness Δ (measured in accordance with Fig. 2b) did not exceed 5 μm for each examined plane AA, BB and CC. The surface roughness expressed by *Ra* parameter met the requirements of the standard ($Ra < 2$ μm).

The selected results of the surface topography (departure from roundness and surface texture) of the metallic balls, obtained during the manufacturing process (MS), are shown in Figs. 7 and 8.

The results show differences in the surface topography of the studied ball components marked as ball A and ball B. Higher surface roughness (defined by *Ra* parameter) is exhibited by the surface of the ball B, whereas the surface of the ball A shows lower roughness – as per the guidelines of the standard, where $Ra(A) < Ra(B) < 0.05$ μm. Departure from roundness Δ, measured in planes AA, BB and CC in accordance with Fig. 2a, is maintained at the same level, ranging from 2 μm to 7 μm, which is also consistent with the requirements of the standard ($\Delta < 10$ μm).

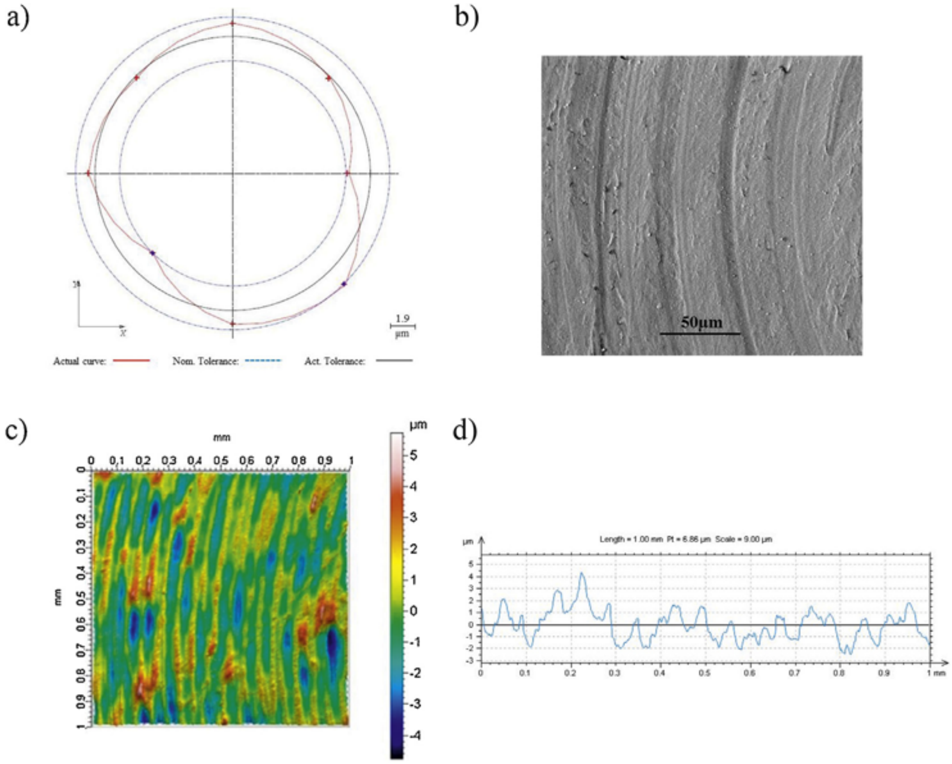

Fig. 6 – Measurement results of polymeric socket (acetabulum) A/B: (a) departure from roundness obtained by using CMM, (b) MS obtained by using SEM, (c) MS obtained by using WLI and (d) MS profile obtained by using WLI.

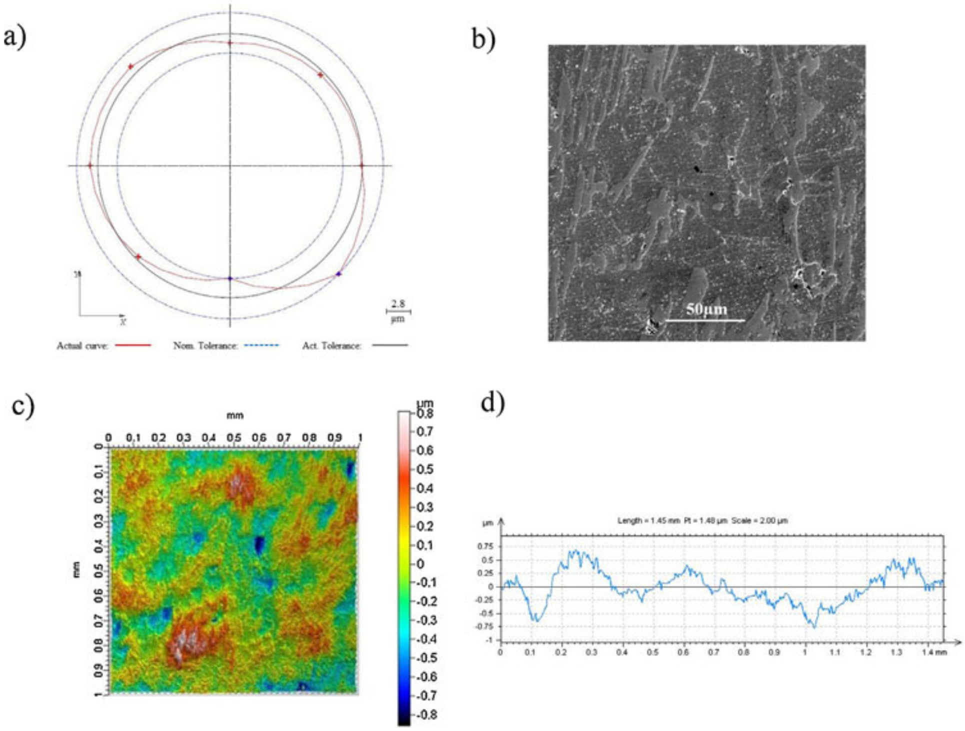

Fig. 7 – Measurement results of metallic ball (femoral head) B: (a) departure from roundness obtained by using CMM, (b) MS obtained by using SEM, (c) MS obtained by using WLI and (d) MS profile obtained by using WLI.

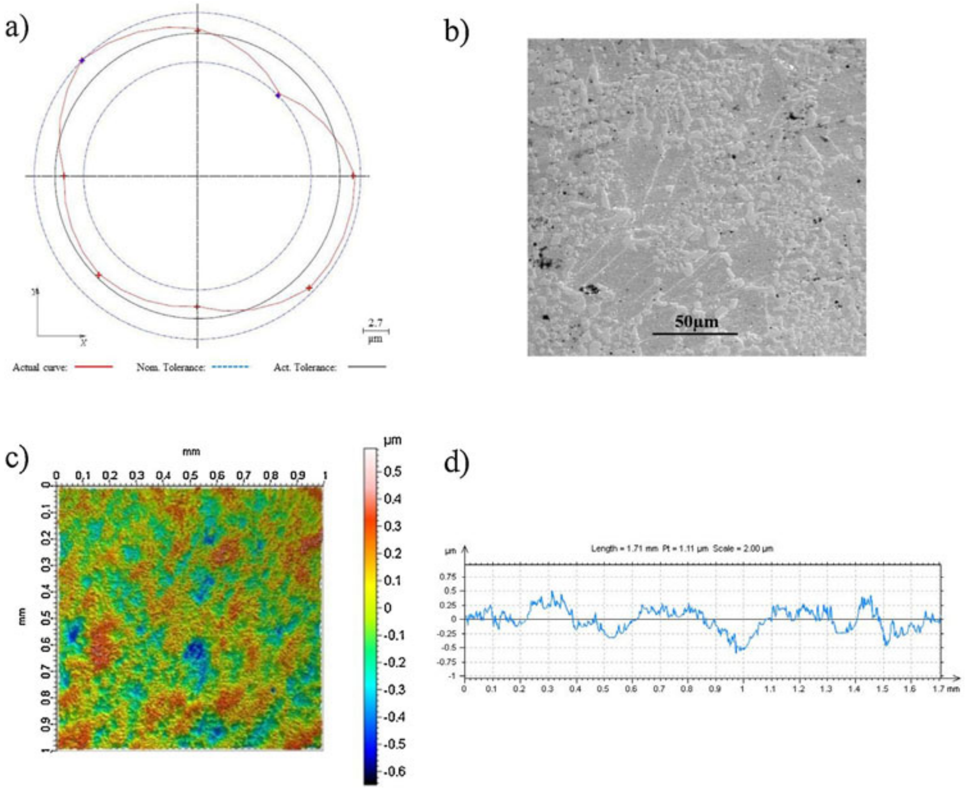

Fig. 8 – Measurement results of metallic ball (femoral head) A: (a) departure from roundness obtained by using CMM, (b) MS obtained by using SEM, (c) MS obtained by using WLI and (d) MS profile obtained by using WLI.

The surface of the ball B is characterized by local, irregular, wide hills, while on the surface of the ball A small densely arranged hills can be seen.

On the surface of the ball B, there are also local cavities with an average width of 0.15 mm and an average depth of 0.70 μm. As for the surface of the ball A, valleys are more densely distributed, but their size is smaller – the average width of 0.10 mm and an average depth of 0.40 μm.

In Table 2, the surface roughness parameters (Sz – maximum height, *Sq* – root mean square height, *Ssk* – skewness, *Sku* – kurtosis, *Spd* – summit density) describing the machined surfaces (MS) were presented.

Large differences in the values of parameters *Sz, Sq* and *Spd* for balls and sockets were easy to notice, however differences in values *Sz*, *Sq*, *Ssk* and *Sku* for the balls were small. Considerable differences were recorded for *Spd* parameter. The differences played an important role in shaping the tribological characteristics of friction pairs: ball-and-socket.

The friction pair surfaces of such topography (functional properties) were tested with the simulator in order to determine which type of the surface structure of the ball (femoral head) would provide the best tribological characteristics of a friction pair.

In Fig. 9, the average values of friction torque of the examined pairs were recorded at each stage of work. It should be noted, however, that these values were determined (in the range of 50,000–250,000 cycles) after friction resistance had been stabilized.

The data which were set in Fig. 9 show that the ball B-and-socket B combination during tribological tests displayed the average friction torque approximately twice lower at each stage of work as compared to the ball A-and-socket A combination.

Measurements concerning the departure from roundness for friction components (ball and socket) after tribological tests (measured in planes AA, BB and CC in accordance with Fig. 2) showed that for sockets these value increased more than twice, whereas for balls (femoral heads) – it got decreased. That means that co-action of the components led to the gradual wear (abrasion) of the polymeric part; wear products, in turn, transferred to the surface of the metallic head filled its cavities. Wear products were visible on the measured surfaces of the

Table 2 – Machined surface (MS) roughness parameters.

	Sz [μm]	*Sq* [μm]	*Ssk* [–]	*Sku* [–]	*Spd* [1/mm^2]
Socket	10.50	1.320	0.201	3.32	173
Ball B	1.67	0.213	0.170	3.42	2189
Ball A	1.23	0.155	0.025	2.85	5041

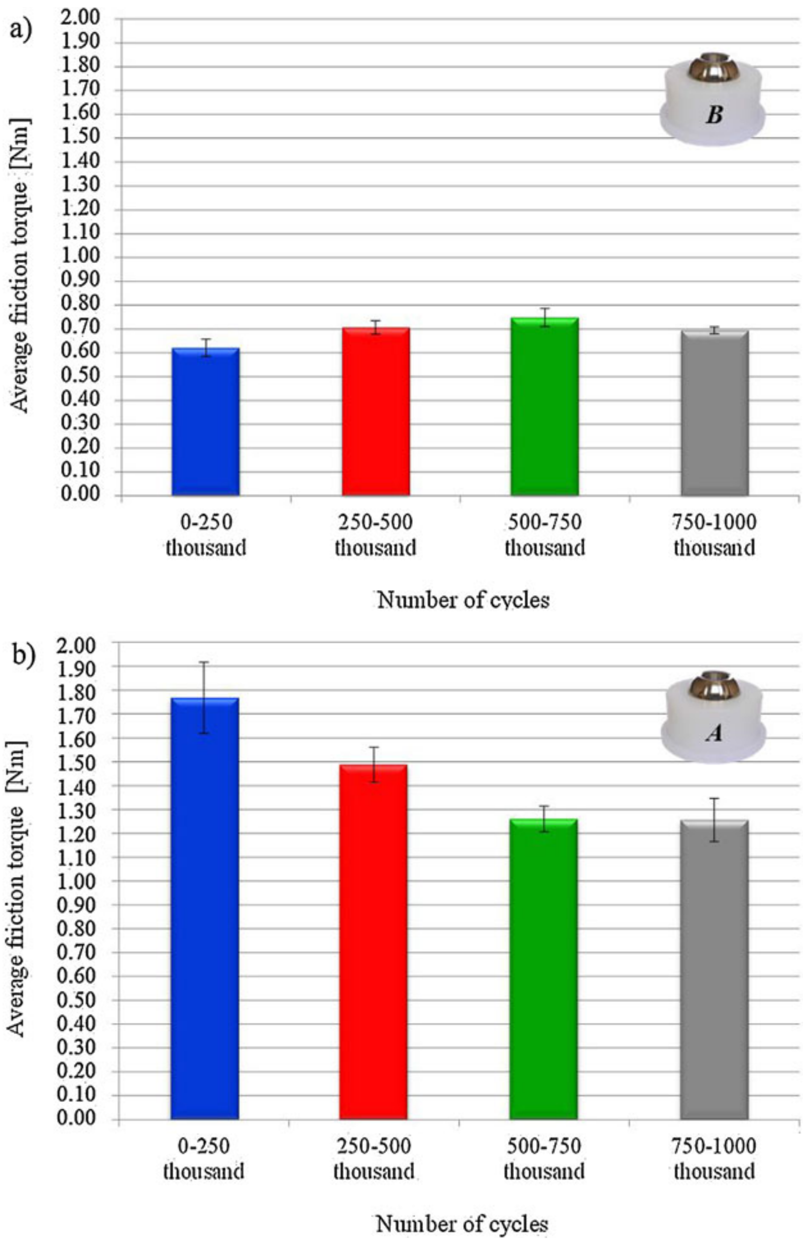

Fig. 9 – The average values of friction torque at each stage of work of studied pairs: (a) ball B-and-socket B and (b) ball A-and-socket A.

ball-and-socket friction pair thanks to the applied measuring devices, i.e. WLI and SEM/EDS.

Figs. 10 and 11 show the surface texture of the metallic balls and the polymeric sockets after completion of tribological tests (after one million cycles) – worn surface WS.

During tribological studies, the polymeric socket has worn away – a part of the material was transferred to the surface of the co-acting metallic ball in the examined pairs. The amount of the transferred material varied depending on the initial machined surface topography (MS) of the ball, which was presented in Figs. 7 and 8.

The socket B articulated against the ball B was worn away to a lesser extent in comparison to the socket A co-acting with the ball A. The greater amount of wear products (polymeric material of socket) was observed on the surface of the ball A.

The surface characterized by smaller surface roughness displayed greater density of summits and increased contact with another co-acting surface.

It seems that hills recorded on the ball A, which were densely spaced and had regular shapes, despite their small size, contributed to abrasion of the material of the socket in the first place. In the subsequent stages of co-action, the polymeric material transferred to the surface of the metallic component clung to the polymeric part due to the process of adhesion. Thus, a larger amount of polymer was visible on the surface of the ball A, with the socket A worn away to a larger extent.

In Table 3, the surface roughness parameters describing the surfaces after the operation process (surfaces after tribological tests – worn surface WS) were presented.

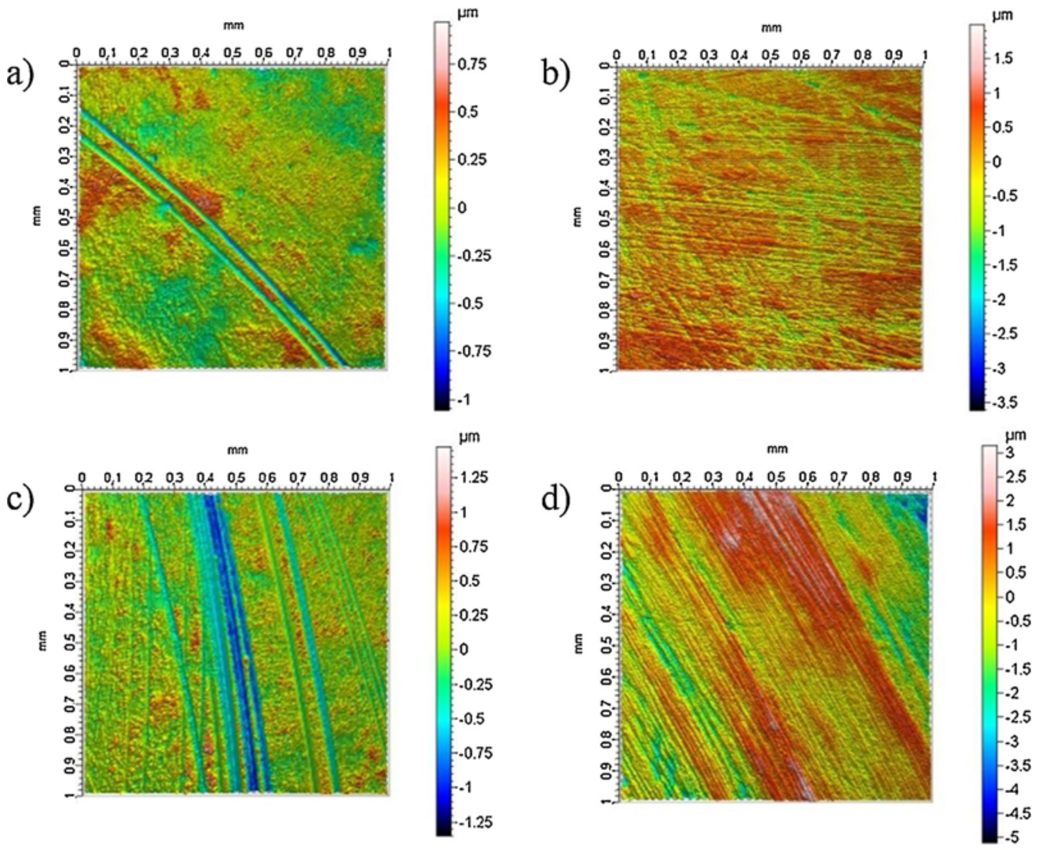

Fig. 10 – Measurement results after tribological tests (worn surface WS) with WLI: (a) ball (femoral head) B, (b) socket (acetabulum) B, (c) ball (femoral head) A, (d) socket (acetabulum) A.

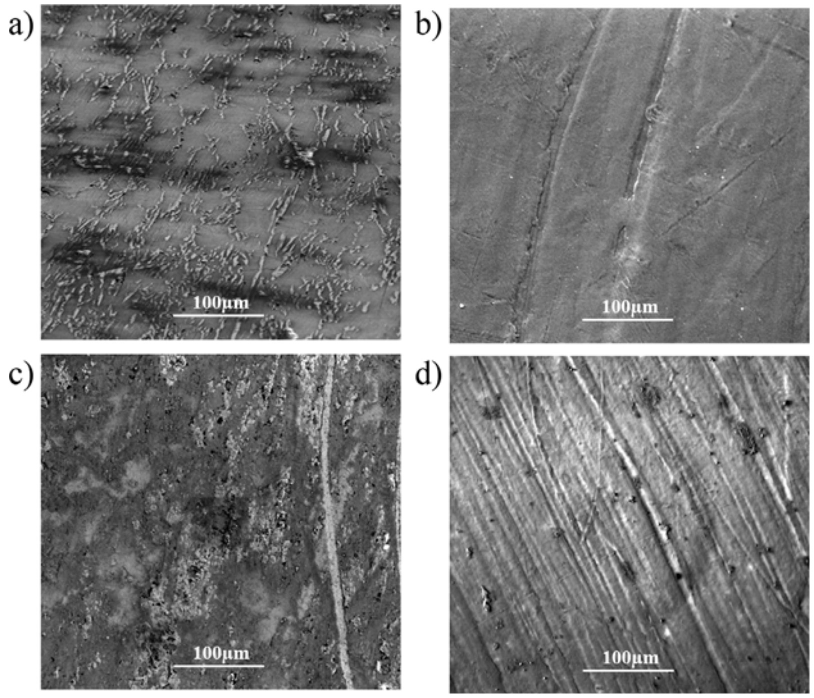

Fig. 11 – Measurement results after tribological tests (worn surface WS) with SEM: (a) ball (femoral head) B, (b) socket (acetabulum) B, (c) ball (femoral head) A and (d) socket (acetabulum) A.

Table 3 – Worn surface (WS) roughness parameters.

	Sz [μm]	*Sq* [μm]	*Ssk* [–]	*Sku* [–]	*Spd* [1/mm^2]
Socket B	5.61	0.387	−0.339	3.17	1164
Socket A	8.26	0.990	−0.115	3.03	609
Ball B	2.03	0.212	0.475	4.28	4706
Ball A	2.82	0.340	−0.031	4.36	5585

The results of surface texture measurements obtained for the friction pair components: ball-and-socket (sample results of measurements in the CC plane) point to the wear of the polymeric component and the transfer of the socket material to the surface of the metallic ball.

The surface of the socket interior exhibited characteristic marks evenly distributed across the studied surfaces – the cavities ($Sku = 3.32$ – MS results in Table 2). The maximum height of surface roughness – parameter Sz equalled 10.50 μm (Table 2). The hills with steep slopes and pointed summits ($Ssk = 0.201$ – MS results in Table 2) got abraded ($Ssk < 0$ – WS results in Table 3) under the influence of roughness characterizing the surfaces of metallic balls (results in Table 2). The maximum high of *Sz*, *Sq* and *Sku* parameters got decreased. An over four-fold increase in the value of the *Spd* parameter was recorded for all the tested sockets.

As far as the surfaces of metallic balls (femoral heads) are concerned, the maximum high of the surface roughness (Sz) equalled 1.67 μm for the ball B, while for the ball A the same parameter equalled 1.23 μm. The hills with steep slopes and pointed summits ($Ssk > 0$ – MS results in Table 2) co-acting with the polymeric socket (acetabulum) caused destruction of its working surface. The wear products, resulting from such an impact, were transferred to the surfaces of the balls, filling cavities and creating local hills. The modified surfaces were characterized by the parameters of varying values, which is presented in Table 3.

4. Conclusions

Based on the obtained results, the relationship between the surface topography created in the precision machining process (machined surface MS), tribological characteristics (friction torque) as well as the surface topography of the co-acting components after the tribological test (worn surface WS/wear traces and products) was established.

- The surface topography of the ball (femoral head) obtained as a result of the precision machining process influenced the wear mechanism of the socket (acetabulum) during co-action.
- The surface topography, along with the shape (sphericity – departure form roundness) and the surface texture (roughness and surface defects) of both polymeric socket (acetabulum) and metalic ball (femoral head), determined the character of contact between the co-acting surfaces.
- For the ball A-and-socket A combination, the average friction torque was twice as high as the friction torque recorded for the ball B-and-socket B pair, which influenced the amount of wear products (polymeric material) transferred to the surface of the examined balls.
- Departure from roundness and surface texture after tribological tests changed; for the sockets, the value increased, whereas for the balls – it got decreased.
- Thanks to the applied WLI and SEM/EDS, wear tracks and products were visible on the measured worn surfaces (WS). A greater amount of wear products was observed on the surface of the ball A; its surface roughness was smaller and hills were spaced regularly.
- The wear mechanism of polymeric sockets (acetabulum) and generated wear products resulted from plastic deformation, abrasive wear, fatigue, or adhesion of the surface layer formed in the course of the co-acting process involving friction pair components: ball-and-socket (femoral head-and-acetabulum). Regardless of the surface topography of the metallic balls (femoral heads), it was the polymeric socket (acetabulum) that was gradually worn away in the friction pair.
- The simulation tribological tests did not confirm the results obtained from model tribological tests. The surface of the metallic ball (femoral head) showing lower surface roughness caused that the polymeric socket (acetabulum) was worn away to a greater extent. Hence, it might be concluded that further simulation tests need to be made in order to verify the received data.
- The human body is not indifferent to wear products [2,7,21,22]. Since the amount of wear products derived from the polymeric component could not be entirely eliminated, but only reduced, further research on the improvement of the ball-and-socket friction pair has to be conducted with respect to materials and shaping of the working surfaces.

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