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PRECISION MACHINING OF SPHERICAL CERAMIC PARTS

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Summary

Physical and mechanical properties of ceramic materials make them useful applications in both mechanical and medical engineering. This paper presents the technological system for precision machining of super hard ceramic materials. As an example of precisely processed ceramic components a circular / spherical element can be given, which was used in an endoprosthesis hip replacement. This paper presents selected characteristics of geometrical surface structure after precision machining and finishing and indicates directions for further research into the development of the technological qualities of ceramic components.

Keywords: zirconium, sapphire, precision machining, surface geometric-structure

Precyzyjna obróbka ceramicznych elementów kulistych

Streszczenie

Materiały ceramiczne charakteryzują się właściwościami fizycznymi i mechanicznymi determinującymi ich zastosowanie zarówno w budowie maszyn, jak również w medycynie. W pracy przedstawiono system technologiczny do precyzyjnej obróbki trudnoobrabialnych materiałów ceramicznych. Podano przy-kłady elementów kulistych do zastosowania na endoprotezy stawu biodrowego. Określono wybrane charakterystyki struktury geometrycznej ich powierzchni po obróbce kształtującej i wykończeniowej. Wskazano kierunki dalszych badań z zakresu kształtowania jakości technologicznej elementów z materiałów ceramicznych.

Słowa kluczowe: cyrkon, szafir, obróbka precyzyjna, struktura geometryczna powierzchni

1. The properties of ceramics materials

The ceramic materials are non-metallic, inorganic materials that obtain its characteristic properties when formed by the action of high temperature of at least 800 Celsius degrees, at least 30% crystalline. Current ceramic materials are considered to be materials with a wide range of physical properties and thus their versatile application possibilities.

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Typically, the ceramic material is required for its main (one) physical property, but in some cases there are even a few, such as in the case of the endoprosthesis for hip or knee, where the materials used for its components meet at least 10 requirements.

The general division of advanced ceramic materials consists of eight groups (by subject) shown in Fig. 1.

Functional ceramics include ceramic materials and parts of ceramic that perform electrical functions (electro-ceramics), magnetic functions (magneto-ceramics), optical functions (opto-ceramics), dielectric functions (active chemo-ceramics), or other special functions (nucleo-ceramics). The applications of the functional ceramics are: temperature sensors, storage systems, fluorescent lamps, enzymes carrier, nuclear fuel.

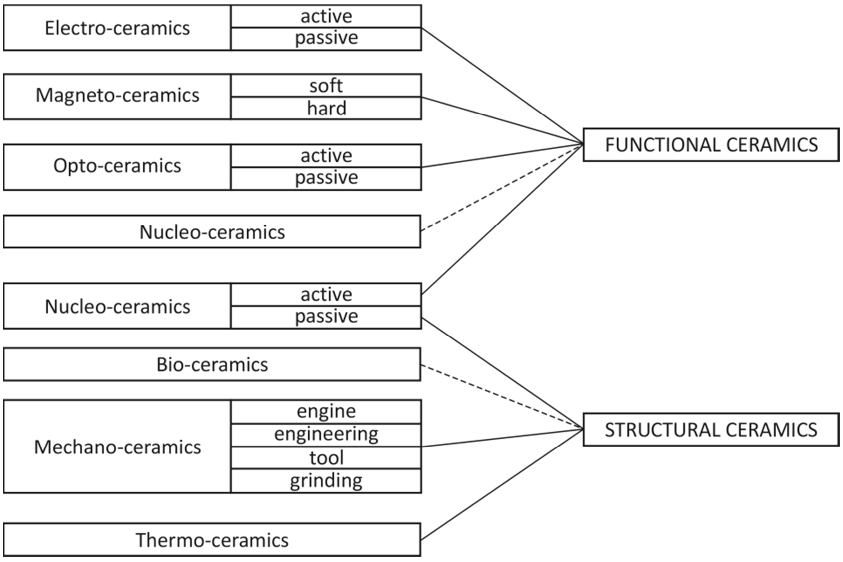

Fig.1. Ceramics division [1]

The structural ceramics, otherwise known as industrial or engineering ceramics, are materials that regardless of the shape of the structural elements have to carry mechanical loads. Their applications include implants, mechanical seals, cutting tools, thermal insulation, etc.

There is an increase in interest in the structural ceramics, due to its unique abilities that allow its use in engineering and medicine [2-4]. Ceramic materials are characterized by a favorable ratio of mass to volume and shape stability, very good mechanical properties, such as: high hardness, mechanical strength at high temperature, high wear resistance, corrosion resistance and creep, thermal properties, such as high melting point and thermal insulation and, electromagnetic properties such as: defined relative permittivity and piezoelectricity and ion conduction, high magnetic permeability, radiation resistance and electrical insulation create wide range of applications in machinery and process equipment and, possible applications in medical engineering due to their good biocompatibility.

Properties of - ZrO_2 (trade name - zircon)

Zirconium, as an element is located in a titanium group in the periodic table. It has a silvery color at room temperature. Zirconium dioxide has a number of advantageous properties, its density is 6g/cm^3; very low coefficient of porosity of < 0.1%; a high melting point – 2700°C; bending strength 1200-1400 MPa. Due to the uniform and compact structure, there is no microcracks, voids or empty space. Advantageous properties such as good mechanical strength, corrosion resistance in an acidic environment, good insulating properties and low ability to absorb ionizing radiation makes it suitable for components operating in harsh operating conditions, including the elements of the endoprosthesis in medical engineering.

Properties of trioxide aluminium Al_2O_3

Aluminum, as an element is located in a boron group in the periodic table. The major advantages of αAl_2O_3 (this is allotropic variety of aluminum trioxide) include low density, low thermal expansion, resistant to high temperatures, high hardness and wear resistance. The adverse properties of aluminium trioxide include mainly low coefficient of fracture toughness, low thermal shock resistance and a low mechanical strength. It is possible to improve the ratio of fracture toughness by forming composites whose matrix is Al_2O_3 and wickers or fiber reinforcement.

Depending on the inclusions, items made of ceramic materials based on aluminum oxide anisotropic properties can take a variety of colors [5]: red – pink (Cr_2O_3); blue (TiO_2+ Fe_2O_3); orange (NiO + Fe_2O_3); orange (NiO + Cr_2O_3); yellow (NiO); green (Co_2O_3+ V_2O_3); dark red (Cr_2O_3 + TiO_2 + Fe_2O_3); purple (TiO_2 + Fe_2O_3 + Cr_2O_3)

Unit cells in the crystallographic structure have an ionic or covalent bonds and very often are mixed with varying participation of both bonds (Fig. 2).

Oxygen ions form a dense network of hexagonal and aluminum ions occupying four of the six available octahedral holes. Sapphire has high hardness and rigidity thanks to strong ionic interactions, due to which it is used in reinforcing fibers or particles in the metal matrix composites.

Basic physical properties of allotropic varieties of aluminum trioxide (sapphire αAl_2O_3) density – 3.98 g/cm^3; bending strength – 280-400 MPa; melting point – 2040°C; resilience – 430÷420 GPa; the thermal conductivity - 29÷30 W/m·K; hardness – 1700÷2000 HV.

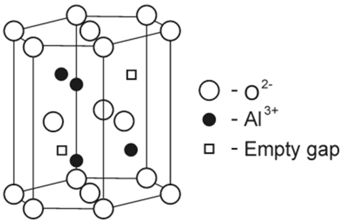

Fig. 2. The unit cell Al_2O_3 [5]

However, high mechanical properties have a negative effect on the formation of ceramic materials during processing. Obtaining a technological quality such as: accuracy of shape and dimension and surface roughness of the product requires special methods and ways of machining [2, 6-11]. To measure and assess the technological qualities of ceramic materials, especially after precision machining, it is necessary to use specialized measuring devices [8, 12, 13]. From an economic point of view for the initial selection of the processing conditions, it is reasonable to use simulation techniques [14, 15].

This paper presents the results of research on precision machining of ceramic materials – zirconium (ZrO_2) and single crystal sapphire (αAl2O3), both can be applied in medical engineering. According to the literature [1, 5], inclusions may affect the density of the material. The density of single crystal sapphire, measured with an accuracy of 0.05% by hydrostatic weighing method, varies from 3.992 to 4.013 g/cm^3 for colored dark red Cr_2O_3 containing 2.97% (chromium dependence is linear). The density, determined experimentally is usually lower than in the calculated values of density, which is associated with the occurrence of micro-cracks or micro-pores in the crystals.

Monocrystalline treated biomaterial α-Al_2O_3 was modified by inclusions of Cr_2O_3 and TiO_2 (0.03÷0.05%). Experimentally determined parameters were: hardness = 1874÷2253 HV; indicator of the fragility I_b = 458 μm$^{-0.5}$, flexural strength σ_z = 700÷1300 MPa; compressive strength σ_s = 2950 MPa, Young's modulus E = 510 GPa, fracture toughness K_{1C} = 3.4÷5.6 MPa · m$^{1/2}$.

2. Shaping of spherical ceramic parts

Institute of Technology Production Engineering at Cracow University of Technology, launched three spindle machining system with no speed control, to form spherical elements using ceramic materials (Fig. 3).

The system was built based on the milling FNX 30P. The formation of spherical elements makes it possible to design and made special tooling for profiling machining and finishing with self-propelled and numerical control.

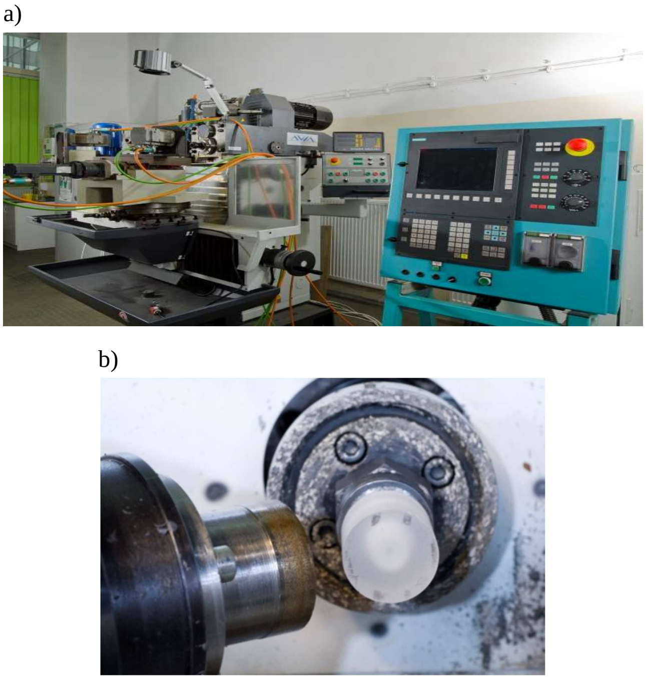

Fig. 3. Machining to create spherical elements from ceramic materials (a), and View of the tool spindle and the object spindle with semi-finished workpiece mounted in the working location of the finishing (b)

To complete the formation process, special abrasive tools were created (Fig. 4), which part was covered with diamond grains (Institute for Superhard Materials is a manufacturer of synthetic diamonds).

Fig. 4. Grinding tools for machining spherical elements

The precision machining of super hard ceramic components, requires the conjunction of three movements: rotational movement of the workpiece and the rotation of the tool and feeder of the tool which is positioned at a certain angle for the workpiece.

As a part of an ongoing research, spherical elements, used as endoprosthesis for hip replacements, were subjected to precision machining, where the head was cut down to 0.10÷0.15 of the diameter of the spherical element. In the work piece an axially symmetrical hole was made to enable the pivot, connecting the work piece with the machine spindle, to be attached.

Selection of the tool diameter and its setting in relation to the work piece capable of producing a desired shape depends on the diameter of the work piece (Fig. 5). While managing the technological process of spherical formation, the potential geometric errors should be taken into account. Attention should be focused on the required dimensional accuracy after the finishing treatment.

The analysis of geometric precision of spherical elements made in the process of pre-machining shows the dimensions of semi-finishers: diameter ϕd_o = 32.45 mm and height h_o = 28.1 mm. The required dimensions of the object after grinding: diameter ϕd = 28.2 mm and height h = 24.6 mm (Fig. 5).

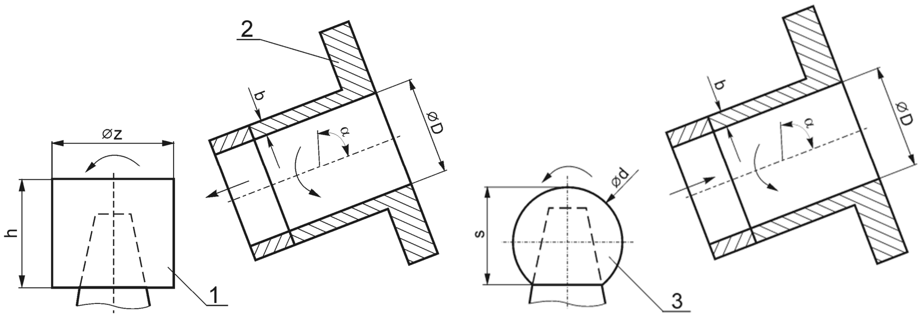

Fig. 5. Semi-finished workpiece (1), tool (2) finished spherical parts (3) along with the main dimensions and marked directions of major movement of the tools and machined parts

Analysis of tool and workpiece geometry led to the determination of the required size and orientation of the tool. Three variants were analyzed: $\phi D_1 > \phi d$; $\phi D_2 = \phi d$ and $\phi D_3 = \phi D_{min}$ (Fig. 6-8.) If $\phi D1 > \phi d$ (Fig. 5), regardless of the angle of the tool axis to the axis of the object, the forming element will have dimensions $\phi d_1 > \phi d$. If the diameter $\phi D_2 = \phi d$ (Fig. 6-7.) the object of the desired shape and size is impossible to achieve, because it will not meet the established requirements for accuracy of form and dimension.

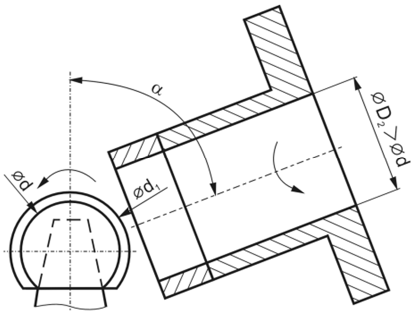

Fig. 6. Diameter $\phi D_1 > \phi d$, then $\phi d_1 > \phi d$; an error of workpiece dimension appears

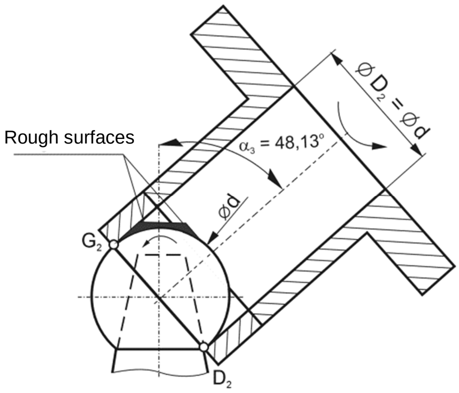

Fig. 7a. Diameter $\phi D_2 = \phi d$, but mismatched angle of the tool axis; a workpiece shape error appears

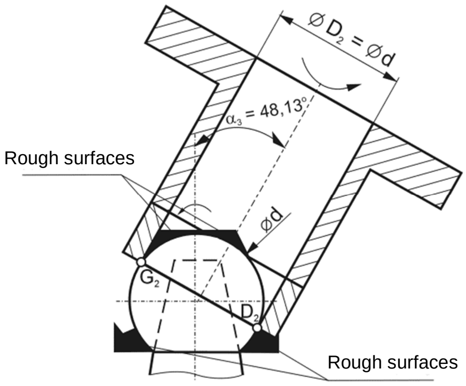

Fig. 7b. Diameter $\phi D_2 = \phi d$, but mismatched angle of the tool axis; a workpiece shape error appears

The correct treatment option for the analyzed case is possible only if the angle of the tool axis to the axis of the object is $\alpha_3 = 69.07^0$ and diameter $\phi D_{\min} = \phi D_3 < \phi d$ (Fig. 8).

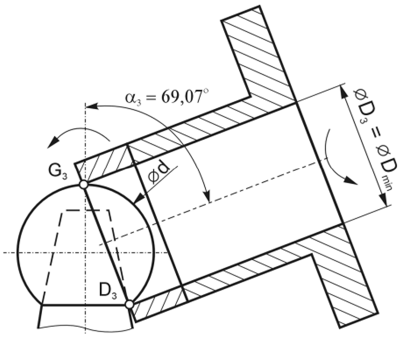

Fig. 8. The angle α_3 of inclination of the axis of the tool is properly chosen, the workpiece is made in accordance with the requirements for the accuracy of the shape and dimension

During the cutting process abrasive wear of the tool occurs. This wear affect the deterioration of the quality – mainly surface quality (roughness) of the workpiece. This issue will be further examined.

Finishing of spherical elements is done with no changes to the mounting of the work piece, in the machine spindle after profiling machining, but by using a special, self-propelled tool, performing additional reciprocating rotary movement. The tool is lapping iron which requires diamond micropowder abrasive paste to be supplied during work. (Fig. 9a). The abrasive paste was made by the Institute of Superhard Materials in Kiev and positioning of the work piece on the machine is shown in Fig. 9b.

3. Technological quality of spherical elements

Technological quality of ceramic spherical parts is determined by a set of parameters, geometric structure of the surface and accuracy of form and dimension. Significant impact on the cooperation of those elements may have defects (discontinuities) that may occur within the ceramic material [8]. The achieved effects of the machining depend on the characteristics of used tools; mainly size and type of abrasive grain, intensity and value of tool wear, the type of lapping tool and, lapping medium composition and size of grains.

To present the technological quality of ceramic spherical parts, selected results of the geometrical structure of the surface have been shown (Fig. 10).

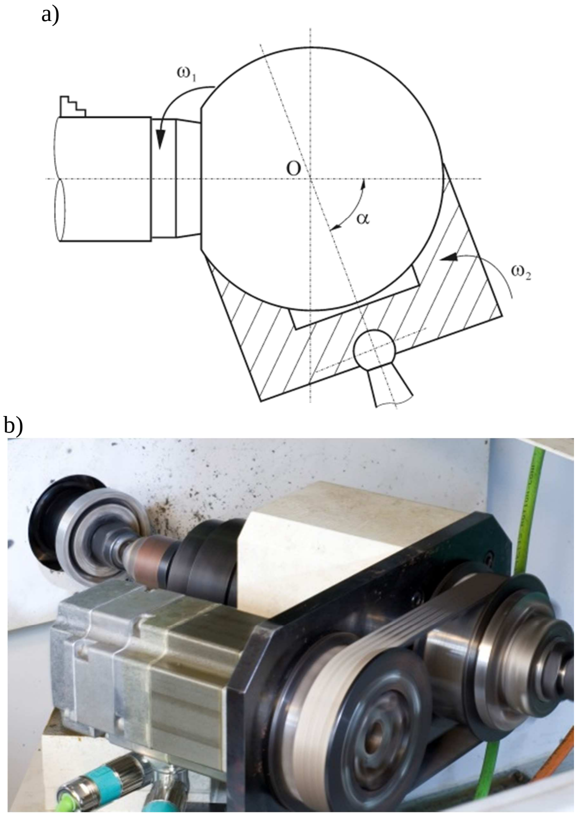

Fig. 9. Kinematics (a) and special equipment (b)
used to lapping of spherical parts

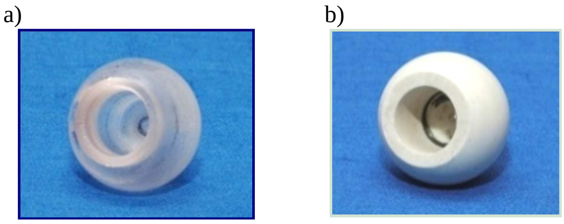

Fig. 10. Elements of spherical artificial hip joint made
of a single crystal sapphire (a) and the zirconia ceramics (b)

During the process of throwing and sintering, some discontinuities may occur in the ceramic materials. Those can reappear during the process of machining, such as grinding or lapping.

It may be particularly disadvantageous for the cooperation between two surfaces, when abrasive grains appear in the micro-hole (Fig. 11) after the lapping process [9].

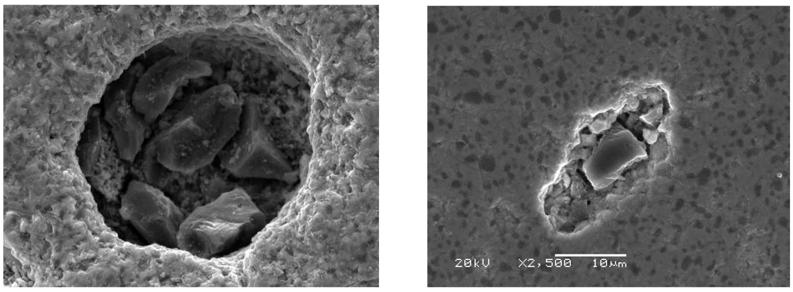

Fig. 11. Example of defects (size 10÷20 µm) in zirconia ceramics with diamond visible micrograins [9]

An advanced machining system allows to obtain technological quality of spherical parts in the following diameters *d* = 20÷40 mm in accordance with the requirements of ISO 3290, such as; surface roughness R_a = 0.04÷0.08 µm; shape accuracy Δ*d* = 0.5÷10 µm; diameter tolerance *Td* = ±10÷16 µm.

The size of the diamond grains and diamond micro-grains have a great impact on productivity in the preliminary profiling machining (grinding) and finishing (lapping) (Fig. 12).

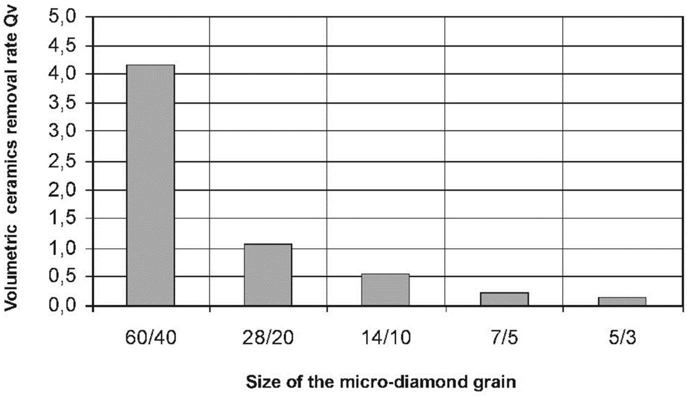

Fig. 12 Relationship between a removal of machining surplus to a micro-grain size in the lapping process of zirconia ceramics

Moreover, the structure and roughness of the surface strongly depends on the size of the applied micro-grains during finishing process (Fig. 13).[1]

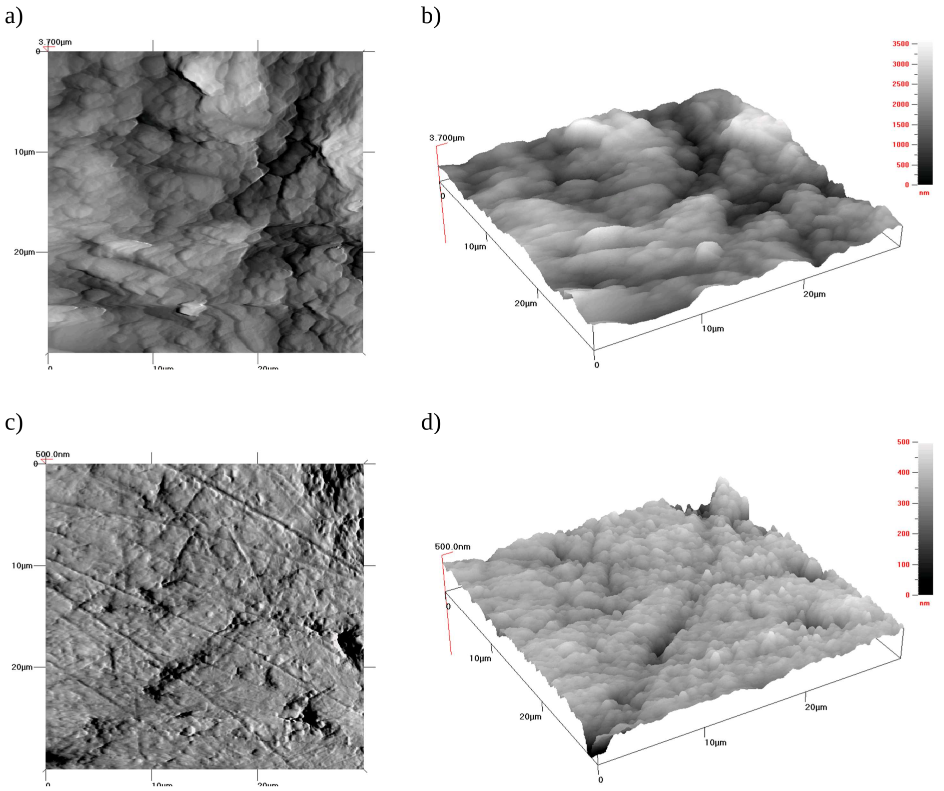

Fig. 13. The geometric structure of the surface after lapping zirconia ceramics: a), b) micro-grain size 60/40, S_t = 3.7 µm; c), d) micro-grain size 5/3, S_t = 0.5 µm; a, c – 2D view; b), d) 3D view

Conclusions

Ceramic materials are materials characterised by high thermal abilities thus are used in a variety of different machines and technological equipment as well as in medical engineering. Even though these materials belong to a group of difficult machinable materials, the appropriate methods and machining conditions can give the required quality of technological products in terms of accuracy of form and dimension and roughness of the machined surface.

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[1] The tests were performed in ITE-PIB in Radom.

Further research will be carried out in this area to determine the effects of weariness of diamond tools in developing high technological quality and special diamond tools.

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