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Theoretical and experimental evaluation of the properties of antifriction diamond-containing ceramics in a wide range of loads

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Abstract
One area of creating innovative friction units is the use of ceramic elements as parts that are involved in direct frictional contact. Existing studies emphasize the complexity of forming oxide mineral-ceramic diamond-containing materials due to the diamond's sensitivity to oxidation at relatively high temperatures. The purpose of this study is to evaluate the properties of antifriction diamond-containing ceramics in a wide range of loads. During this study, a composite diamond-containing ceramic material was obtained, and a technology was presented, according to which, at the first stage of obtaining the material, a workpiece of dispersed aluminum and diamond is sintered, and then its surface layer is modified by the method of microplasma electrolytic oxidation. The formed part combines the physical and mechanical properties of the aluminum matrix, the base, with the tribological properties of the ceramic-hardened layer containing partially graphitized dispersed diamonds. As a result of the study, a positive example of using a friction pair of diamond-containing ceramic material – ceramics as a working unit of a colloid mill (disperser) was obtained. The developed model allows synthesizing diamond-containing ceramic materials with specified tribotechnical properties. The results of the modeling will allow for a preliminary estimate of the area of stable operation of tribounits, based on the value of contact pressure, before conducting expensive full-scale tests.

Keywords
abrasive diamond tool, processing of technical ceramics, contact interaction model, diamond tool wear.

Introduction

One of the directions of creating innovative tribounits is the application of ceramic elements as parts that participate in direct frictional contact. High tribotechnical properties of ceramics are supplemented by unique temperature, anticorrosive, and electrical characteristics. Particularly promising are ceramic composite materials, in which the high-strength, wear-resistant properties of the base are supplemented by the characteristics of abrasive or antifriction fillers (Drozdov, 2024; Bolotov et al., 2018).

For composite materials of friction units operating under conditions of lubricant deficiency, graphite, molybdenum disulfide, or polymeric materials are traditionally used as fillers with low shear resistance. In scientific studies of recent years, special attention is paid to another allotropic form of graphite – diamond as an antifriction component of the ceramic base (Liu et al., 2022; Xia et al., 2023; Jin et al., 2023; Li et al., 2023; Gusakov et al., 2019). Most authors emphasize the complexity of the formation of oxide mineral-ceramic diamond-containing materials, due to the sensitivity of diamond to oxidation at relatively high temperatures. However, the controlled degree of diamond graphitization during the production of the composite and friction leads to a synergistic effect of creating a highly hard and wear-resistant tribosurface with a given gradient of friction properties (Liu et al., 2022; Jin et al., 2023).

As a result of our studies, a composite diamond-containing ceramic material was obtained, which is based on aluminum oxides of α-, β-, and γ-modifications, into which dispersed diamond grains are incorporated (Bolotov et al., 2020a; Bolotov et al., 2020b). A technology has been developed according to which, at the first stage of obtaining the material, a workpiece of dispersed aluminum and diamond is sintered, and then its surface layer is modified by the method of microplasma electrolytic oxidation. The formed part combines the physical and mechanical properties of the aluminum matrix, the base, with the tribological properties of the ceramic-hardened layer containing partially graphitized, dispersed diamonds. Preliminary results have been obtained, showing that when alloying the ceramic base with diamonds of a grain size less than 20/14, the composite ceramic material exhibits good antifriction properties under conditions of a lubricant deficit or even in its absence (Bolotov et al., 2020a).

There are some results showing that the obtained diamond-containing ceramic material (AKM DCCM) consistently exhibits low values of triboparameters over a fairly wide range of pressures. However, with a further increase in contact pressure, the wear intensity increases sharply. Similar conclusions were obtained for composite coatings reinforced with synthetic diamonds and electrocorundum (Kobyakov et al., 2011), and diamond-like coatings (Vysotina et al., 2017). It can be assumed that under certain loads, the type of wear of these materials changes. Establishing a region of rational loads for diamond-containing ceramic materials in dry friction units will significantly extend the trouble-free operation period of tribounits.

A considerable amount of research has been devoted to analyzing the wear of ceramic materials (Drozdov et al., 2008; Kim et al., 2019; Liu et al., 2018; Kuznetsova et al., 2012). The most commonly accepted theoretical models are based on the linear mechanics of elastic fracture and Weibull statistics (Drozdov et al., 2008; Kim et al., 2019; Morozov et al., 2017; Aizikovich et al., 2001). The nature of wear of ceramic diamond-containing materials has been studied to a much lesser extent (Sudnik et al., 2012; Vityaz et al., 2011; Fedorenko et al., 2017; Chepovetsky et al., 1978). This is explained by the fact that the technologies for producing diamond ceramics are innovative, and the friction characteristics of the composite material are determined by the emergence of its structural components. The results of the work (Sudnik et al., 2012) demonstrate the linear-elastic nature of wear in diamond-containing ceramic tools, as well as the adequacy and correctness of the mechanism of fatigue failure and wear for the working layer of materials of this type. Elastic interaction is the most typical mechanism, even in cases where the parameters of diamond-abrasive processing are being calculated (Sudnik et al., 2012; Chepovetsky et al., 1978). Depending on the properties of the bond and the counter-surface material, it is proposed to use mathematical models for elastic, brittle, or elastic-plastic contact, using criteria for the transition from one type of interaction to another. Our analysis of the morphology of the tribosurface of a composite ceramic material (counter-sample ceramics) after testing, in both steady-state and supercritical loading zones, did not reveal any traces of plastic deformation (Bolotov et al., 2020a; Bolotov et al., 2024). It can be assumed that during the process of friction, the elastic nature of the material's deformation is replaced by its brittle destruction, accompanied by the simultaneous removal of diamond grains and part of the surrounding ceramic matrix.

For materials subject to brittle fracture, including diamond-containing composite materials with a ceramic matrix, the flexural strength, microhardness, or microstrength is used as a critical stress (Drozdov et al., 2008; Sudnik et al., 2012; Pushkarev et al., 2017; Mitlina et al., 2024). For composite materials, it is necessary to take into account the influence of the size effect of discrete components on the micromechanical properties. The paper (Pushkarev et al., 2017) demonstrates the validity of using strength characteristics obtained by indentation with a microhardness tester to describe the properties of materials with particle resolution ranging from 250 to 400 µm. It also notes the high information content of the microstrength indicator for assessing the brittle fracture zone.

In Pushkarev et al. (2017), we proposed a model of elastic contact interaction between material surfaces, specifically diamond-containing ceramics and ceramics. However, deformation processes in the case of brittle fracture have not yet been studied. It is also necessary to conduct additional tribological tests to confirm the validity of the selected models and assumptions made.

Materials and methods

The aim of this study is to evaluate the properties of tribocontact between a pair of materials, specifically diamond-containing ceramics, both theoretically, based on a contact interaction model, and experimentally, over a wide range of loads.

Research materials

Samples of the composite material were obtained from aluminum powder and synthetic diamonds of the AC6 brand, with a grain size of 20/14 and 14/10. The bulk density of diamonds τ is 25% and 12.5%, which corresponds to 100% and 50% diamond concentration *K* (the content of diamond powder in the amount of 4.39 carats in 1 cm^3 is taken as 100% diamond concentration in the material).

At the initial stage, a sample blank made of composite material was obtained by powder metallurgy. Aluminum powder and dispersed diamonds were mixed together, loaded into a press mold, and subjected to cold briquetting and sintering in a muffle furnace under vacuum conditions at a temperature of 570-575°C for 30-40 minutes.

At the second stage, the surface of the composite material was modified by microarc oxidation (MAO). Under the action of electrolytic oxidation, a hardened layer is formed, which is a base of aluminum oxides of *α*, *β*, and *γ* modifications, in which grains of partially graphitized dispersed diamond are uniformly distributed. The equipment for microarc oxidation includes: a power source, a galvanic bath with a cooling jacket, a compressor for compressed air, and an exhaust ventilation system. The material was formed in an electrolyte - caustic sodium NaOH (0.5 - 3 g/l), liquid glass Na_2SiO_3 (6 g/l). Current density is 10 A/dm^2 (Bolotov et al., 2020a).

Fig. 1 shows the microstructure of the sample surface before testing: dark grains of graphitized diamond are distributed throughout the volume of the aluminum oxide matrix.

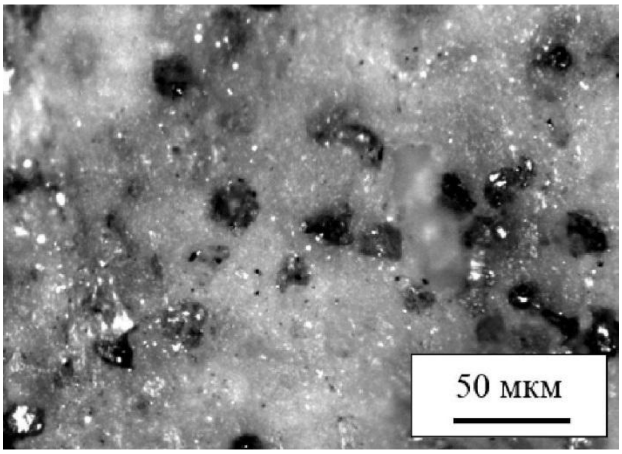

Fig. 1. Microstructure of the surface of diamond-containing material (d = 20/14, K = 100%)

The results of tribological tests were compared with samples of alloy D16, the surface of which was also modified using micro-arc oxidation technology. As a result, a coating with a composition similar to the ceramic bond material, but without diamonds, was obtained on the surface of the samples.

Tribological tests were conducted on the MT-2 friction machine (Jin et al., 2023). The implemented friction scheme is a finger-ring. The materials of the counter-samples were electrical ceramics $BaO\text{-}SiO_2\text{-}AI_2O_3$. The tests were conducted under dry friction conditions and in the presence of water. The linear sliding speed was 0.75 m/s.

The coefficients τ_0 and β were determined using the method and equipment described in the patent (Patent No. 2525585). Here, τ_0 is the tangential stress in the absence of normal stress, and β is the piezoelectric coefficient. The parameters of the microgeometry of the friction surfaces were assessed using standard profilometry methods (GOST 19300-86; Chepovetsky et al., 1978), and the microstructure was analyzed using a metallographic microscope. Microstrength was assessed using a PMT-3 microhardness tester, and a Vickers pyramid was used as an indenter.

Statement of the problem of constructing a contact interaction model

When calculating friction parameters, we will use the molecular-mechanical theory of friction (Kragelsky et al., 1977; Chichinadze et al., 2003). The model should take into account the physical and mechanical properties of diamond-containing ceramics – ceramic materials, their microgeometry, and loading conditions. Let us assume that the nature of the contact between microroughnesses after running-in in a steady state is linear elastic. When the load is critically exceeded, brittle fracture of the ceramic material predominates.

As a criterion determining the change in the nature of deformation, we will consider the load that creates an average elastic pressure on the contact patch equal to the material's micro strength, σ (Pushkarev et al., 2017). Micro strength corresponds to the stress required to form a unit area of brittle fracture.

Let us consider the contact interaction of a rough half-space of a ceramic matrix with diamond grains with a bulk density of τ distributed in it and a rough half-space of a counter-sample (Fig. 2). The size of the diamond grains is comparable with the matrix microroughnesses, which allows us to model the surface of the composite material in the form of spherical segments of the same radius R (Kragelsky et al., 1977; Demkin et al., 1981). Let us introduce the concepts of an equivalent surface and a support curve. Considering the thickness of the diamond-bearing ceramic layer, the influence of the substrate material can be neglected, and Hertz's formulas (Johnson, 1989) can be used to determine the contact characteristics of a single microroughness. Let us assume that the mutual influence of the microroughnesses is negligibly small (Kragelsky et al., 1977; Chichinadze et al., 2003).

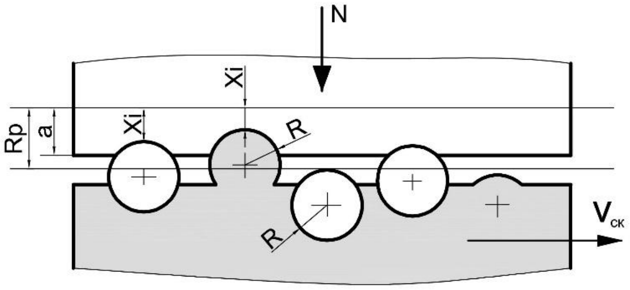

Fig. 2. Diagram of the contact of a rough half-space made of a ceramic matrix with diamond grains distributed in it

Method for solving the problem of contact interaction

The load in the contact zone consists of normal forces perceived by the unevenness of the matrix and protruding diamond grains (1):

$$N = \tau \int_0^a N_{i\,\text{ак}}(a_i)\, n'(x)dx + (1-\tau)\int_0^a N_{i\,\text{ск}}(a_i)\, n'(x)dx,$$
$$n(x) = \frac{t_m \nu A_a}{2pRR_p^\nu} x^{\nu-1}. \qquad 1)$$

Here $N_{i\ ak}(a_i)$ and $N_{i\ sk}(a_i)$ are the load acting on the diamond grain and the matrix microroughness; $n(x)$ is the protrusion distribution function showing the number of protrusions whose tops are located above the x level; ν, R_p, t_m are the roughness parameters of the interacting surfaces (Kragelsky et al., 1977; Demkin et al., 1981); A_a is the nominal contact area. Considering that $a_i = a - x$, and also applying the Hertz formulas for determining the characteristics of elastic contact of individual spherical irregularities, we obtain a formula for calculating the nominal pressure in the elastic contact zone:

$$q_{ay} = \frac{N}{A_a} = \frac{t_m \nu(\nu-1)a^{\nu+0.5}K_3}{1{,}5pR_p^\nu}\left(\frac{\tau}{I_a} + \frac{(1-\tau)}{I_c}\right) \qquad 2)$$

Here K_3 – coefficient characterizing the support curve (Demkin et al., 1981);

$I_a = \frac{1-\mu_a^2}{E_a} + \frac{1-\mu_k^2}{E_k}$, $I_c = \frac{1-\mu_c^2}{E_c} + \frac{1-\mu_k^2}{E_k}$ – elastic constants of the diamond-counterspecimen contact, bond-counterspecimen;

E_a, E_c, E_k– elastic moduli of diamond, matrix, and counter sample materials;

μ_a, μ_c, μ_k – Poisson's ratios of diamond, ceramic bond, and counterspecimen materials..

The elastic convergence of the contacting surfaces is expressed by the formula (3):

$$a_{y} = R_p \left[\frac{1{,}5\pi q_a I_e}{t_m \nu(\nu-1)K_3} \left(\frac{R}{R_p}\right)^{0{,}5} \right]^{\frac{1}{\nu+0.5}}, \quad 3)$$

.
where: $I_e = \left(\frac{I_a I_c}{\tau I_c + (1-\tau) I_a}\right)$ – equivalent elastic constant.

The load on a single micro-roughness under pressure equal to the micro-strength, according to the Hertz relations, is determined as:

$$N_i = a_i R \sigma \pi.$$

Next, extending the solution to multiple contacts of rough surfaces, and conducting an analysis similar to that given above, we find the value of the critical nominal pressure as a function of approach:

$$q_{ax} = \frac{tm\nu\sigma a_x^{\nu}}{2Rp^{\nu}}.$$

From this, we can obtain directly the critical convergence:

$$a_x = Rp\left(\frac{2q_{ax}}{tm\nu\sigma}\right)^{1/\nu}. \quad 4)$$

By equating the approach of the contacting surfaces for elastic (3) and brittle (4) contact, we obtain:

$$q_{ax} = \left(\frac{t_m \nu\sigma}{2}\right)^{2\nu+1} \times \left[\frac{1{,}5\pi I_e}{t_m \nu(\nu-1)K_3}\left(\frac{R}{R_p}\right)^{0.5}\right]^{2\nu}. \quad 5)$$

Formula (5) allows calculating the critical nominal pressure depending on the physical and mechanical constants of materials and the parameters of the friction surface profile.

A change in the type of deformation implies a change in the friction characteristics of the tribocontact. We will estimate the force and coefficient of friction based on the molecular-mechanical theory of friction by I.V. Kragelsky (Kragelsky et al., 1977), as well as the relationships obtained above. We will represent the friction force F_{tr} of rough surfaces in the form:

$$F_{\text{тр}} = \tau_0 A_r + \beta N + \text{К}_x \int_0^{n_r} N_i \sqrt{\frac{a_i}{R}}\, dn_x, \quad 6)$$

where: A_r – actual contact area, τ_0 and β are the shear resistance of the molecular bond in the absence of normal load and the hardening coefficient of the molecular bond. Considering that during frictional wear of brittle and high-strength materials, plastic deformation is not significant, we will accept $K_x = 0.19\alpha_g$, $\alpha_g = 0.02$ – hysteresis loss coefficient (Chichinadze et al., 2003). Accepting $\int_0^{n_r} N_i \sqrt{\frac{a_i}{R}}\, dn_x = \frac{1}{0.75 I_e}\int_0^{n_r} a_i{}^2\, dn_x$ for the friction force in elastic contact, we obtain:

$$F_{tr\,y} = \frac{\tau_0 tmA_a}{2}\left(\frac{a_y}{Rp}\right)^{\nu} + \beta N + 0.19\alpha_g \frac{A_a tm a_y^{\nu+1}}{\pi R Rp^{\nu}(\nu+1) I_e}. \quad 7)$$

For supercritical pressure in the tribounit at $q > q_a$ we will find the friction force as:

$$F_{\text{тр}\,x} = \frac{\tau_0 tmA_a}{2}\left(\frac{a_x}{Rp}\right)^{\nu} + \beta N + 0{,}19\alpha_{\text{г}} \frac{A_a tm\nu(\nu-1)\sigma\pi^2 a_x^{\nu+0{,}5} K_3}{2R^{0{,}5} Rp^{\nu}}. \quad 8)$$

For practical purposes, it is convenient to obtain calculation ratios for estimating friction coefficients in a wide range of loads. In addition, formulas (7) and (8) are convergence functions, which complicates the calculation. Using the definition of $f_{tr} = \frac{F_{tr}}{N}$, as well as formulas (3) and (4) for friction coefficients, we obtain:

$$f_y = \frac{\tau_0\sqrt{tm}\,(\pi\delta I_e)^{\frac{2\nu}{2\nu+1}}}{2\Delta^{\frac{\nu}{2\nu+1}} q_a^{\frac{1}{2\nu+1}}} + \beta + 0.19\alpha_{\Gamma}\frac{tm\Delta^{\frac{\nu}{2\nu+1}}\delta^{\frac{\nu+1}{\nu+0.5}}}{0.75(\nu+1)}\left(\frac{q_a I_e}{\pi}\right)^{\frac{1}{2\nu+1}}, \qquad (9)$$

$$f_{x} = \frac{\tau_0}{\nu\sigma} + \beta + 0.19\alpha_{\Gamma}\frac{1{,}5\sqrt{\Delta}}{\delta\nu}\left(\frac{2q_a}{tm\sigma\nu}\right)^{\frac{1}{2\nu}}, \qquad (10)$$

where $\Delta = \frac{R_p}{R}$, $\delta = \frac{1.5}{\nu(\nu-1)K_3}$.

Results

A typical appearance of a sample of their diamond-containing material after testing is shown in Fig. 3. The tribosurface is polished to a shine, with no scratches or chipping visible.

Fig. 3. External appearance of a sample of diamond-containing material

Estimation of critical pressure under boundary friction conditions

The test results (Fig. 4) show a nonlinear character of the change in wear intensity and friction coefficient under boundary friction conditions depending on the pressure in the contact zone. The wear intensity is stable in a fairly wide range of loads, but when a certain pressure is exceeded, it increases by two orders of magnitude with an increase in pressure in the contact zone by 20-25% (Fig. 4a). The wear intensity of the ceramic material with a diamond filler is lower than that of the oxide MAO coating formed on an aluminum alloy. However, the pressure corresponding to "catastrophic wear" for the diamond-containing material is also lower.

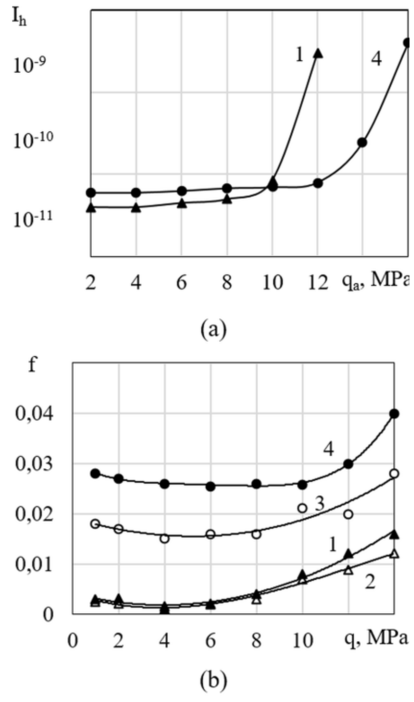

Fig. 4. Evaluation of critical pressure: by wear intensity (a), by friction coefficient (b) under boundary friction conditions. 1 – AKM: d=20/14, K=100; 2 – AKM: d=14/10, K=100; 3 – AKM: d=20/14, K=50; 4 – MAO D16.

The experimentally obtained dependence of the friction coefficient in the presence of lubricant also exhibits a section of stable values, followed by a significant increase several times with an increase in pressure in the contact zone by 20-25% (Fig. 4b). A 1.4-fold decrease in diamond grain size at the same concentration has virtually no effect on the nature of the dependence of the friction coefficient on pressure (Fig. 4b, curves 1, 2). The effect of concentration is more significant: a two-fold decrease in the concentration of diamond grains leads to an increase in the friction coefficient by an order of magnitude (Fig. 4b, curves 1, 3). The friction coefficient of the ceramic coating obtained only from aluminum oxides is significantly higher (Fig. 4b, curves 1, 4) than that of the studied coating with an antifriction additive made of graphitized diamond. The obtained dependencies of the friction coefficient in the case of boundary friction for all the studied materials exhibit an extreme nature: the friction coefficient has a minimum value at a certain pressure. This is consistent with the molecular mechanical theory of friction for the case of elastic contact interaction of rough surfaces.

The critical pressure obtained experimentally and calculated using formula (5) is given in Table 1. Also given in Table 1 are the experimentally measured microstrength and microhardness of the samples under study. A decrease in the grain size of diamonds leads to an increase in the microstrength of the samples and a decrease in their microhardness. The critical pressure in this case also decreases. A decrease in the concentration of diamond grains leads to an increase in microstrength, a decrease in microhardness, and an increase in the critical pressure.

Table 1. Tribological properties of the tested materials

No	Material of the friction pair	Microstrength, σ, GPa	Micro-hardness, H, GPa	Critical pressure, MPa	
				Results of the experiment	Calculation using formula (5)
1	AKM d=20/14, K = 100	1.78	6.71	6.4	5.71
2	AKM d=14/10, K=100	1.96	6. 62	6.2	5.65
3	AKM d=20/14, K=50	2.25	5.83	7.5	6.47
4	MAO D16	2.68	16.48	11.0	10.16

Evaluation of the friction coefficient simulation without lubricant.

Qualitatively, the nature of the dependences of the friction coefficient without lubricant and in the presence of water is close: stable values of f after running-in are replaced by a significant increase when a certain pressure is exceeded (Fig. 5). The increase in the friction coefficient in the absence of lubricant at a pressure of up to 8 MPa, for materials similar in composition, is several tens of times. The most significant change in *f* is observed for diamond-containing ceramic materials with the maximum volume content of diamonds (Fig. 4b and 5a, curves 1 and 2). Despite the increase in the friction coefficient for these materials, it remains comparable to the value of *f* for solid lubricants based on fluoroplastic (Kokhanovsky et al., 2019).

The friction coefficient for diamond-containing materials with the same diamond concentration but different grain sizes has a practically constant value and a similar dependence on contact pressure (Fig. 5a, curves 1 and 2). A decrease in the concentration of diamond grains significantly increases the friction coefficient, similarly to the conditions of boundary friction (Fig. 4b and 5a, curves 3). Of interest is the established result that the growth of *f* under dry and boundary friction for similar materials in the case of a supercritical load in the absence of lubrication is significantly less. For a material with the composition d = 20/14, K = 100 (Fig. 4b and 5a, curves 1), the increase in the friction coefficient under a load above q_{ax} decreases by ≈ 3.5 times. For a coating formed on a base made of D16 material, this parameter is ≈ 1.7 times. The extreme nature of the dependence of the dry friction coefficient of the materials under study is not expressed; the minimum value of *f* in the steady-state friction mode is not revealed.

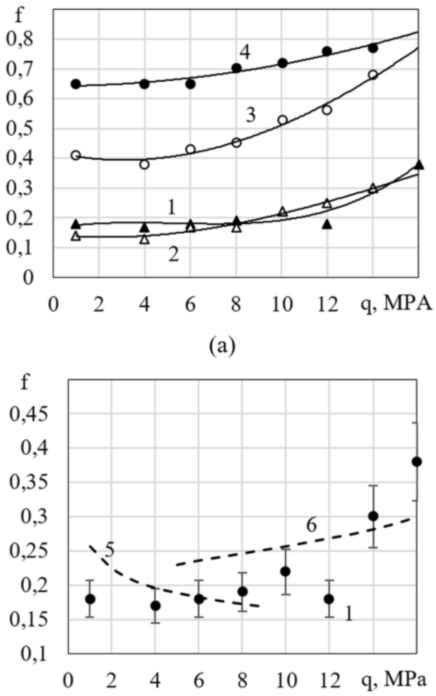

Fig. 5. Estimation of the dry friction coefficient: experimental results (a), comparison of the experimental results and calculations using formulas (9) and (10) (b). 1 – AKM: d=20/14, K = 100; 2 – AKM: d=14/10, K=100; 3 – AKM: d=20/14, K=50; 4 – MDO D16; 5 – calculation using formula (9); 6 – calculation using formula (10).

An example of calculation using formulas (9) and (10) is shown in Fig. 5b. The calculation was performed for a material with the composition: d = 20/14, K=100 (Fig. 5, curve 1). The obtained theoretical dependences satisfactorily describe the nature of the change in the friction coefficient with an increase in contact pressure. The calculation is provided for dry friction conditions, as the friction parameters τ0 and β were more accurately determined, according to accepted methodology, in the absence of lubrication. In the theoretical model, the friction coefficient for elastic interaction decreases more significantly with an increase in contact pressure. The increase in the dry friction coefficient in the supercritical loading region, on the contrary, is expressed less strongly.

The theoretically and experimentally obtained nature of the dependences of the friction coefficient and the magnitude of the critical pressure correlates with the data obtained by the authors (Kobyakov et al., 2011) for gas-thermal coatings strengthened by synthetic diamonds and electrocorundum.

Discussion

1. The test results confirm the nonlinear nature of the change in the friction parameters depending on the pressure in the friction zone: regardless of the friction conditions, a characteristic inflection point can be identified, corresponding to a change in the type of deformation of the friction surfaces. The assumption that the nature of the contact between microroughnesses during friction in the steady state is linear-elastic, and that when the load is critically exceeded, brittle fracture of the ceramic material predominates, was confirmed.

2. The effect of solid lubrication caused by the presence of graphite films has a significant impact on reducing the wear rate and friction coefficient even in the presence of an aqueous lubricating medium. The effect of the presence of partially graphitized diamond in the ceramic base material on the boundary friction coefficient is especially significant.

3. Critical pressures calculated by formula (5) coincide with the values obtained experimentally within 15%, but there is still a tendency to understate the theoretical values. It can be assumed that at the calculated values of q_{ax} the cracking process is just beginning to form, but it becomes significant at higher pressures, at q_x = 1.1÷1.5 q_{ax}.

4. The change in the critical pressure corresponding to the change in the type of contact interaction and wear of composite materials, depending on the concentration and geometric dimensions of the filler, is not obvious at first glance. Experimental and theoretical analysis of q_{ax} shows that with an increase in the granularity of diamond, the right-hand factor in formula (5) increases, but the microstrength decreases, which neutralizes the effect of the change in granularity. An increase in the concentration of diamond reduces the microstrength of the material, which can be explained by an increase in internal stress concentrators and a decrease in the volume of

the matrix binder. The concentration of diamond included in the operator I_e significantly affects the elastic properties of the tribocontact in the case of a friction counter-surface material close in mechanical properties to the material of the ceramic matrix and diamond, as in our case. We can say that an increase in the concentration of diamond reduces the critical pressure.

5. According to the results of the experiment, the friction coefficient of the diamond-containing ceramics-ceramics pair of materials in the case of elastic deformation depends weakly on pressure (Fig. 4b and 5a). Analysis of formula (9) shows that the influence of pressure in the first and last terms should compensate for each other, which is usually the case for metals and polymers. In our case, materials with high elastic moduli are in contact, and, according to theoretical calculations, the influence of pressure is more significant.

6. The results of the experiment and calculation using formula (9) showed that the friction coefficient does not change significantly with decreasing diamond grain size. The diamond concentration affects the friction coefficient through the operator I_e. Generally, as diamond concentration increases, the friction coefficient decreases.

7. When the contact pressure is higher than the critical value, the friction coefficient increases with increasing load (formula (10), Fig. 5b). The molecular component of the friction coefficient (formula 10) does not depend on pressure; the mechanical component increases to the power of 1/2ν, where ν = 1.5÷3. Therefore, the surface roughness (and indirectly the grain size) affects the rate of increase of the friction coefficient. The grain size of the diamond and its concentration affect the brittle friction coefficient indirectly through the microstrength of the material.

8. When the concentration and granularity of diamonds change (especially under dry friction conditions), the coefficients τ_0, β, and α_g change, which is due to the increase in free graphite in the friction zone. The amount of solid graphite lubricant correlates with the total external surface area of diamond grains. For example, when the granularity and concentration of diamonds increase, the volume of free graphite in the friction zone will also increase. The effect of the amount of graphite lubricant on the friction parameters τ_0, β, and α_g during the friction of AKM is to be studied in more detail.

9. The nature of the curves of f dependence on the load for dry and boundary friction is very close; the shift along the vertical axis can be explained by the change in the coefficients τ_0, β, and α_g depending on the type of lubricant and contact pressure. The friction coefficient for diamond-containing ceramics with d = 20/14, τ = 10, and K = 100 for dry friction and in water differs by tens of times. Considering that the theoretical assessment of tribological test results is highly sensitive to experimental conditions, it is challenging to expect high accuracy.

10. It is possible to note good antifriction properties of the diamond-containing material in comparison with the basic ceramic coating without diamonds, obtained by modifying aluminum by microarc oxidation. The friction coefficient of the AKM is lower than that of the oxidized coating by 1.6 (14.4 times for boundary friction and by 1.6 (4.5 times for dry friction). The graphite formed during the oxidation of diamonds is not removed from the friction zone but instead fills the pores of the ceramic matrix, thereby reducing the shear resistance of the surface layers of the material. Largely due to the graphite film, the surface of the AKM samples is smoothed to a mirror shine after testing (Fig. 2).

11. Application of the results of this research in the direction of obtaining and introducing into industry innovative materials and coatings formed using the proposed technology.

With the growing importance of global energy conservation and environmental protection issues, it is crucial to strive for reducing the material consumption of friction units while increasing wear resistance, which is particularly important in the automotive, aviation, space, and shipbuilding industries. In the aerospace industry, it is crucial to minimize the weight of the design being developed as much as possible, making the replacement of individual elements a significant consideration. An antifriction diamond-containing coating on a ceramic base ensures the unit's long-term, trouble-free operation under low temperatures and vacuum conditions.

The use of diamond-containing ceramic coatings formed by the microplasma electrolytic oxidation method is promising for replacing heavy metal alloys. In mechanical engineering, tribological units made of AKM can be used to replace traditional steel parts. In this case, a significant increase in wear resistance and material consumption is predicted (Drozdov et al., 2004; Jin et al., 2023). A significant increase in the dynamic characteristics of moving tribological units is achievable, since the density of the resulting base material is almost 3 times lower than the density of steel.

It is known that friction units are traditionally made of valve metal parts (aluminum, titanium) hardened by microarc oxidation (plain bearings, pistons, cylinders, end seals, etc.). The oxide coating undoubtedly increases the wear resistance of parts, but for some critical industries (for instance, aviation), this surface engineering method is insufficient to provide the specified set of friction characteristics (Jin et al., 2023). In this case, a positive proposal is to use parts made of diamond-containing composite materials modified by MAO to a ceramic-like diamond antifriction coating. Friction pair parts hardened by electrolytic oxidation and operated under conditions of insufficient lubricant or dry friction, which are used in traditional mechanical engineering and can be replaced by parts made of diamond-containing materials, with the prospect of significantly reducing the friction coefficient.

There are data on the positive results of using dispersed diamonds as a solid lubricant for artificial implants (Xia et al., 2023; Gopal et al., 2017). It is known that the service life of metal implants for hip and knee joints is very limited due to wear and corrosion. All materials that make up the diamond-containing ceramic material are non-toxic and biocompatible with the human body. Perhaps, after further research, the developed material can be utilized to address this problem.

Another promising area of application for AKM parts is the production of wheelchair components, crutches, canes, and prostheses for people with disabilities. Traditionally used parts made of aluminum alloys have low resistance to mechanical damage, weak adhesion to paints and varnishes, poor adhesion to the skin of the palms, and are not sufficiently inert to it. Parts made of titanium alloys, in addition to their high cost, can cause allergic reactions. Elements of structures made from diamond-containing ceramics will enhance the corrosion resistance and biocompatibility of medical device parts exposed to frictional effects.

Good results are achieved by modifying aluminum parts through microplasma electrolytic oxidation, which protects them from the effects of aggressive environments, including chemically active solutions, seawater, and extreme atmospheric conditions (Kuznetsov et al., 2019). If the tribotechnical characteristics of the friction surfaces are insufficient, it is possible to replace the material of the friction unit part with antifriction AKM.

Our studies have shown that the tribosurfaces of friction units made of AKM and strengthened by microplasma electrolytic oxidation show very good results in tribounits lubricated with modern magnetic lubricants (Novikova et al., 2023). It is known that magnetic lubricating media have a corrosive effect on contacting surfaces and also wear out the surfaces of agglomerates of magnetic particles (the microhardness of magnetite particles is approximately 5 GPa) (Bolotov et al., 2022).

We have obtained a positive example of using a friction pair of diamond-containing ceramic material – ceramics as a working unit of a colloid mill (disperser). Replaceable bushings made of AKM provided the necessary dispersion of the material being ground. The product being ground was crystalline beta-carotene, characterized by its low resistance, as an unsaturated hydrocarbon, to the effects of light, oxygen, high temperatures, environmental pH, and the presence of metal ions. Thus, the developed material can be recommended for use in the manufacture of friction units of modern equipment in the pharmaceutical, food, and chemical industries.

12. Application of the results of modeling the contact interaction and frictional properties of ceramic composite materials to assess the tribotechnical properties of actually operated friction units.

The developed model allows synthesizing diamond-containing ceramic materials with specified tribotechnical properties. At the design stage, it is possible to vary the grain size (roughness) and concentration of diamond particles to obtain the required friction coefficient at the required contact load of the tribological unit.

The results of the modeling will allow us to preliminarily estimate, before conducting expensive full-scale tests, the area of stable operation of the tribounits based on the magnitude of the contact pressure.

The model can be applied to evaluate the friction characteristics of not only diamond-containing ceramic materials, but also other elastic, two-component composite materials (Bolotov et al., 2018; Liu et al., 2022; Kobyakov et al., 2011; Vityaz et al., 2011). It can also be applied to composite materials obtained using other technologies. Analysis of the physical and mechanical properties of materials, as included in equations (5), (9), and (10), friction parameters τ_0, β, and α_g will allow targeted selection of structural components for creating new composite materials with specified properties.

In previous studies, the authors demonstrated that a similar technology can be utilized to produce not only antifriction but also abrasive diamond-containing ceramic materials. The solution method, also based on the molecular mechanical theory of wear, was successfully employed in the work by Bolotov et al. (2024) to evaluate the performance of an abrasive diamond-containing ceramic material. On the one hand, this fact confirms the validity of the proposed approach. However, we also assume that this means the result obtained in this study can be used to determine the friction coefficient of abrasive materials, which are in high demand in the manufacturing industry. This assumption is planned to be tested in future studies.

Conclusion

As a result of theoretical and experimental studies, the influence of the load in the tribocontact zone on the change in the type of contact interaction, the nature of wear, and the friction coefficient of antifriction diamond-containing mineral ceramics was established. The validity of the classical approach to describing the friction properties of the triboconjugation of diamond-containing mineral ceramics, including those under a wide range of pressures, was demonstrated.

It is confirmed that micro strength can be considered a criterion determining the change in the nature of deformation on the contact patch for ceramic composite materials. Micro strength decreases with increasing grain size and diamond concentration. Critical pressure depends on the parameters of microgeometry, the mechanical properties of the friction pair materials, grain size, and diamond concentration.

The influence of microparameters on the interaction between half-spaces on the friction coefficient, in cases of elastic deformation and brittle fracture, has been established both theoretically and experimentally. With increasing pressure in the elastic region, the friction coefficient decreases, and in the supercritical region, it increases. The nature of the curves of the friction coefficient dependences on the load for dry and boundary friction is close, but differs by an order of magnitude.

Diamond-containing ceramic material has satisfactory antifriction properties in the absence of lubrication. The friction coefficient of diamond-containing material is lower than that of an oxidized coating without diamonds by 1.6 (4.5 times lower in dry friction). The structure of the ceramic matrix helps to retain diamond grains and distribute films of solid lubricant graphite in the friction zone.

The obtained regularities will allow us to optimize the composition of diamond-containing mineral ceramics and select the range of load modes for the operation of tri-units made of materials of this class.

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