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Effect of loading on tribotechnical characteristics of antifriction diamond-bearing mineral ceramics

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ABSTRACT

A calculation and experimental analysis of tribotechnical properties of a pair of materials diamond-bearing mineral ceramics – ceramics in a wide range of loads are shown. The molecular-mechanical theory of friction was used for the analysis. It also accepted a linear-elastic nature of microroughness contact after running in in a steady-state mode. A criterion that determines the change in deformation behavior is the load which creates an average elastic pressure on a contact spot equal to material microstrength. Using both theoretical and experimental approaches, we determined the critical nominal pressure and friction coefficient depending on physical and mechanical constants of materials and friction surface profile parameters.

KEYWORDS

diamond-bearing ceramics • antifriction properties • contact interaction model • microstrength • friction • wear

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Introduction

One of the directions for creating innovative tribounits is using ceramic elements as parts involved in direct friction contact. In addition to high tribotechnical properties of ceramics, there are unique temperature, anticorrosion, and electrical characteristics. Ceramic composite materials with high-strength, wear-resistant properties of the matrix supplemented by abrasive or antifriction fillers' characteristics are especially promising [1,2].

Graphite, molybdenum disulfide or polymeric materials are typically used as fillers with low shear resistance for composite materials of friction units that operate under conditions of lubricant deficiency. Recent scientific studies pay special attention to another allotropic form of graphite - diamond as an antifriction component of a ceramic matrix [3–7]. Most authors emphasize the complexity of forming oxide mineral ceramic diamond-containing materials. This is due to the sensitivity of diamond to oxidation at relatively high temperatures. However, the controlled degree of diamond graphitization during composite preparation and friction process leads to a synergetic effect of creating a highly solid and wear-resistant tribo-surface with a given gradient of friction properties [3,5].

During the research, we obtained a mineral ceramic material, which is a matrix of aluminum oxides of α-, β-, and γ-modifications with incorporated dispersed diamond grains [8,9]. We have developed a technology which assumes that the first stage of material production involves sintering of a dispersed aluminum and diamond billet. Then billet's surface layer is modified by microplasma electrolytic oxidation. The formed part combines physical and mechanical properties of an aluminum matrix, i.e. the base and tribotechnical properties of a ceramic hardened layer with partially graphitized dispersed diamonds. Preliminary results show that when a ceramic base is alloyed with diamonds with a grit < 20/14, mineral ceramic material has good antifriction properties while lubricant is in short supply or even absent [8].

Some results show that the obtained diamond-bearing mineral ceramic material (DBMC) has consistently low values of triboparameters in a sufficiently large pressure range. However, the wear intensity increases sharply with further increase of contact pressure. We obtained similar conclusions for composite coatings hardened with synthetic diamonds and electrocorundum [10] and diamond-like coatings [11]. We can assume that certain loads cause a change in the wear type of such materials. If we establish the rational load area for mineral ceramic materials of dry friction units, the trouble-free period of tribounit operation might be significantly extended.

A lot of research has analyzed wear of ceramic materials [12–15]. The most widely accepted theoretical models are based on linear elastic fracture mechanics and Weibull statistics [12,13,16,17]. The nature of wear of ceramic diamond-bearing materials has been studied to a much lesser extent [18–21]. This is due to the innovativeness of the technologies for obtaining diamond mineral ceramics; the friction characteristics of the composite material are determined by the emergent nature of its constituent structural components. The results presented in [18] show the linear-elastic nature of wear of diamond-bearing ceramic tools. They also show the adequacy and correctness of the fatigue failure and wear mechanisms for the working layer of such materials. Elastic interaction is the most typical mechanism, even in calculating diamond-abrasion parameters [18,21]. Depending on matrix and counter-surface material properties, we propose applying mathematical models for elastic, brittle or elastic-plastic contact, as well as using criteria for transition from one interaction type to another. The analysis of the tribosurface morphology of mineral-ceramic material (ceramic control sample) after tests did not reveal plastic deformation in a steady-state mode and in the subcritical loading area [8,22]. We can assume that the elastic behavior of material deformation during friction is replaced by its brittle destruction while diamond grains are simultaneously removed with a part of the surrounding ceramic matrix.

In case of brittle fracture materials (including diamond-bearing composite materials with ceramic matrix), critical stress is bending strength, microhardness, microstrength, etc. [12,18,23,24]. For composite materials, it is necessary to consider the influence of the dimensional effect of discrete components on micromechanical properties. In [23], it is shown the validity of applying strength characteristics obtained by indentation using a microhardness tester to describe the properties of materials with particle discreteness from 250 to 400 μm. It also notes how informative the microstrength index for evaluating a brittle fracture area.

Earlier in [22], we proposed a model of elastic contact interaction between surfaces of mineral ceramics and ceramics. However, we have not yet investigated deformation processes in the case of brittle fracture. It is also necessary to conduct additional tribotechnical tests to confirm the validity of the selected models and assumptions made. The purpose of the present work is to evaluate tribocontact properties in a wide range of loads based on the model of contact interaction between a pair of materials: diamond-bearing mineral ceramics and ceramics.

Problem statement

The molecular-mechanical theory of friction was used for calculating the friction parameters [25–27]. The model should take into account the physical and mechanical properties of materials diamond-bearing mineral ceramics – ceramics, their microgeometry and loading conditions. Let us assume that the microroughness contact after running-in in the steady-state mode has linear-elastic nature. At critical overloading, brittle fracture of mineral ceramic material prevails.

We take a load that creates an average elastic pressure on the contact spot as a criterion determining the change in deformation behavior. The average elastic pressure on the contact spot is equal to the material microstrength σ [23]. Microstrength corresponds to the stress required to form a brittle fracture unit area.

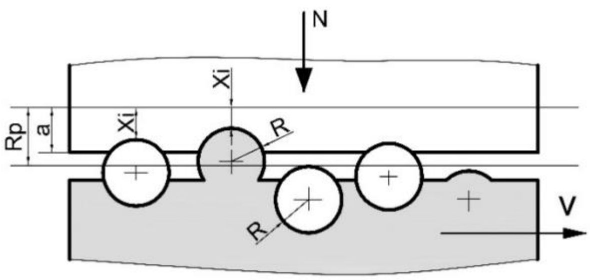


Fig. 1. Contact of a rough half-space made of a ceramic matrix with distributed diamond grains

We consider the contact interaction between a rough half-space made of a ceramic matrix with distributed diamond grains with volume density τ and a rough half-space of a control sample (Fig. 1). The size of diamond grains correlates with matrix microroughnesses. This fact allows modeling the composite material surface as spherical segments of the same radius R [25,28]. Let us introduce the concepts of an equivalent surface and a bearing curve. Due to the thickness of the diamond-bearing ceramic layer, we can ignore the substrate material influence and use Hertz's formulas [29] to determine single microroughness contact characteristics. We assume that the mutual influence of microroughnesses is negligible [25,26].

Solution method

The load in the contact zone consists of normal forces perceived by matrix irregularities and protruding diamond grains:

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

where $N_{i\,\text{ак}}(a_i)$ and $N_{i\,\text{ск}}(a_i)$ are the load acting on a diamond grain and matrix microroughness, respectively, $n(x)$ is a protrusion distribution function that shows the number of protrusions with tops located above the level x, ν, R_p, t_m are roughness parameters of the interacting surfaces [25,28], A_a is a nominal contact area.

We consider that $a_i = a - x$ and apply Hertz formulas to determine the characteristics of elastic contact of unit spherical irregularities. Thus, we obtain an equation for calculating the nominal pressure in the elastic contact area:

$$q_{ay} = \frac{N}{A_a} = \frac{t_m \nu(\nu-1)a^{\nu+0.5}K_3}{1.5pR_p^\nu}\left(\frac{\tau}{I_\text{a}} + \frac{(1-\tau)}{I_\text{c}}\right), \tag{2}$$

where K_3 is a coefficient that characterizes the bearing curve [28], $I_\text{a} = \frac{1-\mu_\text{a}^2}{E_\text{a}} + \frac{1-\mu_k^2}{E_\text{k}}$ and $I_\text{c} = \frac{1-\mu_\text{c}^2}{E_\text{c}} + \frac{1-\mu_\text{k}^2}{E_\text{k}}$ are the elastic constants of a diamond–counter sample and a bond–counter sample contact, respectively; E_a, E_c, E_k are the elastic moduli of diamond, matrix and counter sample materials, μ_a, μ_c, μ_k are Poisson's coefficients of diamond, ceramic matrix (bond) and counter sample materials. We express the elastic convergence of the contacting surfaces from Eq. (2):

$$a_\text{y} = R_p\left[\frac{1.5\pi q_a I_e}{t_\text{m}\nu(\nu-1)K_3}\left(\frac{R}{R_\text{p}}\right)^{0.5}\right]^{\frac{1}{\nu+0.5}}, \tag{3}$$

where $I_e = \left(\frac{I_\text{a} I_c}{\tau I_c + (1-\tau)I_\text{a}}\right)$ is an equivalent elastic constant.

According to Hertz's relations, the load on a unit microroughness at pressure equal to the microstrength is the following: $N_i = a_i R\sigma\pi$. Then, we extend the solution to the multiple contact of rough surfaces and conduct an analysis similar to the above one in order to find a critical nominal pressure value as a convergence function: $q_\text{ax} = \frac{tm\nu\sigma a_\text{x}^\nu}{2Rp^\nu}$.

Therefore, for the critical convergence we obtain the following:

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

After equating the proximity of the contacting surfaces for an elastic (3) and brittle (4) contact, we obtain the following:

$$q_\text{ax} = \left(\frac{t_m \nu\sigma}{2}\right)^{2\nu+1} \times \left[\frac{1.5\pi I_e}{t_m \nu(\nu-1)K_3}\left(\frac{R}{R_p}\right)^{0.5}\right]^{2\nu}. \tag{5}$$

Equation (5) allows calculating critical nominal pressure depending on physical and mechanical constants of materials and friction surface profile parameters. The change in the deformation type implies a change in tribocontact friction characteristics. We estimate the friction coefficient and force based on I.V. Kragelsky's molecular-mechanical theory of friction [25]. We also use the relations obtained above. Let us represent the rough surface friction force F_fr as following:

$$F_\text{fr} = \tau_0 A_r + \beta N + K_\text{x}\int_0^{n_r} N_i \sqrt{\frac{a_i}{R}}\, dn_x, \tag{6}$$

where A_r is an actual contact area, τ_0 and β is shear resistance of the molecular bond when there is no normal load and the molecular bond hardening coefficient. Since plastic deformation is not significant in frictional wear of brittle and high-strength materials, we assume $K_\text{x} = 0.19\alpha_\text{r}$, $\alpha_\text{r} = 0.02$ as a hysteresis loss coefficient [26]. Assuming that $\int_0^{n_r} N_i \sqrt{\frac{a_i}{R}}\, dn_x = \frac{1}{0.75 I_e}\int_0^{n_r} {a_i}^2\, dn_x$ for the friction force at elastic contact we obtain the following:

$$F_\text{fr y} = \frac{\tau_0 tmA_a}{2}\left(\frac{a_\text{y}}{Rp}\right)^\nu + \beta N + 0.19\alpha_\text{r}\frac{A_a tm a_\text{y}^{\nu+1}}{\pi R Rp^\nu(\nu+1)I_e}. \tag{7}$$

For the subcritical pressure in a tribounit at $q > q_{\mathrm{ax}}$, we find the friction force as following:

$$F_{\mathrm{fr\,x}} = \frac{\tau_0 tmA_a}{2}\left(\frac{a_{\mathrm{x}}}{Rp}\right)^{\nu} + \beta N + 0.19\alpha_{\Gamma}\frac{A_a tm\nu(\nu-1)\sigma\pi^2 a_{\mathrm{x}}^{\nu+0.5}K_3}{2R^{0.5}Rp^{\nu}}. \qquad (8)$$

In practice, it is convenient to obtain calculation relations for estimating friction coefficients in a wide range of loads. In addition, Eqs. (7) and (8) are convergence functions, therefore calculations are complicated. Using the definition $f_{\mathrm{fr}} = \frac{F_{\mathrm{fr}}}{N}$, as well as Eqs. (3) and (4) we obtain the following for friction coefficients:

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

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

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

Analysis of modeling results

According to the technology [8], we obtained composite material samples from aluminum powder and synthetic diamonds of AC6 grade with grit 20/14, 14/10. The volume density of diamonds τ was 25 and 12.5 %, which corresponds to 100 and 50 % of diamond concentration *K* (100 % diamond concentration in material is the diamond powder value 4.39 carats in 1 cm^3). We compared the results with D16 alloy samples, which have the surface modified by microarc oxidation (MAO), until obtaining a ceramic-like coating.

We carried out tribotechnical tests on the MT-2 friction machine [6]. We used finger-ring friction scheme and the following materials of control samples: ceramics BaO-SiO_2-Al_2O_3. The tests were carried out under conditions of dry friction and with water. The linear sliding velocity was 0.75 m/s.

We determined the coefficients τ_0 and β according to the methodology and using the equipment proposed in the patent [30]. Evaluation of microgeometry parameters of friction surfaces involved using standard methods of profilometry GOST 19300-86 [21], microstructure analysis involved using a metallographic microscope. We evaluated microstrength using a PMT-3 microhardness tester with a Vickers pyramid indenter.

Fig. 2. Diamond-bearing material sample

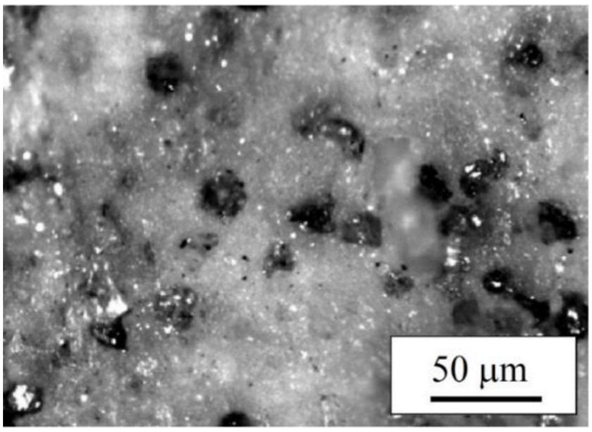
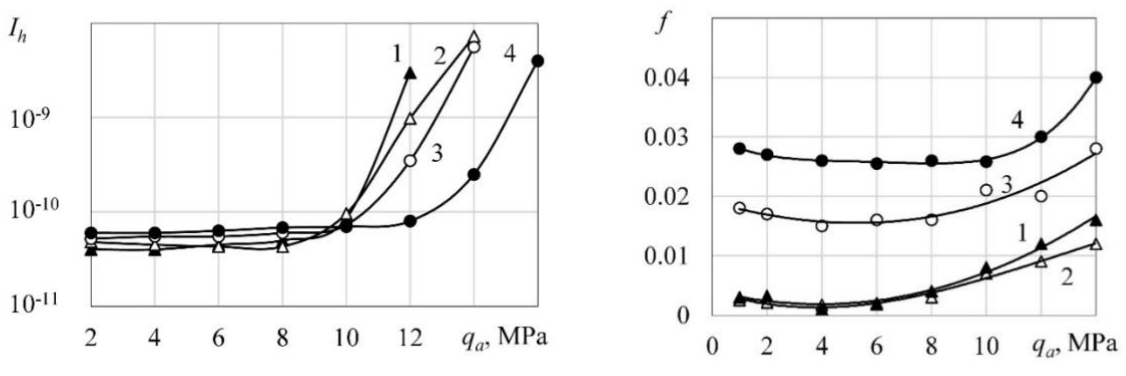


Fig. 3. Surface microstructure of diamond-bearing material (*d* = 20/14, *K* = 100 %)

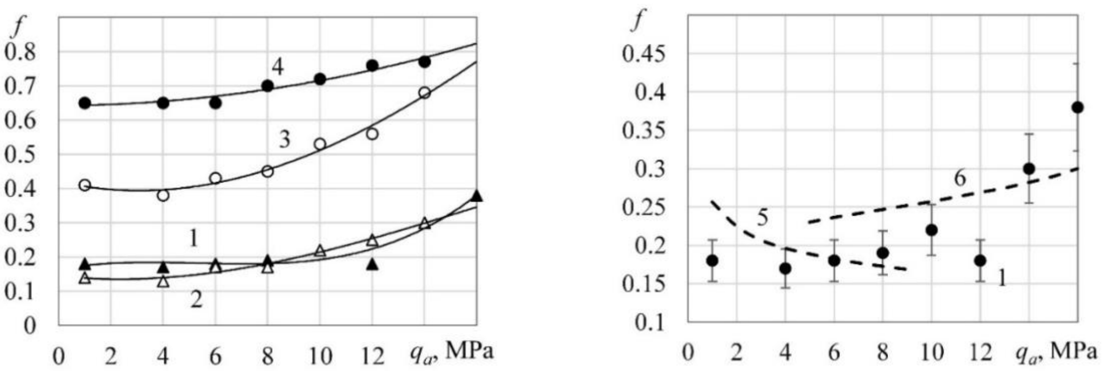
The typical appearance of their diamond-bearing material sample after testing is shown in Fig. 2. The tribo-surface is smoothed to gloss, there are no scratches and displayed crumble. Figure 3 shows the sample surface microstructure before testing: dark grains of graphitized diamond are distributed in the volume of an aluminum oxide matrix.



(a) (b)

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

The test results (Figs. 4 and 5) confirm the nonlinear behavior of triboparameter change depending on pressure in the friction zone: regardless of friction conditions it is possible to identify a characteristic inflection point that corresponds to a change in the deformation type of friction surfaces. Table 1 shows the critical pressure obtained experimentally and calculated by Eq. (5).



(a) (b)

Fig. 5. Dry friction coefficient estimation: experimental results (a); comparing experimental results and calculations by Eqs. (9) and (10) (b). 1 – DBMC: *d* = 20/14, *K* = 100; 2 – DBMC: *d* = 14/10, *K* = 100; 3 – DBMC: *d* = 20/14, *K* = 50; 4 – MAO D16; 5 – calculation by Eq. (9); 6 – calculation by Eq. (10)

Table 1. Tribotechnical properties of tested materials

No	Friction pair material	Micro strength (σ), GPa	Microhardness (*HV*), GPa	Critical pressure, MPa	
				Test results	Calculation by Eq. (5)
1	DBMC *d* = 20/14, *K* = 100	1.78	6.71	6.4	5.71
2	DBMC *d* = 14/10, *K* = 100	1.96	6.62	6.2	5.65
3	DBMC *d* = 20/14, *K* = 50	2.25	5.83	7.5	6.47
4	MAO D16	2.68	16.48	11.0	10.16

Critical pressures calculated by Eq. (5) within up to 15 % coincide with the values obtained experimentally, however there is a tendency of understating theoretical values. We can assume that at the calculated values of q_{ax} the cracking process just starts to form; it becomes significant at higher pressures, at q_{x} = 1.1 ÷ 1.5 q_{ax}. As diamond grit increases, the right coefficient in Eq. (5) increases too, but microstrength decreases, which reduces the effect of grit change. The increase in diamond concentration decreases material microstrength. This is due to the growth of internal stress concentrators and the decrease in the volume of matrix bonding material. The diamond concentration included in I_e operator significantly affects the tribocontact elastic properties if friction counter-surface material is close to ceramic matrix and diamond material in mechanical properties, as in our case. We can state that increasing diamond concentration reduces critical pressure.

According to the experimental results, the friction coefficient of a pair of materials diamond-bearing ceramics – ceramics during elastic deformation depends weakly on pressure (Fig. 4). The analysis of Eq. (9) shows that the pressure influence in the first and the last summand should compensate each other. Usually, it happens to metals and polymers. In our case, materials with high elasticity moduli are in contact, therefore pressure influence is more significant according to theoretical calculations. Experimental results and calculation by Eq. (9) showed that the friction coefficient does not change significantly with decreasing diamond grit. Diamond concentration affects the friction coefficient through the operator I_e. Moreover, the coefficients τ_0 and β change significantly with increasing diamond concentration (especially in dry friction conditions) due to the increase of free graphite in the friction zone. In general, when diamond concentration increases, the friction coefficient decreases.

When the contact pressure is above the critical one, the friction coefficient increases with increasing load (Eq. (10), Fig. 4). The molecular component of the friction coefficient (Eq. (10)) does not depend on pressure; the mechanical component increases to the degree $\frac{1}{2\nu}$, where $\nu \approx 1.5 \div 3$. Therefore, surface roughness (and grit indirectly) affects the friction coefficient increase rate. Diamond grit and concentration affect the brittle friction coefficient indirectly through material microstrength.

The rate of dependence curves f on load for dry and boundary friction is very similar. The shift along the vertical axis is due to the change of coefficients τ_0, β and α_{r} depending on the type of lubricant and contact pressure. The friction coefficient for diamond-bearing ceramics with d = 20/14, τ = 10, K = 100 during dry friction and in water differ by ten folds. Considering the fact that the theoretical evaluation of tribotechnical test results is sensitive to experimental conditions, it is difficult to expect high accuracy. An example of calculation by Eqs. (9) and (10) is shown in Fig. 5(b). Mathematical curves describe the behavior of friction coefficient change with increasing contact pressure adequately. Friction coefficient dependence behavior and the critical pressure value, which were obtained theoretically and experimentally, correlate with the data obtained by the authors [10] for gas-thermal coatings hardened with synthetic diamonds and electrocorundum.

We can note good antifriction properties of diamond-bearing material in comparison with the basic ceramic coating without diamonds, which was obtained through modification of aluminum by micro-arc oxidation. DBMC friction coefficient is lower than the one for oxidized coating by 1.4 ÷ 9.3 times at boundary friction and by 1.6 ÷ 4 times at dry friction. Graphite, which was formed during diamond oxidation, is not removed from the friction zone. It fills the pores of the ceramic matrix, reduces the shear resistance of material surface layers.

Conclusions

Theoretical and experimental studies detected the influence of load in a tribocontact zone on the change in the contact interaction type, wear nature and friction coefficient of antifriction diamond-bearing mineral ceramics. We showed the validity of the classical approach to describing frictional properties of triboconjugation involved diamond-bearing mineral ceramics and ceramics in a wide range of loads.

It is confirmed that microstrength can be a criterion that determines the change of deformation nature at the contact spot for ceramic composite materials. The microstrength decreases with increasing diamond grit and concentration. The critical pressure depends on microgeometry parameters, mechanical properties of friction pair materials, diamond grit and concentration.

We have established theoretically and experimentally the influence of microparameters of interacting half-spaces on the friction coefficient in the case of elastic deformation and brittle fracture. The friction coefficient decreases when pressure increases in the elastic region and increases in the subcritical region. The rate of curves of friction coefficient dependence on load for dry and boundary friction is similar but differs by an order of magnitude.

Diamond-bearing ceramic material has satisfactory antifriction properties when there is no lubrication. The friction coefficient of diamond-bearing material is 1.6 ÷ 4 times lower than the one for oxidized coating without diamonds at dry friction. A ceramic matrix structure enables diamond grain retention and distribution of solid-lubricating graphite films in the friction zone. The obtained regularities allow optimizing the composition of diamond-bearing mineral ceramics and choosing a range of loading modes for operation of tribounits from this class materials.

CRediT authorship contribution statement

Aleksandr N. Bolotov **:** writing – review & editing, supervision; **Olga O. Novikova** **:** conceptualization, investigation, writing – original draft; **Vladislav V. Novikov** **:** investigation, data curation.

Conflict of interest

The authors declare that they have no conflict of interest.

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