MATERIALS PHYSICS AND MECHANICS RESEARCH ARTICLE

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Machinability of nitride ceramics with abrasive powders and their addition to diamond powder

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ABSTRACT

Development of modern engineering is related to development and introduction of new materials and progressive technological processes of their treatment. Unique properties of ceramics allow them to be used in various fields of technology, including, as a cutting instrument and the machines, devices, radio and electronic apparatus details. Due to the high hardness of materials, tooling of instrumental purveyances is possible only with synthetic diamonds, but synthetic diamonds are quite expensive there, so it is necessary to solve the problem of replacing expensive materials with cheaper ones. Improvement of ceramics treatment methods is related to study of conformities to law of difficult multivariable process of polishing. Productivity, quality of surface, wear and firmness of instrument, power charges are determined by properties of ceramics, descriptions of diamond instrument, modes and by technological features of equipment. Providing high quality surface at exact ceramic details is a difficult requirement specification. Next to a subzero roughness that is limited to parts of microns, a specific requirement is absence of surface defects (coulisse, microcracks, microcavities). As ceramic materials are fragile then at loading under act of cutting or polishing instruments of good from them tend to spalling. Point loading during a small enough flowage result in that under act of grains of diamond of ceramics, feeling strong mechanical and thermal loading, painted as a result of it there is a ditch width of that exceeds the area of collision of diamond grain with material.

KEYWORDS

vibro-magnetic-abrasive processing • material removal rate • surface roughness • CBN ceramics

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Introduction

Problem with processing superhard ceramics is that intensity of its processing depends on presence of artificial diamonds in abrasive mix. Diamond is a rather expensive material. Therefore, the hard material has to be processed more delicately. This issue has been studied by many domestic and foreign researchers. Tamarkin M.A. et al. [1] were engaged in vibration processing in granular abrasive media. Kuzin V.V. [2] studied tools with ceramic cutting plates. Feng Y. et al. [3] investigated manufacturing methods and cutting characteristics of self-lubricating ceramic cutting tools with microtexture. Lebedev V.A. and Dyachenko E.A. [4] were engaged in modeling performance of vibro-abrasive finishing treatment. Khalimonenko A.D. [5] worked on quality control of turning process using cutting ceramic tools. Klimenko S.A. et al. [6] studied surface finishing in production of details. Akulovich L.M. et al. [7] analyzed influence of properties of working technological environment on surface roughness and productivity during magnetic abrasive processing, investigated influence of properties of working technological environment on surface roughness and productivity during magnetic abrasive processing. Arulkirubakaran D. et al. [8] studied texture of cutting tools. Burlakov V.I. et al. [9] explored processing of cutting ceramics. Liu Y. et al. [10] tested cutting tool with certain texture. Savenkov A.A. et al. [11] investigated role of tools with certain texture in improving processing performance. Golobokov A.V. et al. [12] carried out simulation modeling of grinding process of workpieces. Farwaha H. et al. [13] carried out mathematical modeling of processes. Sugihara T. et al. [14] were engaged in development of new CBN cutting tool for high-speed machining. Ranjan P. and Hiremath S. [15] studied role of texture tools in improving machining productivity. Serga G.V. et al. [16] investigated increasing productivity of finishing and hardening machining systems. Cheng K. et al. [17] considered metal machining using the magnetic method. Rogov V.A. and Shkarupa M.I. [18] carried out comparative analysis of mechanical processing of superhard materials by grinding. Slipchenko K. et al. [19] investigated mechanical properties and cutting ability of CBN-based cutting tool. Cheng K.C. et al. [20] were engaged in describing characteristics of magnetic-abrasive method. Sergiev A.P. et al. [21] conducted research of influence of amplitude-frequency characteristics of vibration turning on roughness parameters. Paswan S.K. and Singh A.K. [22] analyzed magnetic abrasive machining. Maksarov V.V. et al. [23] investigated technological features of magnetic abrasive machining under digital technologies. Popov M.A. et al. [24] studied influence of cutting-edge rounding radius on improving quality of surface layer of detail. Filipenko R.A. et al. [25] scrutinized problem of technological quality assurance of edges of flat products using magnetic abrasive machining. Damskiy D.B. et al. [26] conducted assessment of reliability of technological process of vibro-abrasive machining. Tishchenko E.E. et al. [27] developed hardening technologies and coatings. Mordovtsev A.A. [28] conducted assessment of use of vibration processing in conditions of 'smart production'. Rogovenko D.A. [29] was engaged in analysis of schemes and methods for intensifying process of magnetic-abrasive processing of flat surfaces. Purpose of this article is to prove that soft abrasive is capable of taking part in processing of nitride ceramics using the vibration-assisted magnetic abrasive method.

Material and Methods

A promising finishing method is vibration-abrasive machining [1] which allows not only reducing roughness of tool surfaces but also to control size of rounding radius of their cutting edges and relieve residual stress. Until now, there is experience in using such processing in manufacture of cutting tools equipped with a working part made of hard alloys [2,3]. Considering widespread use and high cost of tools made of polycrystalline super hard materials (PSHM) based on cubic boron nitride (CBN) [4,5] improving their manufacturing methods is of significant scientific and practical interest. Vibro-abrasive machining, as a finishing method, which in traditional applications is characterized by high productivity and is effective when it is necessary to ensure high quality of treated surface can be very effective in this case. It should be kept in mind that products made from PSHM have high hardness, are difficult to machine and process of their vibration-abrasive processing is characterized by a few significant features.

During the process of vibration-assisted magnetic abrasive finishing material being processed and subjected to mechanical abrasive action, influence of magnetic field that is constant in magnitude and direction which has a beneficial effect on properties of surface layer of product. This circumstance allows vibration-assisted magnetic abrasive processing to be distinguished as an independent method of finishing processing [6]. Features of ViMAO method are continuous contact of powder with workpiece surface being processed that reduces cyclic loads on "machine-fixture-tool-workpiece" system and helps to increase accuracy of geometric dimensions and shape of workpiece surface, absence of rigid fastening of abrasive grain in bond that contributes to involuntary leveling of cutting tool relative to shape of surface being processed and eliminates likelihood of critical pressures and temperatures appearing in cutting zone, improving physical and mechanical quality indicators of surface layer of product material, ability to control rigidity of tool and, due to this, ensure regulation of metal removal from forming surface of product; absence of friction of bond on surface of product that significantly reduces temperature in abrasive processing zone, ability to cut with the sharpest edge of magnetic abrasive powder grain (this does not require periodic re-sharpening of the tool), maintaining geometric dimensions within tolerance left for the finishing operation.

Following powders were used as abrasive material: monocorundum, green silicon carbide, black silicon carbide, white electrocorundum, pink electrocorundum, ruby-corundum electrocorundum, sol-gel corundum, normal electrocorundum. In all powders, grain size according to GOST 12 is 150–125 μm. Wide range of abrasives is explained by differences in properties of abrasive powders [7]. Abrasive tools based on electrocorundum are used in roughing and stripping operations for processing workpieces made of materials with a high tensile strength, in finishing and finishing operations for processing workpieces and tools made of various steels, semi-finishing and finishing operations for processing workpieces made of medium- and high-alloy steels, etc. Use of traditional abrasive materials as cutting tools in ViMAO is impossible, since they must have not only abrasive but also high magnetic properties. Use of diamond tools helps to accelerate pace of technical progress and allows introduction of new progressive technological processes that ensure higher precision and quality of processing, increased service life and improved reliability of machines and devices [8].

Compared to conventional abrasives, diamond tools provide increasing accuracy of tool and part processing, increase in tool durability after diamond sharpening by 1.2–2.5 times, increase in labor productivity up to 50 %, improving working conditions and production culture, reduction of processing costs by 1.5–2.0 times. Ultradispersed diamonds (UDD) are nano-diamonds obtained by detonation synthesis under influence of explosion energy [9,10]. Uniqueness of UDD product lies in combination of diamond core structure, diamond hardness, chemical inertness on the one hand and nano-sized particles, rounded shape, developed and active surface on the other one. Unlike natural and known synthetic diamonds, UDD forms multi-level aggregates of varying density and structure depending on environment. UDD suspensions and hydrosols have high aggregation and sedimentation stability. Physicochemical properties of UDD allow identifying main areas of its application: protective electrochemical and chemical coatings in electroplating, friction modifiers in production of lubricating compositions, polishing compounds, fillers at production of composite polymer materials, sorbents in pharmaceuticals.

Ultra-fine diamonds ensure perfect fit of parts and significantly reduce friction. This allows effect of sliding friction to be replaced by rolling friction. Concentration of ultra-dispersed diamonds can reach $(20-25)\cdot 10^{12}$ on an oil film area of 1 cm². It is important to note that there is no “abrasive” effect in process of operation of "UltraDiamond" products, since threshold of "abrasiveness" is size of a diamond of 10 nm and more. Therefore, they cannot cause any damage during friction process [11]. Diamond powder is used for production of diamond tools; in addition, it is also used in an unfixed state (in the form of suspensions and pastes).

One of the most common brands is cubic boron nitride ceramics. Cubic boron nitride (CBN) is a super hard material obtained by synthesis at high temperature and pressure. According to properties and performance characteristics CBN differs significantly from synthetic diamond, it is more brittle and has lower strength. Cubic boron nitride is most widely used as a tool material for processing steels and alloys [11–13]. Synthesis of CBN crystals is carried out from supersaturated solutions of boron nitride in melts of alkaline, alkaline earth metals and their compounds. As a rule, spontaneous crystallization from a multicomponent reaction composition is used.

In the process of chip removal during diamond processing ceramics, individual diamond grains are involved in combination with ferromagnetic components. When studying nature of destruction of ceramic surface by diamond grain it was found that grain at the beginning and end of scratch leaves a clear trace without obvious chips along edges of trace. Diamond grain, having sufficient hardness, immediately upon contact with material begins to cut off chips. Middle part of scratch has significant breaks along edges along its entire length. Appearance of chips when a certain depth of grain penetration is reached is explained by the fact that with an increase in cutting depth more and more edges of diamond grain come into work as a result of which micro-cutting forces in zone of its contact with sample material increase and along with formation of highly dispersed chips large areas of breakouts are observed. Forces that arise during finishing determine stability of abrasive tool, quality of processing and allow selection of rational technical parameters [14].

When processing ceramics, condition of surface layer largely depends on cutting forces. Knowledge of patterns of change in the latter allows one to reasonably select optimal processing conditions. Nature of change in cutting forces can also be used to judge physical phenomena occurring in processing zone. Abrasive wear is caused by the fact that product material acts on tool with its contact surfaces, scratching ceramics acting as micro-cutters. Due to high hardness of CBN particles, abrasive wear of tool depends on amount of hard abrasive. Abrasive wear of tool can be associated with phenomenon of "self-wear" [15]. Source of particles that cause "self-wear" is rounded section of tool cutting edge from where particles are removed due to fatigue phenomena and adhesive interaction with material of product and getting onto contact surfaces of tool form their wavy relief. This mechanism determines wear.

Although diamond abrasive wears out due to the specific nature of processing, it does not stop because magnetic field presses sample against tool. Sufficiently high pressure in the cutting zone causes the resulting powder to act as a lapping paste. As a result, a harder material is processed with a softer one and this process is carried out using the vibration-assisted magnetic abrasive method. Knowing wear intensity of abrasive material, it can be understood that after what time processing will switch to lapping mode and with a soft material. This approach to wear ensures consistent processing of ceramics with virtually any type of abrasive material. Thus, hypothesis about impossibility of processing a hard material with a softer one is not always confirmed. One more thing to note is that abrasive wear which is wear of material under action of abrasive should not be confused with wear of abrasive material. The first one occurs as a result of action of hard abrasive on part, and the second one occurs when soft abrasive is applied to a harder surface [16].

In a free state powder crystallizes into spherical microparticles that corresponds to thermodynamically most favorable form with a minimum surface area and a maximum volume. When using ViMAO method as the main operation in processing of super hard ceramics the process is based on micro-cutting. Micro cutting is processing of part surface layers mainly with an abrasive tool. During the processing, tool is pressed against surface of part with force of 100–200 N that leads to decrease in roughness and increase in wear resistance.

Samples of CBN-based PSHM (Fig. 1) with following dimensions and shapes were processed, namely, square plate 12.7 × 12.7 × 3.0 mm^3 (brand "Borsinit", hardness of 38–40 GPa) and a cylinder ∅ 7.5 × 5.0 mm^2 (brand "Composite 05IT", hardness of 18–20 GPa). During cutting, under influence of forces pressing grain against part, it enters material of part being processed to a depth of *h* and removes chips of length *a* (Fig. 2).

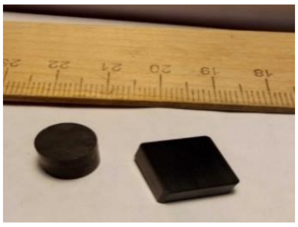


Fig. 1. External appearance of ceramic samples (38–40 GPa)

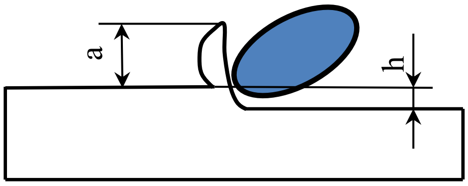


Fig. 2. Scheme of operation of a single grain at ViMAO method

Over time, cutting properties of grains decrease due to their destruction. Therefore, empirical dependence to take into account operating time of magnetic powder can be introduced:

$$1 - e^{-C_u t}, \tag{1}$$

where C_u is the tool life coefficient, *t* is total operating time of magnetic powder.

Then amount of removal Q_c of workpiece surface during time *t* (taking into account wear of powder) can be found using the equation:

$$\Delta Q_c = \Delta V_p = \left[ah\mathrm{arctg}\frac{h\mathrm{tg}\alpha}{a} - r_0^2\sin\alpha\cos\alpha\right]\frac{ak_c hN\pi rn\rho}{r}\left(1 - e^{-C_u t}\right). \tag{2}$$

Area of ellipsoid segment of cutting grain in axial section is equal to:

$$S_{segm} = ah\mathrm{arctg}\frac{h\mathrm{tg}\alpha}{a} - r_0^2\sin\alpha\cos\alpha,\ \alpha = \mathrm{arctg}\frac{x_0}{y_0}. \tag{3}$$

With regard to taking into account all factors influencing processing, it is necessary to introduce a coefficient that depends on formation of chips k_c that is equal to ratio of actual area of metal removed taking into account elastic-plastic deformations of material being processed to area of cutting grain segment [17,18]. Numerical value of coefficient

k_c is determined from reference books on abrasive processing operations.

Then material volume removed from surface of workpiece by one cutting grain will be:

$$V_c = S_c a k_c = \left[ah\text{arctg}\frac{h\text{tg}\alpha}{a} - r_0^2\sin\alpha\cos\alpha\right] a k_c. \quad (5)$$

Knowing density of material being processed, it is possible to calculate material removal rate Q that is expressed through mass from surface of workpiece by cutting grains arranged in a row [19,20]:

$$Q = V_p = \left[ah\text{arctg}\frac{h\text{tg}\alpha}{a} - r_0^2\sin\alpha\cos\alpha\right]\frac{a k_c h N \pi r n \rho}{r}. \quad (6)$$

Obtained mathematical dependencies are shown on Fig. 3. Judging by the graph, over time soft abrasive turns into powder, but processing does not end there. Material removal becomes more extended in time, but soft abrasive continues to work.

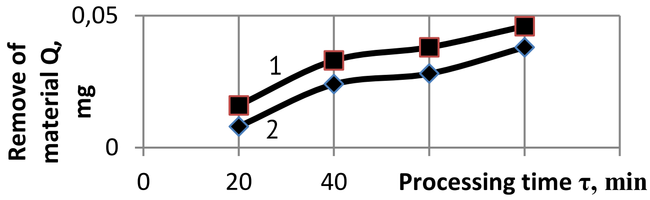


Fig. 3. Dependence of removed material on processing time: 1 – processing with small addition of artificial diamonds; 2 – processing with soft abrasive

Above given dependencies and mathematical models allow to conclude that soft abrasive can process harder material. Process of grinding ceramics can be represented as a set of individual acts of interaction between diamond indenter and brittle body. Although concept of fragility is very relative, high deformation rates and increase in rigidity of stress state diagram can significantly increase fragility of sample being studied while increase in temperature, on the contrary, brings body closer to plastic state. What is important is that these factors act together during processing. Contact area of diamond tool with workpiece can be viewed from three different positions. Firstly, as a nominal contact area determined by the geometric dimensions of interacting bodies. Secondly, as a contour determined by contact areas of individual sections due to macrogeometric deviations of surfaces of tool and workpiece. Thirdly, the actual contact area which is sum of actual contact areas of tool and workpiece as two rough surfaces.

Considering that grinding depth is immeasurably small compared to grinding area and processed material is uniform in three directions it can be argued that contact area of abrasive with sample can be a decisive factor in determining quality and productivity of diamond abrasive processing of super hard ceramics [21].

Diameter of elementary contact spot is determined by below given the equation if microgeometry of grains is practically the same:

$$d = \frac{V\Delta t}{2}, \quad (7)$$

where Δt is contact time of abrasive and sample surface.

Area of elementary contact patch is determined by the equation:

$$\Delta A_r = \frac{\pi}{16}V^2\Delta t^2. \quad (8)$$

Contact area of abrasive and sample during movement can be calculated:

$$A_r = n'\Delta A_r = \frac{\pi}{16}V^2\Delta t^2 n', \quad (9)$$

where *n′* is number of grain projections that came into contact.

Contact time of abrasive and sample surface is determined based on full revolution of electric motor shaft with eccentric since processing was carried out only when ceramic sample passed through abrasive columns and passage was carried out due to vibration action [22]. Number of contact projections was determined by examining imprints of several crystals of hard and soft abrasive materials on cellophane film. Film was placed between abrasive and press, and loading took place (Fig. 4).

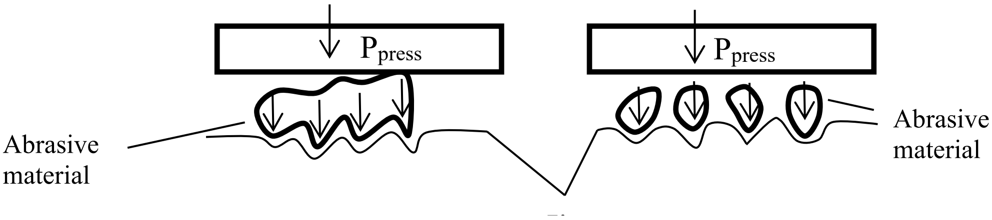


Fig. 4. Scheme for determining number of contact grains when using diamonds

Marks remained on the film at points of contact that were then counted. Thus, calculations were made for soft ($A_{r\,s}$) and hard ($A_{r\,h}$) abrasives and results were compared: $d_h = \frac{0.9 \cdot 0.022}{2} = 0.05$ mm, $d_s = \frac{0.9 \cdot 0.028}{2} = 0.062$ mm, $\Delta A_{rh} = \frac{3.14}{16} 0.9^2 \cdot 0.022^2 = 7.6 \cdot 10^{-5}$ mm^2, $\Delta A_{rs} = \frac{3.14}{16} 0.9^2 \cdot 0.028^2 = 1.2 \cdot 10^{-4}$ mm^2, $A_{rh} = 5 \cdot \frac{3.14}{16} 0.9^2 \cdot 0.022^2 = 3.9 \cdot 10^{-4}$ mm^2, $A_{rs} = 7 \cdot \frac{3.14}{16} 0.9^2 \cdot 0.028^2 = 8.7 \cdot 10^{-4}$ mm^2.

Analyzing calculated contact area, it can be concluded that contact area of soft abrasive grain is somewhat larger, therefore, processing took place and material removal rate may be somewhat higher than when processing with hard grain [23–25]. This result was also obtained due to the fact that when processing with soft abrasive it is necessary to slightly increase force of pressing tool onto sample. Increasing pressure results in increase of actual contact area of soft abrasive tool with sample. Analysis of dependence shows that material removal is approximately equal both when processing with a soft abrasive and when processing with a harder abrasive.

Use of diamond tool powder in processing of cutting ceramics helps to accelerate pace of technical progress, allows introduction of new progressive technological processes that provide higher precision and quality of processing, increase service life of tool and improve reliability of machines and mechanisms.

Results and Discussion

The research has shown that the most productive method is vibro-abrasive machining with application of magnetic field to working chamber using a suspension containing UDM diamond powder (Fig. 5). This is explained by ability of UDM diamond particles to maintain their cutting ability due to constant microchipping of contact areas as a result of vibration and micro-impact loads in processing zone.

Use of suspensions with monocorundum and diamond powders in different concentrations during vibration-assisted magnetic abrasive processing significantly

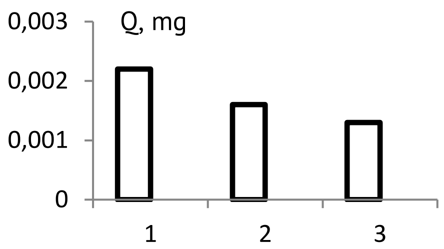


Fig. 5. Influence of diamond powder grade on amount of material removed during ceramic processing: 1 – UDM; 2 – AC6; 3 – ASM

affects amount of material removed from PSHM samples. As can be seen from graph, use of diamond powders in suspension in addition to monocorundum significantly increases removal rate. Figure 6 shows material removal results depending on abrasive material. Analyzing dependence shown on Fig. 6, it can be concluded that synthetic diamond ASM 28/14 that showed high result on its own worked more productively when mixed with monocorundum [26].

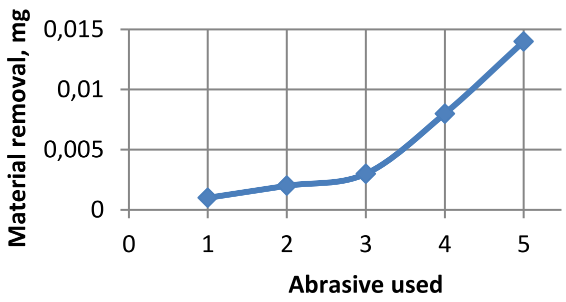


Fig. 6. Material removal from applied abrasive material (mixture): 1 – monocorundum; 2 – monocorundum + white corundum; 3 – monocorundum + 15 % ASM 20/14; 4 – monocorundum + 15 % AC6; 5 – monocorundum + 15 % UDA

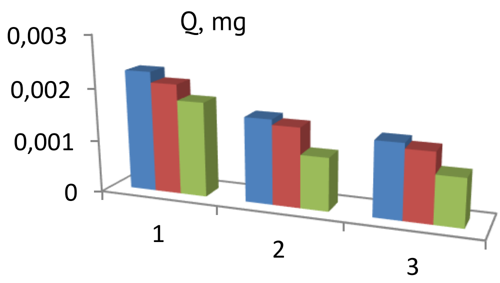


Fig. 7. Influence of diamond powder concentration in suspension on amount of material removed during ceramic processing: 1 – UDM (15, 10, 5 %, respectively); 2 – AC6 (15, 10, 5 % respectively); 3 – ASM (15, 10, 5 % respectively)

As established earlier, material removal depends on physical and mechanical properties of material being processed. Then time for removing micro-roughness will also depend on this parameter. It is possible to determine time for removing microroughness knowing influence of physical and mechanical properties of processed samples during vibration processing and intensity of material removal.

In addition to question of using synthetic diamond as an additive in processing, it was important to find out in what quantity to add synthetic diamond powder. Figure 7 shows dependence of powder concentration on processing intensity. By analyzing dependence conclusion can be drawn about advisability of using certain concentration of diamond powder. When vibration-assisted magnetic abrasive processing of nitride ceramics using suspensions with synthetic diamond powder in concentrations of 10 and 15 % amount of material removed is approximately the same, and it is significantly higher than when using 5 % concentration [27].

Moreover, similar picture is observed when using suspension with any used diamond powder. Finally, it can be said that since difference in removed material with 10 additive and 15 % additive is approximately the same it is more appropriate, based on economic assumptions, to use 10 % additive. Surface roughness was measured in five directions shown on Fig. 8 to eliminate random results. Figure 9 shows surface profiles of samples after 10, 30 and 40 min of processing in one direction.

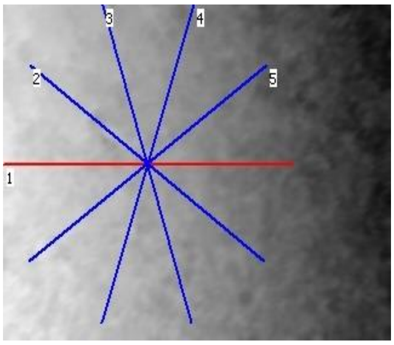


Fig. 8. Orientation of directions for measuring height of microroughness on surface of each sample

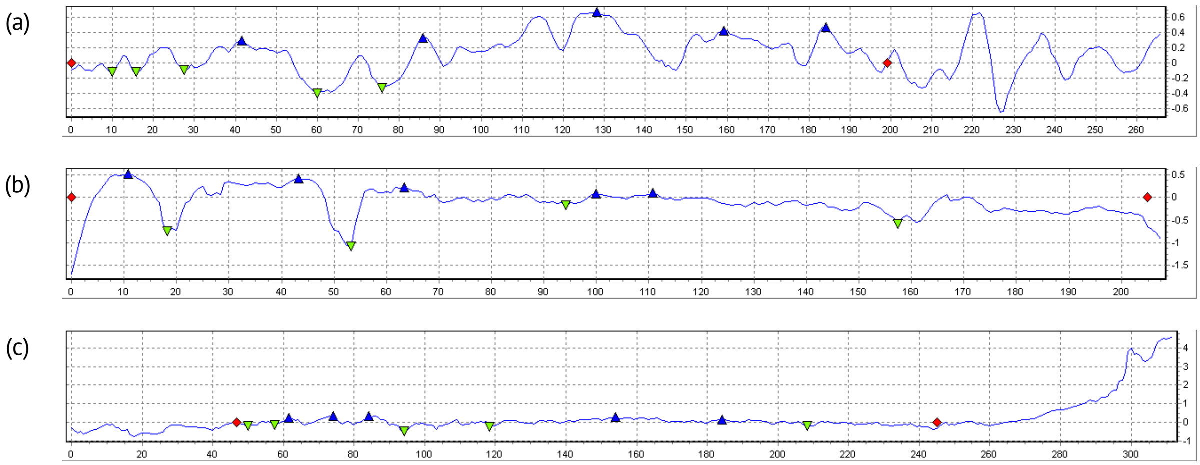
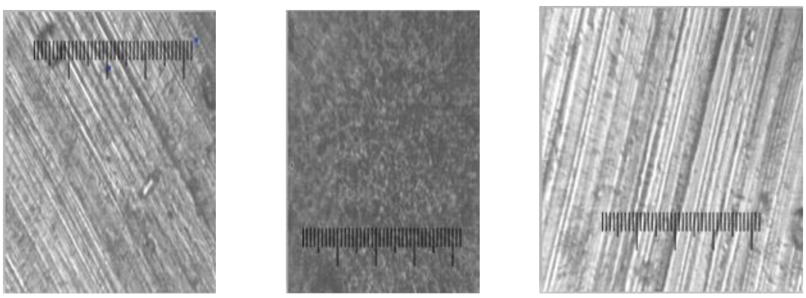


Fig. 9. Surface profiles after (a) 10, (b) 30, and (c) 40 min of processing. R_a = 0.21× 10^3, 0.19× 10^3, and 0.13× 10^3, respectively



(a) (b) (c)

Fig. 10. Optical microscopy images of sample surface (×500) after (a) 10 , (b) 30, (c) 40 min of processing

Research has shown that according to surface treatment profilograms after 10, 30, and 40 min of work it can be concluded that the lowest roughness was equal to R_a (3) = 0.11 μm after 30 min of treatment. These conclusions are confirmed by images of fragments of surfaces that were processed. It is evident from them that the most even surface was the one shown on Fig. 5 that corresponds to exactly 30 min of processing. The fragments of surfaces after processing are shown in Fig. 10 [28].

Analyzing profilograms it can be concluded that the highest quality processing occurred with a mixture of monocorundum and UDA diamond powder at concentration of 10 %. Average R_a = 0.11. Profilograms shown above confirm drawings (Fig. 11) made in 3D. They clearly show difference in surface profile of samples treated with different materials [29] diamonds.

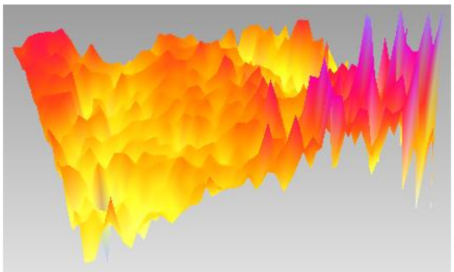


Fig. 11. Plate surface profile (×10^3) after processing in 3D mode: processing time is 30 min. Mixture of UDA diamond powder and monocorundum was used as a tool

Conclusions

1. Process of machining superhard ceramics with softer material is possible with ViMAO due to increase in contact area of abrasive material with sample and increase in pressing force of abrasive material to sample being processed.
2. Obtained mathematical model of machining superhard ceramics with softer material that is possible with ViMAO confirms assumption about processing with softer abrasive.
3. The study demonstrated that using a soft abrasive (monocorundum) in the ViMAO process achieves a material removal rate comparable to that of hard abrasives, albeit requiring approximately 20 % longer processing time to achieve a similar result.
4. Sample surface treated with mixture of monocorundum and UDA diamond powder at concentration of 15 % has more uniform surface compared to other samples.
5. Roughness parameter of ceramic plate after vibration treatment is R_a = 0.11 that is significantly lower compared to other samples.

CRediT authorship contribution statement

Viktor I. Bulakov: conceptualization; **Viktor G. Artiukh**: investigation; **Daria A. Kitaeva**: data curation; **Nikolay V. Korihin**: data curation.

Conflict of interest

The authors declare that they have no conflict of interest.

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