TECHNOLOGICAL SYSTEMS OF SHAPING ELEMENTS OUT OF DIFFICULT-O-MACHINE MATERIALS

Józef GAWLIK, Joanna KRAJEWSKA, Magdalena NIEMCZEWSKA-WÓJCIK

Abstract: The purpose of this paper is to describe the main characteristics of difficult-to-machine materials, in particular ceramic materials such as: glass, aluminium and zirconium ceramics. The paper presents the developed and manufactured prototype-research work-stations and examples of conducted studies which concentrated on machining processes and the quality characteristics of the obtained surfaces. The main focus of the research was the precision machining of the small-dimensions components.

Keywords: difficult-to-machine materials, machining work-station, surface quality.

1. Introduction

The usage of materials with special properties such as: high fatigue strength, wear resistance, corrosion, reduced weight, and other special features, increases.

Those materials belong to the group of difficult-to-machine materials therefore; the need for research aiming to determine and describe the most optional technological, machining conditions is so great, for example, the techniques of the precision-finishing processes for shaping the materials to meet the required high-quality standards.

The scale of the precision-finishing techniques and manufacturing processes for difficult-to-machine materials increases for both minimal-dimension parts as well larger components.

There is an increasing demand for weight-reduction in manufactured machinery and equipment while maintaining and/or even increasing its endurance parameters. In consequence it leads to the development of the manufacturing technology of super-hard materials (up to 70 HRC) with high chemical and thermal resistance.

Amongst the unconventional methods used for manufacturing of the electromechanical systems, the micro-machinated electro discharge, electrochemical, laser or ultrasonic-machining [5, 6, 9] can be mentioned. Those systems play a crucial role in the preparation stage of the production such as: manufacturing of moulds, stamps and tools and, designing, modeling and testing of the new solutions.

2. Characteristic of difficult-to-machine materials

Various types of materials, characterized by specific physical, chemical and mechanical properties, are used to produce spatial microstructures (e.g. used in MEMS systems in the medical and pharmaceutical industry). The most commonly used are:

- glass, silicon oxide (SiO_2), silicon nitride (Si_3N_4), silicon carbide (SiC), quartz, diamond, gallium arsenide (GaAs),
- aluminium nitride (AlN),
- aluminium oxide (Al2O3),
- polymers (PMMA) and a shape memory material (Ti - Ni alloys) and metals (usually Ag, Al, Au, Cu, Ir, Ni, Ti).

Glass lacks a long-range ordered structure, it's arrangement of the elementary units in the lattice resembles the arrangements of the molecules in liquids. However, they lack the movability or it is very insignificant due to it's high viscosity. According to the U.S. norm ASTM-162 (1983), glass is defined as an inorganic product of fusion which has cooled to a rigid condition without crystallizing.

The most important characteristics of glass include: high chemical resistance, low electrical conductivity, low thermal conductivity; bio- acceptability, high hardness, high brittleness, low tensile strength. One of the most commonly used heat-resistant glass is borosilicate glass Pyrex consisting of 8% of boron oxide and 85% silicon oxide.

Ceramic materials are an important group that includes all inorganic and non-metallic materials, which are fabricated using a thermal treatment at a temperature above several hundred degrees Celsius, such as sintering or calcining.

Lattice of ceramic materials is more complex than in metals. As one of the formatting methods, the engineering ceramic can be distinguished, which includes materials formed by sintering at high temperature (~ 1500 to 2100 ° C) out of very pure, synthetic, fine powders (particle size less than 1μm), without any involvement of the vitreous phase, from compounds such as: oxides, carbides, nitrides, borides, phosphides, and their warps' complex compounds [3].

The most characteristic features of ceramic materials include: high melting point, light weight, high endurance, high brittleness, high compressive strength, low tensile strength, low thermal expansion, and low heat conductance, resistance to high temperatures, chemical resistance, good dielectric and insulating properties.

Ceramic materials are widely used in various industries such as: construction, metallurgy, electronics, land, sea and air transport, the space industry. They are used in areas exposed to weathering, aggressive inorganic and organic chemicals and high temperature. They are successfully used as the piezoelectric elements in pressure sensors and ultrasonic generators.

Ceramic is also used in medicine, mainly in prosthetics, as the head of a hip prosthesis (due to the high biological tolerance, and good mechanical properties), knee joints and dental prostheses (due to chemical inertness and aesthetics.) Bioactive, ceramic materials are also used in partial bone defects where they stimulate remodeling, and even rebuild the bone tissue. In the manufacturing of MEMS system, ceramics are used in micro-accelerators, chemical micro-reactors, micro-pumps, micro-fluidic devices, medical devices (sensors of flow, medication dispenser).

Construction materials, classified as difficult-to machine materials, are characterized by:

- high mechanical strength, at high temperatures, which lead to the formation of large cutting forces;
- low thermal conductivity, which hinders the heat spread and dissipation the cutting zone, which results in the generation of high temperatures during the cutting process, especially at the cutting edges;
- alloying elements, which appear in the workpiece, often intensify abrasive wear of blades;
- hardening may occur during machining of the material (e.g. super alloys);
- large cutting forces, intensive use of blades tools and high temperature, lead to a significant deformation of the machining elements (e.g., thin-walled bodied inside which precise and highly accurately holes are made).

3. Selected aspects of the shaping processes

A significant limitation, in difficult-to-process materials, is low durability of cutting tools, which is impacted by, inter alia, higher cutting temperatures compared to those which occur in the treatment of materials with good machinability.

The appropriate treatment process should include potential correction of machining errors such as:

- increasing the cutting speed (HSC) for the treatment of microproducts;
- optimizing the cutting parameters (f_z , v_c) due to the minimization of cross-cutting layer (reduction of the components of the cutting forces, temperatures in the cutting zone).

Tool's manufacturers recommend treatment parameters for various materials. An example can be given for recommended cutting parameters for titanium and HRSA alloys turning operations, recommended by ISCAR and Sandvik - Coromant (Table 1).

Tab.1. Examples of recommended cutting tool materials and different types of tools

Material	Cutting speed [m/min]	Types (ISCAR)	Types (SANDVIK -Coromant)
Titanium alloys	30 - 60	IC 907, IC07, IC 20, IC 908, IC 08	GC 1025, H13A
HRSA (cobalt-based alloys)	20 - 30	IC 907, IC 20, IC 07, IC 908, IC 08	GC 1005, GC 1025 S05F, H13A
HRSA (nickel-based alloys)	25 - 50	IC 907, IC 07, IC 20, IC 908, IS-9, IB 50	GC 1005, GC 1025S05F, H13A
HRSA (iron-based alloys)	50 - 150	IC 907, IC 3028, IC 908, IC 928	GC 1005, GC 1025 S05F, H13A
Stainless steel	40 – 200	IC 20N, IC 570, IC 9025, IC 320, IC 908, IC 9025	GC 1025,GC 2015, GC 2025, GC 2035

As presented in Table 1, the wide range of recommended cutting speed can differ in certain circumstances for the given pair: blade – work material. Although it is possible to find a number of these type of recommendations, in specific industrial applications it becomes necessary to search for individual solutions.

To implement such projects, NCBiR sponsored a research and development project NR03 0031 10, which aims to develop and build prototypes of machining work-stations for precise laser processing, EDM and machining and grinding.

4. Work-station for precision machining of difficult-to-cut materials

It was assumed that the work-station will be characterized by the following:

- possibility to use different methods machining techniques;
- reconfigurable capability to adjust the work-station to wide range of research;
- adaptability of the processing conditions to the properties of the machining

workpiece.

Three prototypes of the work-station for precision machining mostly small-scale components were developed, ie:

- work-station for the precision laser processing,[1]
- work-station for the precise EDM,2
- work-station for the precision machining and grinding.3

Prototype of the work-station for precision laser processing

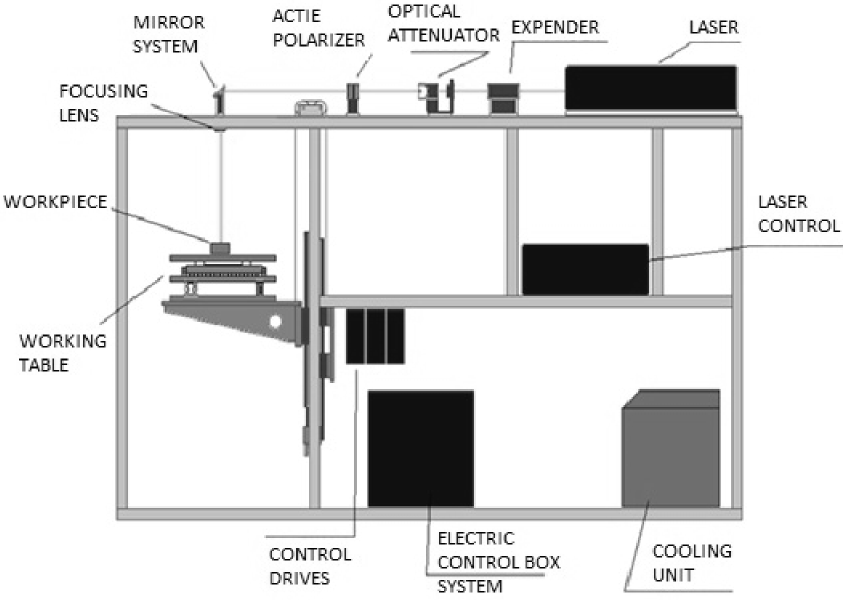

Fig. 1. Plan of the work-station for the precision laser processing

The main component of the above work-station is **Patara laser** produced by Northop Grumman Cutting Edge Optronic. It belongs to a group of laser designed to emit a laser beam with high power semiconductor light-emitting diodes (DPSS). The Patara's laser active medium is a neodymium doped yttrium aluminum garnet and is equipped in a system generating high-energy pulses. The output includes 532 nm wavelength pulses for a duration of 60-80ns and at a frequency of 4÷10 kHz.

The laser was optimized for industrial production systems. Moreover, it is suitable for applications where spatial stabilization of the beam and pulse repetition is required. The shape of the laser beam's cross section is more than 90% in line with the circular cross-sectional.

The expander is an optical device that allows to increase the laser beam diameter from 2 to 8 times. However, in consequences it reduces the density of energy for individual optical components (protection against damage). Furthermore, the diameter of the laser's beam incident concentrating on the focused lens has a decisive impact on the size of the

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[1] Work-station developed under the direction of D. Wyszyński

[2] Work-station developed under the direction of P. Lipiec and S. Skoczypiec

[3] Work-station developed under the direction of J. Gawlik

laser beam spot (the larger the beam's incident diameter is, the smaller the diameter of the focused beam spot is).

The optical attenuator is an optical instrument that allows smooth control of the laser's beam power without affecting the geometry and polarization state.

The function of the **active polarizer** is to set the laser's beam incident polarization surface in relation to the cutting direction during machining.

For the high precision of cutting to be achieved, the electric field vector must be set up perpendicularly to the cutting direction. This can potentially cause problems when cutting curved elements.

Figure 2 presents a prototype of the work-station that was made for laser machining.

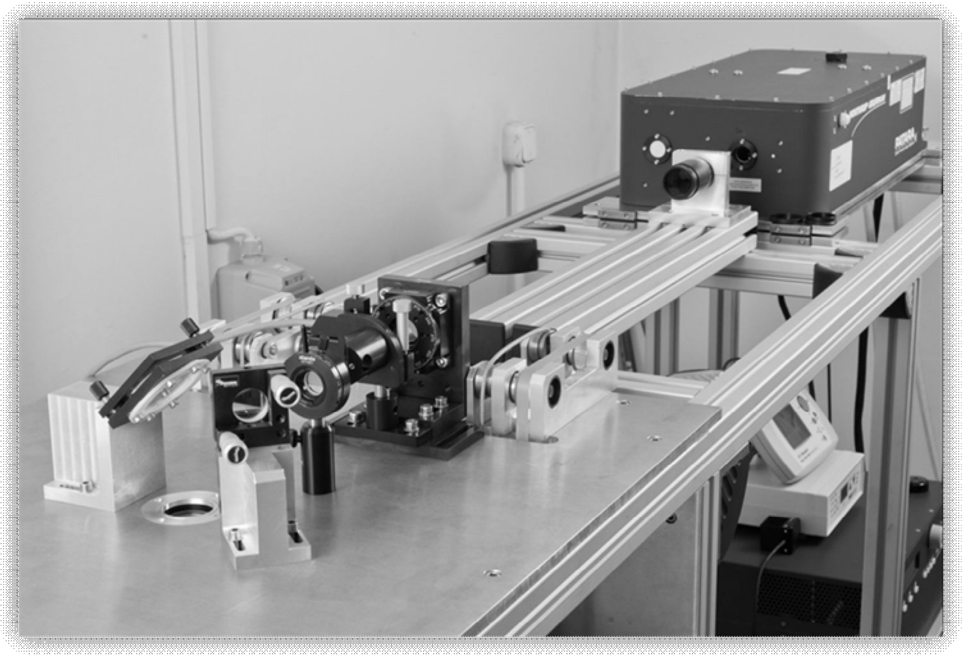

Fig. 2. Prototype work-station for laser machining

The prototype of a work-station for precise EDM

To conduct an effective EDM of the ceramic materials that conduct electricity poorly, it requires to address a numerous of technical problems already at the lathe's construction stage. Initial concept and technological assumptions for the work-station were developed based on the hypothesis from the analysis of the phenomena occurring inside the inter-electrode gap.

Those assumptions led to the development of the plan for the work-station (3), the fastening system EROVA ITS 50 (Fig. 4) and how to provide the dielectric into the treatment zone (Fig. 5).

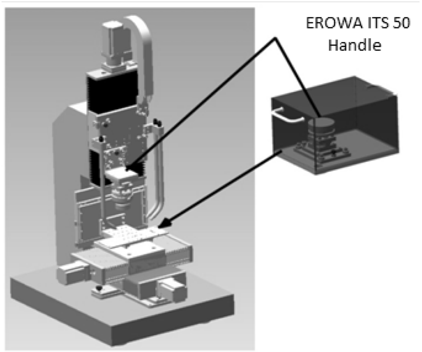

Fig. 3. Plan of the EDM work-station with handles ITS 50 produced by EROWA

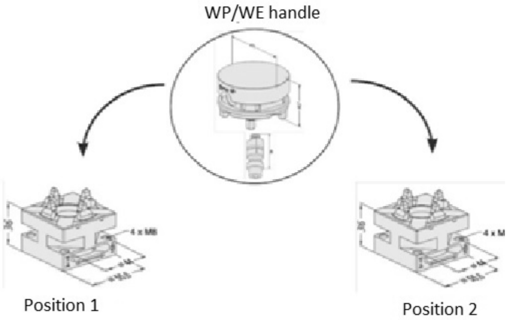

Fig. 4.The diagram showing the mechanism of a fastening and positioning system of the workpiece (WP) or the working electrode (WE) produced by EROWA, ITS type 50

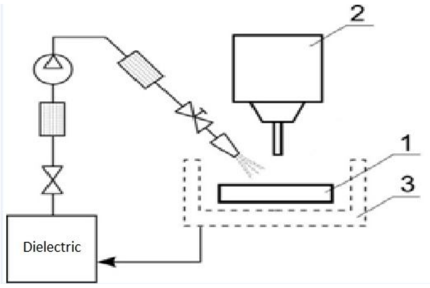

Fig. 5.The circulation system of a dielectric: 1- treatment area, 2 - handle of the working electrode, 3 - bath flow

A prototype work-station for precise EDM (Fig. 6) is equipped with the following functional systems: the mechanical part, control and process control panel; direct electric current supply system, fluid gauging and circulating system.

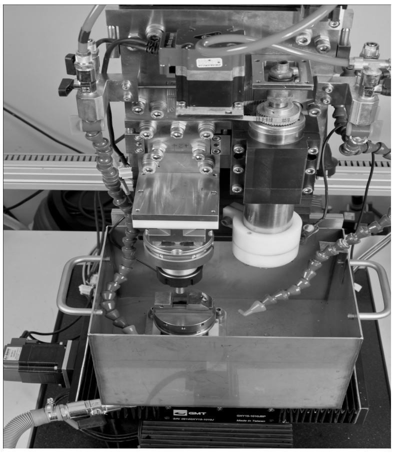

Fig. 6. A prototype of a work-station for precise EDM with a visible working head, fastening system for workpieces and dielectric liquid bath

A work station prototype for precision machining and grinding

The reconfigurable prototype of the work-station for precision machining has to be adaptable for machining and grinding research. It was proposed to equip it with the independent machining modules (fig. 7), which can be used depending on the research type.

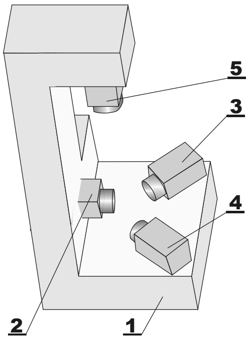

Fig. 7. The machining structure for the precision machining and grinding

The machining system was built based on the FNX 30P milling machine, produced by the Factory of Precision Machine Tools AVIA S.A. The main parameters of the system are: the maximum spindle speed - 3000 rpm / min, stepless speed, variable spindle speed and the feed motion speed. Depending on the equipment, the work-station can be used to study machining process with a horizontal or vertical table; drilling and milling deep cavities with drawable spindle; threading (using frames compensation); milling with a rotary table; boring with rotating heads, grinding using a multiplier or heads powered by compressed air. Figure 8 shows a work-station together with a CNC control system.

Fig. 8. A prototype work-station for machining and grinding

5. Selected examples of technical quality research of ceramic components

Ceramic materials, such as single crystals of sapphire and zirconium dioxide were supplied by the Institute of Technology for Super-hard Materials of the Ukrainian Academy of Sciences in Kiev (in collaboration with the Institute of Mechanical Technology at Cracow University of Technology) [2].

Preliminary tests were performed on flat samples prepared by grinding using diamond grinding wheels and lapping with lapping cast iron [2,4,10].

Obtained example of the surface quality parameters are presented in Table 2. Lapping parameters of the flat samples

- pressure force F = 0,147 MPa (1,5 kG/cm^2),
- micro-grains diamond paste: ACM 10/7,
- number of double strokes n = 20 stroke / min,
- the amplitude A = 60 - 80 mm.

Tab.2. Exemplary parameters of flat surfaces roughness after lapping

Sample	Amplitude parameters						Spatial parameters				Functional parameters		
	S_a [µm]	**S_q** [µm]	**S_z** [µm]	**S_t** [µm]	**S_{sk}** [-]	**S_{ku}** [-]	**S_{ds}** [pks/mm^2]	**S_{tr}** [%]	**S_{fd}** [-]	**S_{al}** [mm]	**S_{bi}** [-]	**S_{ci}** [-]	**S_{vi}** [-]
ZrO_2	0,0147	0,0184	0,126	0,139	-0,1460	3,09	2197	27,2	2,41	0,0105	0,570	1,50	0,120
Al_2O_3	0,0132	0,0167	0,124	0,132	-0,0191	3,06	2600	65,2	2,62	0,0117	0,454	1,55	0,114

The distributions of inequality and area capacity curves of flat samples are shown in Fig. 9 ÷ Fig. 10. The evaluation of isotropic surfaces obtained in zirconium and sapphire (Fig. 11) should be noted. It shows a certain difference in workability (cut ability) of these materials.

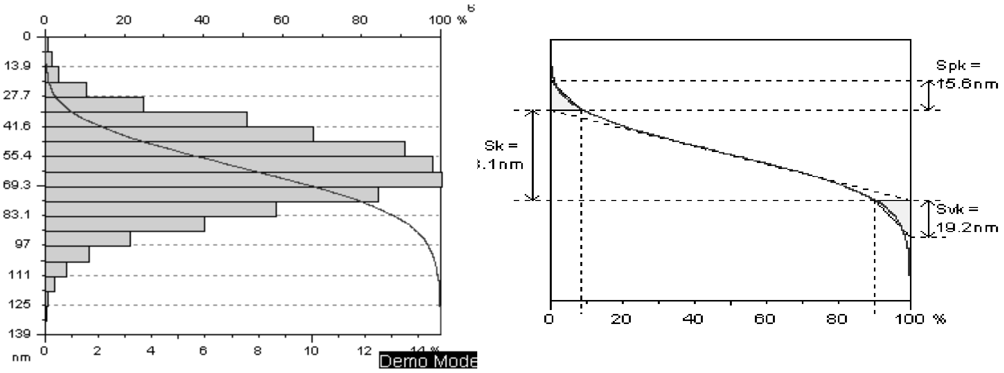

Fig. 9.The distribution of the inequality and surface area-capacity curve of zirconium ZrO_2 obtained after the process of lapping with diamond paste

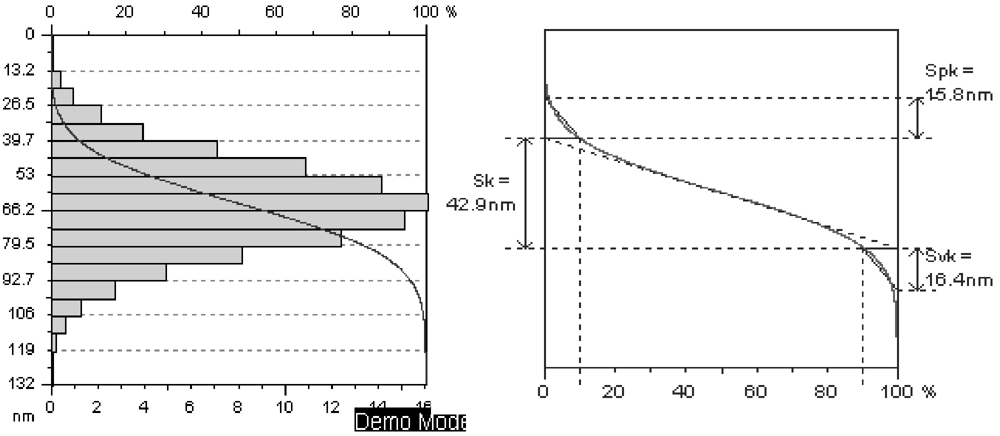

Fig. 10.The distribution of the inequality and surface-area capacity curve of Al_2O_3 obtained after the process of lapping with diamond paste

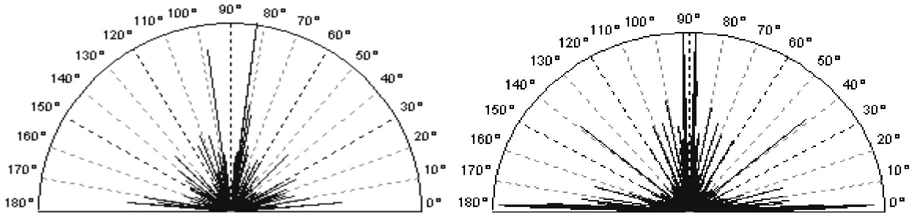

Fig. 11. Isotropy geometric structure of the surface
a) ZrO_2 (27,2%); b) Al_2O_3 (65,2%)

The second stage of the research was carried out on a prototype of a work-station (Fig. 8) using special abrasive tools for shaping treatment of spherical elements. After the shaping treatment, the elements were lapped using lapping iron. The choice of this type of product was dictated by the possible application of this technology to manufacture ceramic hip replacements (this phase of the research was undertaken in collaboration with the Jagiellonian University Medical College).

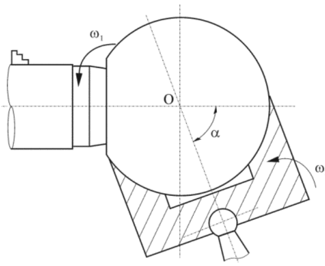

Fig. 12. Plan of forming a spherical element

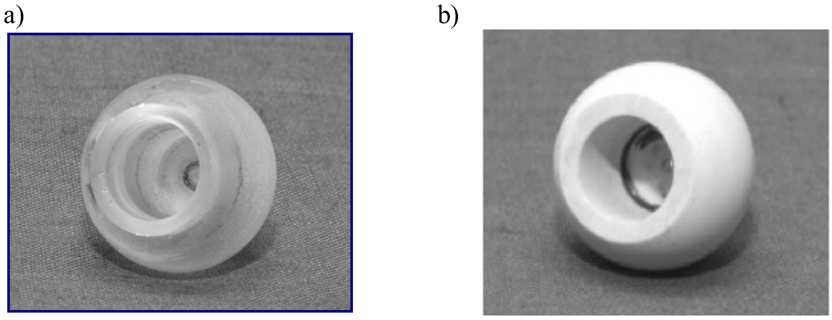

Fig. 13. Examples of produced spherical components: a) single crystal sapphireAl_2O_3; b) zirconium ZrO_2,

The spherical elements obtained as a result of a finishing treatment were analyzed in terms of quality and evaluated with main focus of accuracy of form and dimension. Moreover, the quantitative (parametric) analysis of the geometric structure of the studied ceramic materials' surface (SGP) was conducted as well as the microscopic analysis of the surface state after the tribological tests [7, 8]. The tribological tests were performed at the Institute of Terotechnology -National Research Institute in Radom.

Due to the foreseen usage of the technology for the ceramic heads for hip replacements, it was crucial to determine the SPG parameters, which describe the conditions of the future collaboration between a head with polymer components (chiluren) applied / used on the head of hip replacement.

The following SGP parameters were analyzed:

- R_a parameter, the parameters of amplitude: S_q, S_t, S_{sk}, S_{ku};
- volumetric parameters: Smvr, Smmr;
- spatial parameters: Sds, Str;
- functional parameters: Sbi, Sci, Svi;
- parameters describing the capacity curve: Spk, Sk, Svk.

Figure 14 and Figure 15 presents already measured and unfiltered surfaces and selected profiles for produce ceramic spheres. Parametric characterization of the analyzed surface of spheres is presented in Table 3.

Tab. 3. Analyzed parameters of spheres surfaces

Parameter	**Sapphire sphere**	**Zirconia sphere**
R_a [µm]	0.0193	0.0302
Amplitude parameters		
S_q [µm]	0.0402	0.0676
S_t [µm]	0.788	1.540
S_{sk} [-]	-3.05	-4.56
S_{ku} [-]	28.4	47.6
Volumetric parameters		
S_{mvr} [mm^3/mm^2]	0.000195	0.000200
S_{mmr} [mm^3/mm^2]	0.000594	0.001340
Spatial parameters		
S_{ds} [pks/mm^2]	2359	2098
S_{tr} [%]	7.9	56.6
Functional parameters		
S_{bi} [-]	0.285	0.516
S_{ci} [-]	1.21	0.843
S_{vi} [-]	0.143	0.186

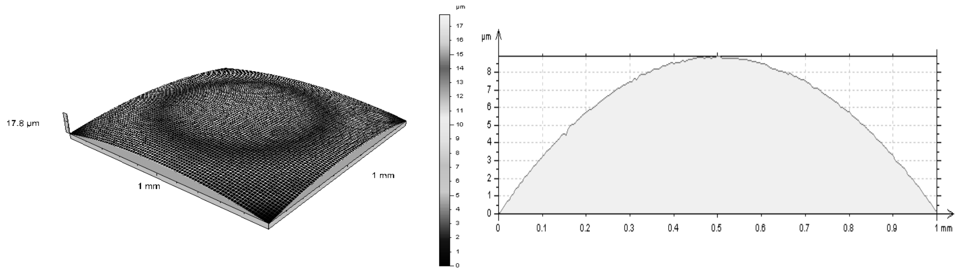

Fig. 14.The image of the SGP and the selected profile of sapphire head

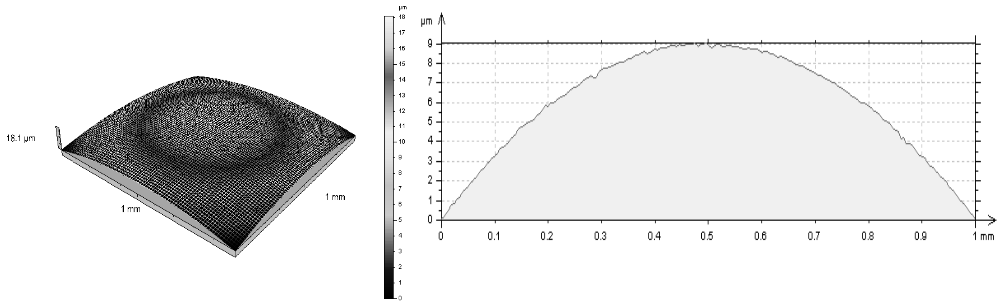

Fig. 15.The image of the SGP and the selected profile of zirconia head

The density of vertices' local elevation S_{ds} provides information on the capacity of the surface. For the tested spheres, the sapphire head (S_{ds} = 2359 pks/mm^2) has higher capacity - Figure 16.

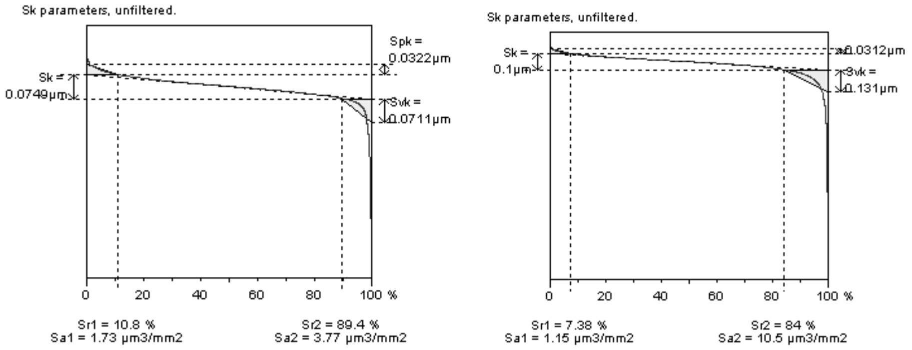
a) b)

Fig. 16. Surface curves capacity of a) zirconium sphere b) sapphire sphere

Taking into account the possibility of using the developed method of machining the spherical elements, special accuracy of form and dimension's tests were conducted on produced spheres (Fig. 17). With regard to the requirements for spherical elements of implants, it was found that they meet all the demands. An error occurred for the sphere sapphire within the range: 1.0µm ÷ 2.0µm, while the zirconium sphere's error was within the range: 0.9µm ÷ 1.4µm. The shape error of 1.0 µm in the largest diameter of the cross section with was observed, and the largest errors occured in closer to the pole of the sphere planes.


a) b)

a)

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Notation '                  Producer :               Draw  No  '
Ser. No. .                  Part No. :               Department.
Element  ' CIR_2

Diameter '   27.7967      Form       '  0.0010
X-Coord        0 0018     Tolerance    0 0100
Y-Coord. '   -0.0005      Err.Magn.'     5000
Z-Coord        1 9968     No  Pts        1036

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Date .....' 27-JUN-2008
Time ...... 16.05.35
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b)

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Notation '                  Producer :               Draw  No  '
Ser. No. .                  Part No. :               Department.
Element  ' CIR_4

Diameter '   27.1188      Form       '  0.0012
X-Coord        0 0020     Tolerance    0 0100
Y-Coord. '   -0.0008      Err.Magn.'     5000
Z-Coord        4 0000     No  Pts        1019

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Fig.17. Accuracy of form and dimension's charts a) zirconium sphere, b) a sapphire sphere

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