A composite ceramic material for an abrasive tool

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Abstract. The paper describes the features of the electrochemical formation of a modern abrasive tool material. The technology for obtaining the material consists in obtaining a composite diamond-bearing ceramic layer on the surface of diamond-aluminum sintered blanks by microarc oxidation. It was established that the degree of diamond metallization with copper and the relative density of a sintered blank affects oxidation the most. It was impossible to obtain a composite ceramic material by microarc oxidation with diamonds coated with nanodispersed copper with a metallization degree of over 100%. The relative density of sintered blanks should be 80–90% to form a composite material with optimal physicomechanical and tribotechnical properties. Diamond concentration did not affect the creation of stable spark discharges that form aluminum oxide. The optimal alkali concentration in the electrolyte to reach the maximum thickness of the diamond-bearing composite material was about 2 g/l. Comparative tests showed that the wear resistance of a diamond-bearing composite material with a ceramic matrix based on aluminum oxide was notably higher than traditional analogues under similar friction conditions. Finally, the paper determines the scope of the obtained diamond-bearing ceramic material as a tool for precision processing of superhard materials in precision engineering, instrumentation engineering, and the medical industry.

1. Introduction
The demand for diamond-bearing abrasive tools for precise processing of superhard materials in modern machine-building industry and instrument engineering is extremely high [1–7]. Using ceramic materials as a matrix for cutting diamond grains can significantly boost the productivity of diamond abrasive processing [8–12]. Nowadays, the matrix in tool diamond materials on a ceramic basis is most often made of oxide glass. One of the main operational disadvantages of such materials is their low wear resistance, therefore, high rates of diamond specific consumption, as well as insufficient technical and economic efficiency [10].

Using microarc oxidation [13–15] of powder metallurgy parts from aluminum powder and finely dispersed diamond, we obtained a new tribotechnical diamond-bearing ceramic material [15–17] with abrasive diamond particles fixed in matrix of wear-resistant aluminum oxide. The electrochemical oxidation parameters of the state when the formed diamond-bearing ceramic material layer has the greatest thickness, and the composite material has a set of necessary tribotechnical characteristics, are developed insufficiently.

The research objective was to study the process of electrochemical plasma formation of diamond-bearing composite ceramic material for a new generation abrasive tool.
2. Methods
Microarc oxidation modes were tested on sintered blanks obtained from PAP-1 aluminum powder, synthetic diamonds of AC6 GOST 9206-80 grade, 63/50 grain size coated with nanodispersed copper [18]. The density of sintered blanks Q ranged from 75 to 100%.

The equipment for sintered blank oxidation included a power source, an electroplating bath, conductive rod to fix the processed blank, a compressor for compressed air, exhaust ventilation, a distiller. The power source provided high voltage that allows spark breakdown of an aluminum oxide dielectric film formed on the surface of aluminum particles under ordinary conditions. The current strength and voltage can be adjusted. The electroplating bath design provides jacket cooling. Compressed air mixed the electrolyte using a bubbler, which is a hollow tube with small openings. The exhaust ventilation system removed oxidation products, explosive gas in particular.

Friction tests were carried out on an MT-2 friction machine [19]. The obtained diamond-bearing ceramic material was compared with standard diamond-bearing abrasive materials on a metal M1 and organic B1 bond.

3. Results and discussion

3.1. Features of microarc oxidation of diamond-bearing ceramic material samples with different percentage of components
Microarc oxidation is a multifactorial electrochemical process [20–23]. It depends on the electrolyte composition and temperature; blank composition and structure; current density and a processing mode. Since the sintered aluminum powder part undergoes oxidation, there are additional factors:

1. High concentration of aluminum oxide in the mixture; it is formed on the surface of dispersed aluminum particles, since its large surface reacts with atmospheric oxygen.
2. Compared to aluminum, composite materials have high porosity, which contributes to forming a complex blank surface, which is a combination of numerous curvilinear microscopic holes extending into the depth of the blank material.
3. Dielectric dispersed particles in the mixture that might have metals on their surface; it is copper in our case.

Considering the above, it is important to create conditions for stable spark discharges at the initial stage of microarc oxidation. Otherwise, there might be corrosion areas that will impede the creation of a highly rigid ceramic bond between diamond grains. The conditions of the experiment were the following: sodium hydroxide NaOH (2 g/l) that was an electrolyte, liquid glass Na₂SiO₃ (6 g/l), current density was 10 A/dm².

Figure 1 (a) shows the dependence of voltage on the microarc oxidation time at various degrees of M diamond grain metallization. The graphs show that the initial oxidation stage time (a linear portion of the curves) increases significantly with an increase in the metallization degree up to 100%. When the metallization degree of diamond grains increases over 125%, the voltage is at its minimum value, there is practically no linear portion of the curve, which indicates that there are large leakage currents that pass without spark discharges. There are also extensive electrochemical corrosion spots. There is no sparking on the part surface. The high copper content in the material composition without a stable oxide dielectric layer on its surface contributes to forming leakage currents. Therefore, it is near impossible to use diamond grains with a metallization degree of more than 100% when creating a composite ceramic material by the microarc oxidation method.

The dependence of stress on the microarc oxidation time at various degrees of K diamond grains concentration is shown in Figure 1 (b). The presented graphs show that despite the increase in the diamond concentration in the material, which significantly distort the electric field in the material due to their dielectric properties, there are linear sections of the oxidation graphs for forming stable spark discharges, which form highly rigid aluminum oxide. Therefore, we can conclude that the diamond concentration degree is selected from the necessary tribotechnical properties of a tool material, as well as physicomechanical properties of a work part.
Figure 1. The dependence of the voltage on the time of microarc oxidation of blanks (Q = 90%) with a different metallization degree (a) at K = 100% and with a different degree of diamond concentration at M = 25%.

The graphs in Figure 1 can be divided into three sections. The voltage rises sharply in the first graph. In this case, the sparking mode starts much earlier than the linear section ends. In the second graph plot, the voltage gradually increases reaching the maximum value, which corresponds to the end of the microarc oxidation process, as well as the formation of the maximum thickness of a diamond-bearing ceramic layer. In the third graph plot, the voltage decreases sharply, which corresponds to the appearance of powerful arc discharges that cause catastrophic destruction of a composite ceramic layer. Microarc oxidation of the diamond-bearing ceramic material ceases after about 3 hours.

We studied the time to reach the galvanoluminescence mode from the relative density of a blank at various metallization degrees of diamond grains (Fig. 2).

Figure 2. The dependence of the time for starting the sparking mode on the relative density of the material (K = 100%). M: 1 – 0%, 2 – 25 %, 5 – 50%, 4 – 75%, 5 – 100%.

The presence of spark discharges indicates that there are no leakage currents; the probability of forming electrochemical corrosion spots is minimal. When relative density decreases, the time to start the galvanoluminescence mode significantly increases. A sufficiently large startup time increases the electrochemical corrosion probability, which significantly reduces physical, mechanical and tribotechnical properties of the diamond-bearing ceramic material.

3.2. The analysis of forming the maximum thickness of the diamond-bearing ceramic material
The performance of the tool diamond-bearing material is largely determined by the thickness of the diamond-bearing layer. The thickness of the diamond-bearing layer and its physicomechanical
properties are most affected by the power of electric discharges penetrating the barrier oxide layer located on the surface of aluminum particles. The occurrence, distribution and power of spark discharges on the processed blank surface being is determined by the electrolyte conductivity, which in turn depends on the content of chemical reagents in it. In our case, alkali has the greatest influence.

We researched the effect of alkali and the relative density of the blank on the coating thickness (Fig. 3). Test mode was the following: current density – 10 A/dm², Na₂SiO₃ liquid glass content in the electrolyte – 6 g/l. Figure 3 (a) shows that with an increase in the C concentration and alkali in the electrolyte to 2 g/l, the ceramic layer thickness S sharply increases regardless of the concentration of diamonds, as the conductivity increases. In this case, the power of spark discharges increases. With an increase in the NaOH concentration over 2 g/l, the ceramic layer thickness decreases. A large amount of alkali has a destructive effect on SiO₂, Al₂O₃, which are formed during spark discharges. In addition, due to the high conductivity of the electrolyte, there are local powerful single arc discharges that destroy a ceramic layer. Therefore, the optimum alkali concentration in the electrolyte for the maximum thickness of the diamond-bearing ceramic material is about 2 g/l.

![Figure 3](image-url)

Figure 3. The dependence of the formed coating thickness S on the alkali concentration in the electrolyte (a) (Q = 85%), and on the composite material relative density Q (b) (C = 2 g/l).

The dependence of the diamond-bearing ceramic material thickness on the blank relative density is also extreme (Fig. 3 (b)). It has been established that the optimal relative density of the blank is 80–90%. If it is less than 80%, then the material structural strength is insufficient, and the ceramic layer destroys itself under the influence of spark discharges during microarc oxidation. If the optimal relative density increases more than 90%, the ceramic layer thickness also decreases. This is due to the difficult access of the electrolyte deep into the blank surface due to a porosity decrease.

3.3. Tribotechnical properties of the diamond-bearing ceramic material

The comparative tribotechnical tests determined wear resistance of the obtained diamond-bearing materials in relation to the conditions of intensive abrasive processing. The numerical value of wear resistance was calculated as the ratio of the mass of diamonds in the worn diamond-bearing layer to the mass of the material removed from the processed counter sample. It was found that the wear resistance of a diamond-bearing composite material with a ceramic matrix based on aluminum oxide is significantly higher than traditional analogues under similar friction conditions (Fig. 4). An increase in the matrix hardness significantly affected the increasing wear resistance of the diamond-bearing ceramic material. The matrix for Al₂O₃ is comparable to the hardness of a diamond and a counter sample. Reduced diamond consumption when using a diamond-bearing composite material positively affects the technical and economic indicators of abrasive processing.

Figure 5 presents the images of the surface structure of diamond-bearing composite material samples with a ceramic matrix obtained under the above optimal conditions. The surface morphology of the obtained coatings is characterized by a homogeneous structure with an anisotropic pore distribution by size and coating volume. Pores in the material structure provide a free volume for wear
particles, reduce the chance of abrasive tool surface loading. Metallized dispersed diamond particles, which are distributed evenly in the material volume and determining its high cutting ability, are clearly visible.

Figure 4. Wear resistance of diamond-bearing composite material with various types of matrices (K – 100%): 1 – ceramic matrix, 2 – M1 matrix, 3 – B1 matrix.

Figure 5. The surface structure of the diamond-bearing material with a ceramic matrix: Q = 85%, M = 75%, K = 100%.

4. Conclusion
The study has identified the factors that determine the features of electrochemical formation of a diamond-bearing composite material on blanks of various bulk density and with a varying percentage of the components of the material.

The degree of diamond metallization significantly affects the oxidation process. Obtaining a composite ceramic material by microarc oxidation with diamonds coated with nanodispersed copper with a metallization degree of over 100% is almost impossible.

A change in the diamond concentration in the material does not affect the creation of stable spark discharges that form α-modification aluminum oxide. Therefore, the choice of diamond concentration, as well as its grain size, can be based on the required tribotechnical properties of a tool material and physical and mechanical properties of a part to be processed, its surface roughness.

The relative density of the sintered blank to create a diamond-bearing composite material using microarc oxidation should be 80–90%. In this case, a material has optimal physical, mechanical and tribotechnical properties. The optimal concentration of alkali in the electrolyte to reach the maximum thickness of the diamond-bearing composite material is about 2 g/l.

Morphological analysis of the obtained material surface structure allows us to assume its high tribotechnical properties. It is expected that the obtained material will be in demand for the production of abrasive cutting equipment used for precision processing of superhard materials.
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