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Modeling of vibro-magnetic-abrasive finishing tools and analysis of their influence on the surface quality of cutting ceramics

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ABSTRACT

A model of a tool for machining cutting ceramics is proposed with an aim to provide a detailed analysis of its durability. The development of effective abrasive materials capable of operating under extreme conditions is discussed. The use of tools made from diamond-containing composite materials is necessitated by the exceptional hardness of diamonds. While many researchers have investigated finishing processes, the combination of vibrational and electromagnetic components to achieve a high-quality and productive lapping process for superhard ceramics has not been previously accomplished. The process of synthetic diamond manufacturing is described.

KEYWORDS

superhard materials • workpiece processing • diamond-containing composite materials • tool life high-performance workpiece processing • wear process

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Introduction

A critical scientific and technical challenge is the selection of an abrasive tool for the vibro-magnetic-abrasive finishing (VMAF) of cutting ceramics that ensures high quality of the machined surface and extends the service life of ceramic tools [1–3].

The process involves subjecting the processing medium and workpieces in the vibration machine's chamber to a constant magnetic field perpendicular to the plane of the medium's circulatory movement. Vibration drives the medium, aligning the ferromagnetic abrasive, Al_2O_3 granules, and synthetic diamonds (adhered to the granules) along the magnetic field lines. The dense abrasive packing prevents workpiece collision. Vnukov Y.N. [4] studied ceramic cutting plate processing and advanced tools. Kozyrev N.V. et al. [5] investigated synthetic diamond production. Liao Y.S. and Lin H.V. [6] explored advanced tool creation. Rogov V.A. and Shkarupa M.I. [7] compared mechanical processing of superhard materials by grinding. Lebedev V.A. and Dyachenko EA. [8] modeled vibro-abrasive finishing performance. Novikov N.V. and Klimenko S.A. [9] designed superhard material tools. Suslov A.G. [10] also contributed to tool research. Malinin P.V. et al. [11] studied centerless grinding preparation. Skryabin V.A. et al. [12] researched fine-media finishing. Skryabin V.A. and Svechnikova G.I. [13] experimentally studied finishing productivity for various profiles. Zubarev Y.M. and Yuryev V.G. [14]

designed abrasive tools and grinding operations. Volkovsky A.A. and Makarov V.F. [15] assessed surface quality in flat grinding. Rodionov I.V. and Kambulov S.V. [16] investigated burr removal on small parts via vibro-abrasive machining. Losev A.V. et al. [17] emphasized the need for finishing technologies in engineering. Zverovshchikov V.Z. and Zverovshchikov A.E. [18] worked with free abrasives. Tamarkin M.A. et al. [19] used free abrasives. Qi J. et al. [20] simulated grinding. Kazakov D.V. et al. [21] worked in abrasive grain environments. Tishchenko E.E. et al. [22] engaged in finishing. Rowe V.B. [23] studied modern material cutting processes. Wang G. et al. [24] formed profiles in abrasive media.

Residual tensile stresses play a key role in ceramic fracture, while compressive stresses are most detrimental. Thus, tensile stresses can be beneficial in machining, whereas compressive stresses must be eliminated. This study aims to maximize tool life by minimizing residual stresses and utilizing their presence during processing.

Material and Methods

In the cutting mode, friction occurs in several ways: chips rub against the tool's rake face, the flank face rubs against the workpiece, leading to wear, tool blunting, and the need for re-sharpening. This applies to edged tools. Abrasive machining can be viewed as material removal by individual grains; more grains result in higher quality and productivity. The concept of tool life also applies to abrasive tools, defined as the total operating time between the start of material removal and its practical cessation. Tool life for turning inserts is 30–90 min, depending on the tool and workpiece materials, cutting conditions, geometry, and machining environment. Abrasive tool life depends on the workpiece material, machining parameters, and abrasive type. This study focuses on the durability of corundum and synthetic diamond mixtures.

Cutting tool wear differs from general machine part wear due to the high chemical purity of the contact surfaces and the extreme pressure and temperature in the cutting zone [4]. Avoiding critical wear is essential to prevent tool failure, reduce repair effort, and extend service life. Excessive flank wear also increases surface roughness.

Tool wear in metal cutting involves abrasive, diffusion, and adhesive mechanisms. The dominant mechanism depends on the tool and workpiece properties and cutting conditions, including speed [5]. Specialized metalworking tools offer advantages through their edge geometry and processing technology, enabling efficient, high-quality machining. Using diamond abrasive tools mitigates but does not eliminate wear, merely delaying it. Abrasive tools wear during machining, with the rate and nature of wear depending on the workpiece and tool materials, and operating conditions. Abrasive tool performance is determined by its hardness — the ability to retain grains. Grains wear through abrasion and fracture, which are natural under grinding conditions [6].

When machining superhard ceramics with diamond tools, the lack of self-sharpening increases cutting forces, negatively affecting the surface layer. Controlling this impact through variable oscillations reduces cutting forces and preserves tool geometry. This approach is also applicable to the less-understood free abrasive method. Total abrasive wear comprises grinding wear and layer removal. Wear is quantified by the mass, volume, or area of removed particles, termed mass, volumetric, or surface wear, respectively [7].

Practical experience shows that the choice of tools and parameters affects not only accuracy, roughness, and productivity but also tool consumption, wear resistance, and processing cost [8]. New abrasive materials can reduce tool consumption and enable unique processing. High-quality machines require high-quality tools. Their rational use unlocks modern equipment's potential, justifying the investment in advanced tooling [9]. Wear-resistant tools boost productivity by reducing setup time. Multifunctional tools minimize the tool range and machine time per operation [10]. The life of superhard material tools depends on the same factors as carbide-tipped tools, with proper sharpening and edge preparation being critical.

Results and Discussion

When processing cutting plates using vibration processing with free diamond abrasive average durability (Fig. 1) increased several times compared to the abrasive material made from mixture of monocorundum and 15 % additive of the artificial diamonds of ASM 20/14 brand (synthetic diamond micropowder) and processing with the abrasive material made from the monocorundum alone, that can be seen on Fig. 1.

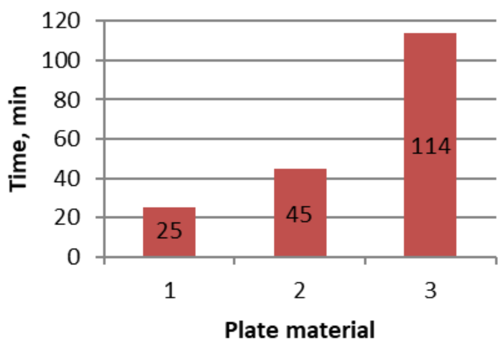


Fig. 1. Dependence of cutting plate durability on type of material:
1 – monocorundum; 2 – monocorundum + 15% ASM 20/14; 3 – monocorundum + 15 % UDD

As can be seen from Fig. 1, tool life turned out to be most acceptable when processed with a mixture of monocorundum with 15 % addition of UDD (ultradisperse diamond) brand artificial diamond materials. This is relatively new nanomaterial that is ultra-dispersed detonation synthesis diamond. The diamond was obtained using a developed technology which involved subjecting an ampoule containing a carbon material (usually graphite) to shock compression at pressures exceeding 10^5 atm during the detonation of an explosive charge, which was accompanied by heating to several thousand degrees. Under these conditions, carbon recrystallized into diamond, i.e., the essence of the method was to use the energy of an explosion to create conditions under which phase transition of graphite into diamond occurred. A 20-fold excess of copper or nickel powder was added to the ampoule to quickly remove heat to prevent the diamond from turning back into graphite when pressure dropped. The resulting product contained micron-sized diamond particles and was used for technical purposes, for example, as effective abrasive for rough grinding of parts [8].

As stated above, the tool's durability was determined by time of its continuous operation until complete failure i.e., breakdown. A series of experiments were conducted which made it possible to determine that over time the amount of material removed from

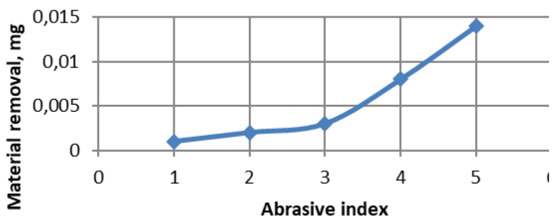


Fig. 2. Material removal from applied abrasive material (mixture): 1 – monocorundum; 2 – monocorundum + white corundum; 3 – monocorundum + 15 % ASM 20/14; 4 – monocorundum + 15 % AC6; 5 – monocorundum + 15 % UDD

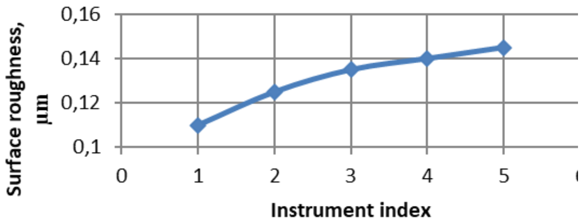


Fig. 3. Dependence of surface quality on used abrasive material (mixture): 1 – monocorundum; 2 – monocorundum + white corundum; 3 – monocorundum + 15 % ASM 20/14; 4 – monocorundum + 15 % AC6; 5 – monocorundum + 15 % UDD

the surface of the plate began to noticeably decrease. Analysis of the graph presented in Fig. 2 shows that not only durability of the tool itself must be taken into account but also removal of material being processed when using different abrasives.

Tool management also addresses the problems of using old tools that prematurely fail or fail to perform the required operations. Furthermore, automated production systems place higher demands on metal-cutting tools [9]. For example, an expensive tool may be damaged if, during operation of an end mill, one of non-resharpenable carbide inserts fails prematurely. In this regard, the task of increasing the tool life is a critical objective.

Since the main factor influencing tool wear is cutting temperature, the thermophysical characteristics of the tool material, which significantly affect the cutting influencing temperature, also influence tool wear. Thus, a 15 % addition of diamond abrasive material to monocorundum significantly increases the service life of cutting tools, which is essential for the domestic industry. Along with increase in tool life, quality of machined surface also improved [10]. The graph presented in Fig. 3 clearly confirms the above statement.

From the graph presented in Fig. 3 it is clear that productivity increases proportionally with the cutting ability of abrasive tool. Contact parameters are linear pressing force of abrasive tool [8]. The use of diamond-based technology significantly enhances capabilities of manufacturing industry. Using diamond tools ensures high-quality processing of any surface, providing high productivity and guaranteed reliability.

During the chip removal process at the diamond machining of ceramics individual diamond grains are combined with ferromagnetic component. Study of nature of ceramic surface damage by diamond grains revealed that a grain leaves a clear mark at both the beginning and the end of a scratch without obvious chips along edges. Being sufficiently hard, the diamond grain begins to cut off chips immediately upon contact with material. Middle part of scratch, however, has significant breakouts along its entire length at edges. 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 cutting edges the of diamond grain become engaged, 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 [11].

Condition of the surface layer is significantly influenced by the cutting forces when machining ceramics. Understanding the patterns of these forces allows for informed selection of the optimal machining conditions. Nature of cutting force changes can also be used to assess physical phenomena occurring in machining zone.

Abrasive wear is caused by the workpiece acting on tool's contact surfaces, where hard particles in the material scratch the tool, acting as micro-cutters. Due to high hardness of CBN (cubic boron nitride) particles, abrasive wear of tool depends on amount of hard abrasive. This abrasive wear of tool can also be associated with phenomenon of "self-wear" [12]. Source of particles that cause "self-wear" is rounded section of cutting edge of tool. Particles are removed from this area due to fatigue and adhesive interaction with workpiece material. They form a wavy pattern when they reach contact surfaces of tool. This mechanism determines wear.

Although diamond abrasive wears out due to the specific nature of process, it does not stop because the magnetic field presses the sample against the tool. Sufficiently high pressure in cutting zone causes resulting powder to act as a lapping paste. It results in the processing of a harder material with a softer material, a process achieved using vibro-magnetic-abrasive method.

Knowing the wear rate of the abrasive material allows for determining how long it will take for the machining process to transition to lapping mode even with soft material. This approach to wear ensures consistent performance on ceramics with virtually any type of abrasive material. So, the hypothesis that it is impossible to process a hard material with a softer material is not always confirmed. It is also important to note that abrasive wear which is the wear of a material under action of an abrasive should not be confused with the wear of an abrasive material. The former occurs as a result of the action of a hard abrasive on the part and the latter occurs when a soft abrasive is applied to a harder surface [13].

In a free state powder crystallizes into spherical microparticles which correspond to the thermodynamically most favorable form with minimum surface area and maximum volume. The process resembles lapping when using VMAF as the primary operation for machining superhard ceramics. Lapping is the machining of the surface layers of a part with a tool. During the lapping process the tool is pressed against the surface of the part with a force of 100–200 N that leads to a decrease in roughness and an increase in wear resistance.

Initial magnetic-abrasive mixture is held by magnetic forces (when magnetic field of installation is turned on) caused by the magnitude of the magnetic field in working space. Samples of cutting plates made of polycrystalline boron nitride (PCBN) are oriented in the space of the working zone according to the principle of least resistance to movement when vibrations are applied and when performing translational movements they pass through a compacted magnetic-abrasive layer performing surface treatment. Unbound powder grains move inside the working chamber [25–27]. The magnetic field forms a cutting tool with controlled rigidity from a ferromagnetic abrasive powder mass in accordance with its functional purpose. Each surface of PCBN samples being machined is in contact with the magnetic-abrasive layer [14].

It is impossible to use only traditional abrasive materials as cutting tools in vibro-magnetic-abrasive machining because they must have not only abrasive but also high magnetic properties. The key property of magnetic abrasive powders is the strength of the bond between ferromagnetic and abrasive components. This bond significantly influences the stability of powder grains under thermal and mechanical loads. The microhardness, particle shape, manufacturing processability and cost of magnetic abrasive powder are also important. Thus, powders of ferroalloys, iron, cermets and other substances are used as cutting elements in VMAF which are selected depending on the material of the workpieces, the condition of their surface and the initial roughness.

A portion of magnetic abrasive powder is held by magnetic forces caused by the magnitude of the magnetic field in working space when magnetic field is turned on. Samples are pressed against the abrasive material and superhard ceramic is machined because the workpiece moves up or down. This removes excess material and creates a surface with a new microrelief. The frictional forces between the grains help the magnetic field to hold the powder within the working gap [15].

Each processed surface of the sample is in contact with a grain. The surface is subject to cutting force (if the grain has embedded itself in the surface and is performing microcutting or grinding the against sample surface) and friction force. These forces tend to capture the contacting grain along with moving workpiece and return it relative to its own center of inertia. The movement of grains along workpiece surface and their rotation are impeded by the surrounding grains, which under the influence of the magnetic field, compact and form columns of ferromagnetic powder.

If during gradual deepening of cutting grain into the surface being machined cutting force exceeds resistance of grain to rotation from the environment surrounding it or if obstacle in the form of increased microroughness or hard foreign inclusion appears on the path of the rubbing grain (cutting) then such grain returns and new sections and new cutting edges come into contact with the workpiece grain. By these turns intermittent nature of lines called traces of abrasive cutting on the surface of the workpiece can be explained.

A distinctive feature of abrasive cutting in VMAF is observed sharp changes in productivity of process when the processing conditions change. The unique cutting tool formed by the magnetic field from magnetic abrasive powder is characterized by increased elasticity. The depth of penetration of each grain into the surface being processed (and, therefore, volume of material cut by it), in the result of stable equilibrium in each individual case between the forces pressing the grain to the surface being processed and the forces of resistance of the workpiece material to the introduction of

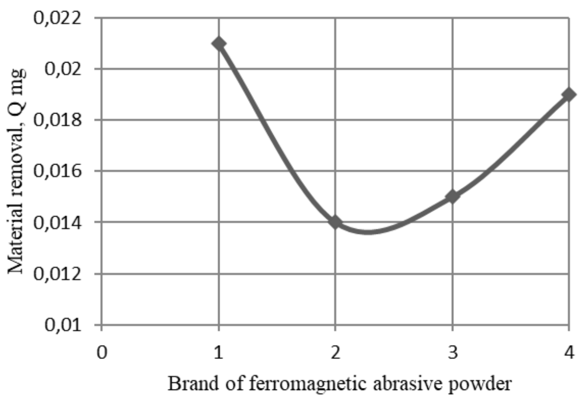


Fig. 4. Dependence of processing performance on dispersion of powder FEROMAP: 1 – FEROMAP 630/400 μm; 2 – FEROMAP 400/315 μm; 3 – FEROMAP 315/200 μm; 4 – FEROMAP 200/100 μm

the grain [16]. In order to determine grain size several observations were made during processing. The purpose of this was to determine the degree of dependence of processing productivity on the grain size of the abrasive (Fig. 4).

Previous studies have shown that when processing with powders such as FEROMAP 630/400 μm, FEROMAP 400/315 μm, FEROMAP 315/200 μm and FEROMAP 200/100 μm better surface quality was obtained than when using powders such as DCK 630/400 μm, DCK 630/400 μm and round-shaped powders such as POLYMAM-M 400/315 μm and PR R6M5 300/250 μm. Moreover, all of these powders have poor cutting properties. Therefore, FEROMAP powders of varying fineness were used for the studies [17].

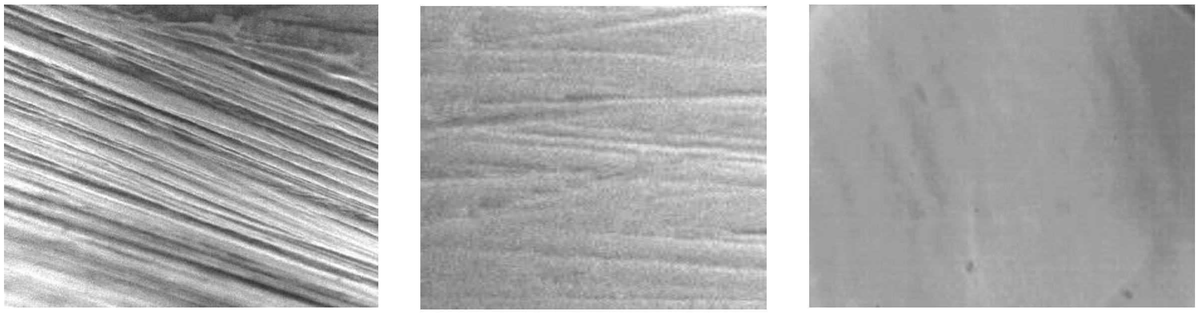
Experiments have shown that FEROMAP 630/400 μm proved to be the best but use of the vibration force almost eliminated differences. This happened because without the use of vibration, the grain size played the primary role but it was vibration component that became decisive in choosing more productive and less expensive material. This is why FEROMAP 200/100 μm was chosen as the primary cutting material. During VMAF electric currents can be induced in them when the poles of the magnetic inductor act on electrically conductive powders and when samples are moved within working space relative to abrasive columns. The reasons for the appearance of induction currents can also be periodic changes in the magnetic flux density in the working space if inductor creates magnetic field [18].

Induction currents of workpiece influence the magnitude and the distribution of the magnetic field in working gap because they are always directed in such a way that their own magnetic field prevents a change in the external magnetic field that generates them. According to functional purpose of magnetic field, in each specific case, all known magnetic-abrasive machining schemes can be divided into five groups one of which has the following meaning where magnetic field forms cutting tool with controlled rigidity from a powder ferromagnetic abrasive mass and creates cutting forces. Other schemes are not functionally suitable for VMAF.

The process of vibro-magnetic-abrasive machining is a process in which material removal begins simultaneously with the activation of vibration and the creation of a magnetic field in the processing area. Determining the forces acting during VMAF is important for understanding the material removal mechanism because forces directly influence formation of the finished surface [19].

Surface quality was determined using a non-contact interference 3D profilograph the "Micron-alpha" [28]. The quality of the cutting edge surface is formed during finishing operations but pre-processing and preparation process also affect surface quality due to the technological inheritance of the original properties of the workpiece at all stages of its processing [29,30]. Surface roughness is determined by the adopted machining method which characterizes the size, shape and direction of the machining strokes. Cutting conditions influence formation of surface roughness [20,22].

Looking at examples of surfaces of superhard ceramic samples, it can be concluded that after processing with DCK 630/400 μm surface has randomly located features and large scratches. The number of scratches decreased sharply and they became less chaotic after processing the same sample with the POLYMAM-M 400/315 μm. This indicates that



(a) (b) (c)

Fig. 5. Surfaces of superhard ceramic samples treated with VMAF using various ferromagnetic abrasive materials (×500): (a) by DCK 630/400 μm; (b) POLYMAM-M 400/315 μm; (c) by FEROMAP 200/100 μm

some processing of superhard ceramics took place but it was not possible to achieve the required surface roughness [21]. Figure 5 shows fragments of surfaces that have been treated with the VMAF.

Thus, when processing with DCK 630/400 μm (Fig. 6(a)) surface microrelief changed for the better; when processing with POLYMAM-M 400/315 μm (Fig. 6(b)) microrelief became better; when processing with FEROMAP 200/100 μm (Fig. 6(c)) surface acquired quasi-homogeneous characteristics which is an indicator of high-quality processing. These indicators show that quality of processing of FEROMAP 200/100 μm has significantly increased compared to the other ferromagnetic materials [23,24].

(a) (b) (c)

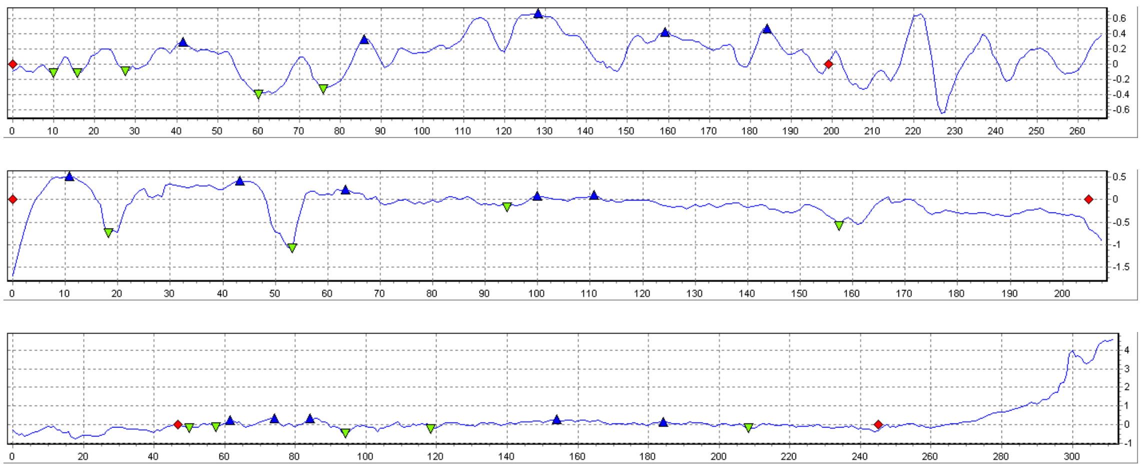


Fig. 6. Profilograms of the cutting ceramic surface after treatment by:
(a) DCK 630/400 μm; (b) POLYMAM-M 400/315 μm; (c) FEROMAP 200/100 μm

Conclusions

Only abrasive particles with spheroidal grain shape can be recommended for use as a magnetic abrasive tool. In addition, it can be used to provide increased polishing and strengthening capacity due to grinding of the treated surface that will be realized to lesser extent when using abrasive powders with different particle shape, performing primarily micro-cutting and dispersion of material from the surface of the workpiece.

FEROMAP 200/100 µm is the most suitable for processing superhard ceramics because after its action, the plate surface looks quasi-homogeneous and has the least roughness. The durability of cutting ceramic tools increases by almost 2–2.5 times.

CRediT authorship contribution statement

Viktor I. Bulakov: conceptualization; **Galina Yu. Burlakova:** 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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