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MODELING THE INFLUENCE OF METAL PHASE IN DIAMOND GRAINS ON SELF-SHARPENING OF GRINDING WHEELS ON CERAMIC BONDS

Abstract. *The article presents the results of theoretical studies using finite element modeling, which made it possible to determine the rational characteristics of diamond wheels based on ceramic and polymer bonds. The effect of the parameters of the diamond-bearing layer on the change in its stress-strain state in the process of microcutting of hard alloys and superhard materials has been studied. It is established that the determining factor in the occurrence of critical stresses during grinding is the temperature in the cutting area, the increase of which in the presence of metal phase inclusions in diamond grains with high values of thermal expansion coefficient can lead to destructive stresses in grains and, consequently, their premature destruction. It is advisable to use diamond grains with a minimum content of metal phase and the use in the manufacture of synthetic diamonds solvent metals with a low value of this coefficient, which will significantly increase the use of potentially high resource diamond grains.*

Keywords: *diamond grinding wheel; processed material; diamond grain; superhard materials; wheel bond; stress-strain state; finite element method; equivalent stresses; self-sharpening; grinding modes.*

Introduction. The development of computer technology opens new perspectives for virtual integrated research of the processes of manufacture and operation of diamond abrasive tools (DAT). In recent years, based on the finite element method (FEM), a number of software packages with even more advanced capabilities have been developed. These primarily include *SIMULA Abaqus*, *SolidWorks Simulation*, *ANSYS* and *LS-Dyna*. Their use for simulation experiments on the developed models makes it possible to significantly reduce the volume of estimated machine research.

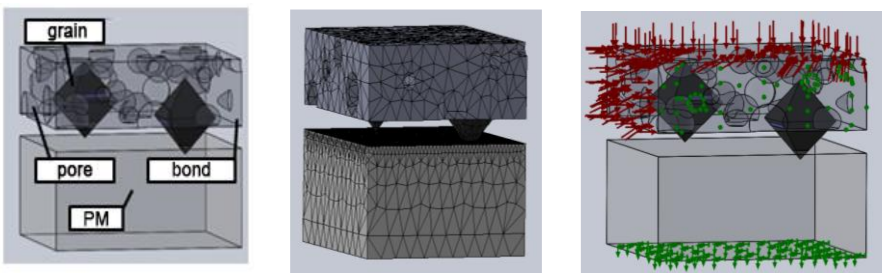
1. Articulation of the problem. As is well known, diamond wheels on organic and ceramic bonds are designed mainly for operation in self-sharpening mode. In world practice, one of the most promising approaches to improving the processing of diamond abrasive tools is based on the creation of prerequisites for the implementation of the necessary mechanisms for specific processing conditions (macro- or micro-destruction or a combination thereof) of self-sharpening of diamond grains and diamond layer as a whole. And for this you need to know the physics of the processes that occur both in diamond grains in particular and in the grinding system in general. Significant results in this direction can be obtained in the case of using the methodology of 3D modeling of the stress-strain state of tool systems and processing systems and refinement of the results by using machine experiments. This will allow to predict and implement in practice the optimal conditions for creating a controlled process of self -sharpening of diamond grains in particular and the diamond-bearing layer in general, and,consequently, significantly increase the efficiency of the grinding process.

2. Literature Review. Along with the choice of the bond grade, grain and grinding modes, the choice of the quantitative and qualitative composition of the metal phase, which is part of the diamond grains (DG), is of paramount importance. A significant number of studies are devoted to the study of the influence of the metal phase on the specific consumption of diamonds, the productivity of grinding and the roughness of the processed surface, [1, 2, 3, 4]. Most of the recommendations for choosing a grade of diamond grains in wheels on ceramic bonds apply to the processing of carbide products, high-speed steels, titanium alloys. Model studies carried out by the authors [5, 6] indicate that a comprehensive selection of the grade of grains and their relative concentration can lead to a significant increase in the efficiency of the diamond grinding process. By the calculation method, it is possible to determine the stress-strain state (SSS) of the diamond-bearing layer not only during the manufacture of diamond-abrasive tools, but also at the stage of grinding various groups of processed materials (PM).

Modeling the limiting stress values by the finite element method [7] will allow avoiding expensive experimental studies and in the future create prerequisites for developing recommendations for grinding a wide range of grinded materials.

3. Methodology of conducting model experiments. *SIMULA Abaqus*, *SolidWorks Simulation*, *ANSYS* and *LS-Dyna* software packages were used for computer simulation of DAT operation processes.

Models of the "bond - DG – metal phase - PM" grinding system were developed for conducting simulation experiments (Fig. 1).



a) b) c)

Figure 1 – 3D model (a), constructed finite element grid (b) and the stress scheme of the model (c) in the study of processes and grinding

When creating models, the shape, size and properties of its elements were taken into account, which were considered as elastic solids. Since the most common form of diamond crystals is considered to be an octahedron [8], DG was taken with its geometry. Grain sizes varied according to the grain size of diamonds (50/40, 100/80, 125 × 100, 200 × 160). Local inclusions of the metal phase in the DG were created in the form of arbitrarily oriented parallelepipeds, the volume content of which was set depending on the grain grade (AC-4 - 7.5%, AC6 - 6%, AC15 - 2.2%, AC32 - 0.6 %) [9–10]. The bonds were reproduced as prismatic fragments ranging in size from 250 × 250 × 125 μm to 1000 × 1000 × 500 μm depending on the size and concentration of grains in the diamond-bearing layer. In the volume of the bond the grain placing surfaces were put in a free order, the number of which varied depending on the concentration of diamonds (25%, 50%, 100%, 150%, 200%), which was set as a percentage ratio of the bond volume and the total volume of DG. The element of the system "PM" was modeled in the form of prismatic fragments with dimensions from 250 × 250 × 125 μm to 1000 × 1000 × 500 μm.

Finite element analysis was performed using octagonal *SOLID* elements. The *ANSYS* program selected the type of finite elements from the package library for each component of the system, the construction of a finite element grid and its selective thickening. Elements such as *Hex Dominant* and *Tetrahedron* were used to create the grid for metal phases. Grid thickening was performed in the areas of DG bonding, in the areas of their contact with the PM and the inclusion of metal phases, as well as on the contact surfaces of the system elements. This approach allowed to more accurately simulate the deformation of fragments of the model, taking into account the distance of the areas of ultimate effects.

Fixing of the model (setting of zero or other necessary displacements) was carried out using the attributes of the geometric model (points, lines, surfaces) [11]. The model was pt under stress with static uniaxial evenly distributed load in the form of pressure and temperature values.

The choice of load limit parameters was made taking into account the temperature and force loads that accompany the grinding process.

When modeling the process of diamond abrasive grinding, the model was loaded with static uniaxial evenly distributed load P_y in the form of added values of normal force 0.5-4.0 N, which simulates the clamping force of the wheel in accordance with the technological parameters of diamond abrasive processing [12]. The feed motion of the S_{feed} and the rotation of the wheel were simulated by the longitudinal motion of the "bond - DG" element along the element of the "PM" system. Depending on the simulated cutting speed, different speeds of the "bond - DG" element were set. To increase the reliability of the simulation results, the value of the temperature load in the range of 400-800ºC was chosen according to the data of works [13, 14], in which the values of temperatures in the grinding area during processing of materials of different hardness were experimentally established.

The following characteristics of system elements were included in the calculation model: modulus of elasticity (*E*), modulus of volumetric compression (*G*), coefficient (CTE) of linear thermal expansion (α), Poisson's ratio (μ), yield strength (σ_0), coefficient of thermal conductivity (λ). Specifications of grain properties were performed according to reference data [15–17], taking into account information on temperature dependences of synthetic diamond properties (Fig. 2).

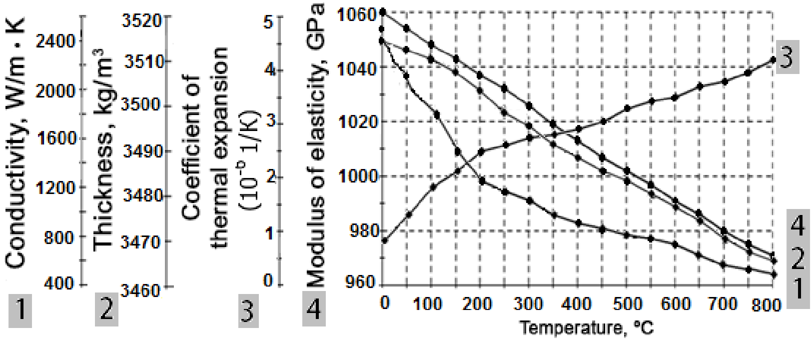


Figure 2 – Temperature dependences of synthetic diamonds properties

Since in the real grinding process the considered system is loaded with both force and temperature, in the course of researches depending on the total thermal and forece load the value of equivalent stresses σ_{eq} in elements of the system "metal phase - DG - bond - pore - PM" was determined. The bond was considered broken if the equivalent stresses (σ_{eq}) exceeded the corresponding strength limits.

4. The results of model experiments. The decisive factor in increasing the stability of DAT, along with the rational choice of components of the diamond wheel is the use of scientifically sound grinding modes, which can significantly increase the service life of the tool.

To determine the rational parameters of grinding, a series of experiments was conducted to study the effect of normal pressure and temperature in the grinding area on the SSS of the microvolume of the diamond-bearing layer in the grinding area. The study was performed on a model that simulates grinding with a single grain.

Since the temperature in the grinding area dominates among the factors that determine the process of diamond abrasive processing, it is important to study the influence of this factor on the behavior of the "bond - DG – metal phase - PM" system. It is known that the temperature in the cutting area can rise significantly due to "salinization" of the working surface of the diamond wheel with sludge particles, while excessive heating of the bond and DG, which can lead to their destruction and premature failure of the tool. Therefore, a comparative analysis of the SSS system that imitates diamond grinding was performed at different temperature loads (400 °C, 600 °C and

800 °C).

It is established that with the increase of the clamping force of DG in the specified range of values, the level of maximum stresses σ_{eq} increases by 1.3%. More influential is the temperature factor that occurs in the cutting area during grinding: an increase in temperature from 400 ºC to 800 ºC causes an increase in the level of stresses in the grain more than twice. On the one hand, the information obtained indicates the feasibility of cooling the cutting area, and on the other hand, ceramic bonds are known to be heat-resistant, which allows their use in dry grinding. Processing of the simulation results showed that the dependence of equivalent stresses on the grinding temperature is linear and is satisfactorily described by the equation $\sigma_{eq}=1.5265 \cdot T_{gr}+1.328$ (approximation reliability $R^2 = 0.99$).

However, as shown in [18], the possibility of reducing the heat load during grinding by optimizing the cutting modes is much lower than, for example, determining the optimal characteristics of DAT, which reduces the friction of the wheel with PM. And this is an important condition for reducing the energy consumption of the grinding process.

During the research, a model was used that allows to observe the change of SSS of the system "metal phase - DG - bond - PM" depending on the qualitative and quantitative characteristics of the metal phase (Fig. 3).

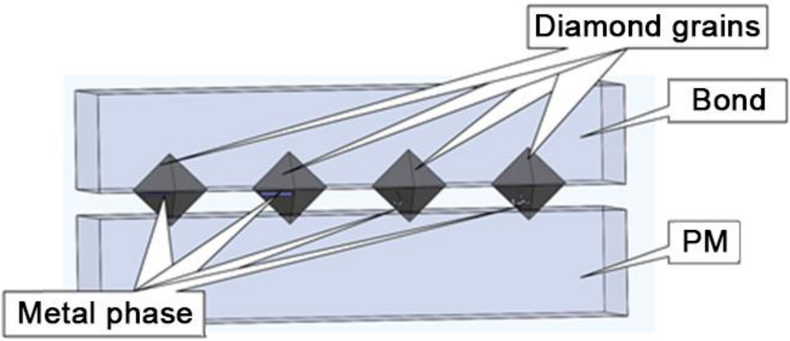
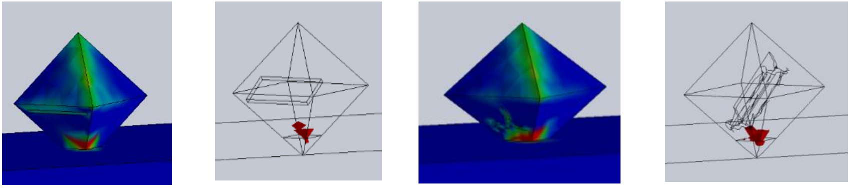


Figure 3 – 3D model for determining the influence of the metal phase on SSS of the system "metal phase - DG - bond - PM"

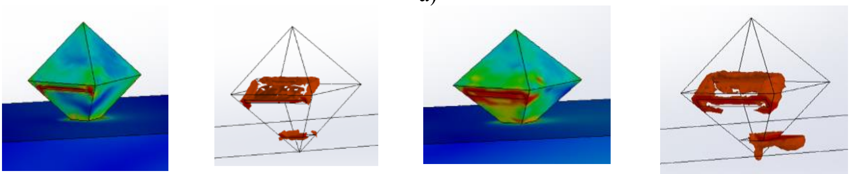
To identify the role of shape, size and composition of the metal phase, calculations were performed on models that imitate grains of grades AC6 and AC15 with a grain size of 125/100. According to the literature data [9, 19], the metal phase was modeled both in the form of rectangular parallelepipeds (simplified) and in the form of irregularly shaped elements, the volume of which was 2.2% and 6% of the grain volume, respectively, which corresponds to diamond powders of the AC15, AC6 grades. The level of maximum equivalent stresses (σ_{eq}) and the volume of destructive stresses in the grain

($V\sigma_{destr}$) were fixed as a criterion that determines the probability of self-sharpening of DG during grinding due to their micro-destruction under the action of stresses caused by temperature-force factors.



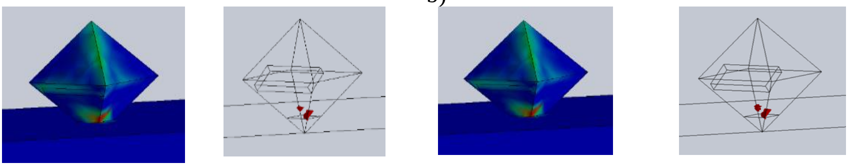
σ_{eq} = 562,77 MPa | $V\sigma_{destr}$ = 3,34% | σ_{eq} = 575,06 MPa | $V\sigma_{destr}$ = 3,36 %

a)



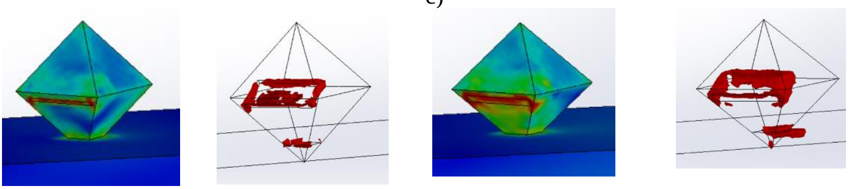
σ_{eq} = 570,91 MPa | $V\sigma_{destr}$ = 15,13 % | σ_{eq} = 584,01 MPa | $V\sigma_{destr}$ = 23,27 %

b)



σ_{eq} = 230,31 MPa | $V\sigma_{destr}$ = 2,11 % | σ_{eq} =263,65 MPa | $V\sigma_{destr}$ = 2,8 %

c)



σ_{eq} = 558 MPa | $V\sigma_{destr}$ = 9,96 % | σ_{eq} =572,05 MPa | $V\sigma_{destr}$ = 17,57 %

d)

Figure 4 – Distribution of stresses in the grain in the contact area "grain - PM": a) inclusion of metal phase $Fe_{95}Si_5$ of simple and complex shape in AC15 grains (2%); bond K1-01; PM - VK8; T = 440 ºC; b) metal phase $Fe_{95}Si_5$ in grains AC15 (2%) and AC6 (6%); bond K1-01; PM – ASPK; T = 800 ºC; c) metal phase $Fe_{95}Si_5$ i $Ni_{39,6}Mn_{59,6}$ $(Cr_3C_2)_{0,8}$ in grains AC6 (6%) bond K1-01; PM – alloy VK8; T = 440 ºC ; d) metal phase $Fe_{95}Si_5$ in grains AC15 (2%) and AC6 (6%); bond K1-01; Sital AC-418; T = 760 ºC

Examples of simulation results are given in Fig. 4, where it is seen that the areas where the maximum load level is recorded, are localized mainly in the area of inclusions of the metal phase, as well as in the area of contact of the DG with PM.

Calculation results showed that for cases of simple and complex shape of the metal phase with the same size of inclusions (Fig. 4 a), the stresses σ_{eq} practically do not change, and $V\sigma_{destr}$ differs by only 0.7%. This indicates the feasibility of modeling the metal phase in the form of simple forms (plates), which reduces the calculation time. As the size of metal phase inclusions of the same composition increases, other conditions being same (Fig. 4 b), the stress level σ_{eq} increases by ~ 2 ÷ 2.5%, while $V\sigma_{destr}$ increases 2 times.

When grinding different PM in the case of identical in composition and size inclusions of the metal phase with increasing hardness of PM there is a tendency to increase the maximum stresses at the contact "DG - PM" and in adjacent areas (Fig. 4 c), while the value of $V\sigma_{destr}$ increases from 2.1 % to 3.65%. With increasing the CTE of the metal phase for the considered solvent alloys while maintaining other equal conditions (Fig. 3 d) recorded an increase in the level of σ_{eq} by 5 ÷ 10% and almost twofold increase in $V\sigma_{destr}$ (from 2.12% to 4.32%) in the row: $Ni_{39,6}Mn_{59,6}(Cr_3C_2)_{0,8}$ > $Fe_{95}Si_5$ > $Fe_{44}Co_{44}(Cr_3C_2)_{12}$.

The influence of the composition and size of the metal phase on the level of σ_{eq} can be traced by the simulation results summarized in Table 1.

Table 1 – Maximum equivalent stresses (MPa) according to the results of modeling the process of grinding with a diamond wheel on the K1-01 bond

Metal phase composition	Processed material	Local temperature of the ground surface T_{max}, °C [20, 21]	Volumes of destructive stresses in grain ($V\sigma_{destr}$, %) when using grains of different grades (grain size 125/100)		
			AC4 (7,5%)*	AC6 (6 %)*	AC15 (2,2 %)*
$Ni_{39,6}Mn_{59,6}(Cr_3C_2)_{0,8}$	ASPK	800	42.57	39.55	20.39
	Sital AC-418	760	26.37	23.35	13.24
	Alloy VK8	440	5.81	2.80	0.38
$Fe_{95}Si_5$	ASPK	800	26.29	23.27	15.13
	Sital AC-418	760	20.58	17.57	9.96
	Alloy VK8	440	5.13	2.11	0.29
$Fe_{44}Co_{44}(Cr_3C_2)_{12}$	ASPK	800	23.43	20.41	10.11
	Sital AC-418	760	14.73	11.71	6.64
	Alloy VK8	440	4.43	1.41	0.19
* the relative volume of metal phase inclusions $Fe_{95}Si_5$, %					

Therefore, the composition of the metal phase is of great importance, especially in the case when the CTE of the metal phase significantly exceeds the CTE of the diamond. The shape of the metal phase inclusions plays a secondary role, as does the modulus of elasticity. Based on the obtained data, it can be stated that according to the degree of influence on the level of stresses arising in the volume of DG during grinding, the specified parameters (shape, size, the CTE of metal phase, and hardness of PM) can be arranged in a row: metal phase composition> metal phase size > type of PM> metal phase shape.

The grinding temperature of the material has a decisive influence on the stresses arising at the contact of "DG - PM". According to [20, 21], the local temperature in the cutting area differs significantly from 440 ºC for VK8 alloy to 800 ºC for ASPK diamond. The results of the calculations showed that when grinding parts made of hard alloy VK8 in the self-sharpening mode, it is advisable to grind without cooling. In this case, the formation of wear areas on the grains will be accompanied by an increase in temperature in the cutting area, which will ensure rational self-sharpening of the grains.

Wheels with AC15 grains will also provide rational self-sharpening during dry grinding of the AC-418 sital under the condition of using diamond powders, mixing the metal phase based on alloys of the growth system with reduced CTE (for example, $Fe_{95}Si_5$ або $Fe_{44}Co_{44}(Cr_3C_2)_{12}$). Instead, grinding of products from ASPK and sital AC-418 with wheels containing grains of grades AC2, AC4, AC6 should be carried out with cooling to prevent their thermal destruction.

It is established that the difference between the CTE of DG and metal phase determines the level of stresses at the contact of "DG – metal phase", which cause the appearance of microcracks in the grain during sintering of the diamond-bearing layer. Based on this, it is concluded that with increase of the CTE of solvent alloys used in the synthesis of diamonds, the effect of sintering temperature increases, which leads to the destruction of DG during grinding. This conclusion is generally consistent with the data of [22], where it is shown that with increasing grinding temperature above 650 ° C, the loss of grain strength is greater, the greater the difference between the CTE of the metal phase and DG. This fact should be taken into account in the manufacture of diamond wheels and the development of grinding modes.

5. Conclusions

The influence of qualitative and quantitative characteristics of diamond wheels on the SSS of the system "bond – metal phase - DG - PM" in the area of cutting diamond grains of brittle difficult-to-process materials has been calculated. The factors that determine the intensity of mutual destruction of the elements of the diamond-bearing layer of the wheel during grinding were identified. It is shown that in the considered range of force and temperature loads, that reproduce the real modes of diamond processing, the wear of diamond wheels is determined by the process of accumulation and development of microcracks in the bond and diamond grains.

It is established that the determining factor in the occurrence of critical stresses during grinding is the temperature in the cutting area, the increase of which in the presence of inclusions in the DG metal phase with high CTE leads to destructive stresses in the grains and, consequently, their premature failure. It is advisable to use DG with a minimum content of metal phase and the use in the growth of synthetic diamonds of solvent metals with low CTE, which will significantly increase the utilization of DG. Otherwise, the grinding area must be forcibly cooled.

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МОДЕЛЮВАННЯ ВПЛИВУ МЕТАЛОФАЗИ В АЛМАЗНИХ ЗЕРНАХ НА САМОЗАТОЧУВАНІСТЬ ШЛІФУВАЛЬНИХ КРУГІВ НА КЕРАМІЧНИХ ЗВ'ЯЗКАХ

Анотація. *В останні роки на основі методу кінцевих елементів (МКЕ) розроблено ряд програмних пакетів зі ще більш розширеними можливостями. До них в першу чергу відносяться SIMULA Abaqus, SolidWorks Simulation, ANSYS та LS-Dyna. Їх використання для проведення імітаційних експериментів по розробленим моделям дає можливість значного скорочення об'єму коштовних верстатних досліджень. В світовій практиці одним з найперспективніших підходів до удосконалення процесів обробки алмазно-абразивним інструментом є такий, що базується на створенні передумов для реалізації потрібних, стосовно конкретних умов обробки, механізмів самозаточування алмазних зерен (АЗ) і алмазоносного шару в цілому. А для цього треба знати фізику процесів, які відбуваються як в алмазних зернах зокрема, так і в системі шліфування в цілому. При створенні моделей враховували форму, розміри і властивості її елементів, які розглядали пружними суцільними тілами. Оскільки найпоширенішою формою кристалів алмазу вважається октаедр, АЗ приймали з його геометрією. Розміри зерен варіювали відповідно зернистості алмазів. Локальні включення металофази в АЗ створювали у вигляді довільно орієнтованих паралелепіпедів, об'ємний вміст яких задавався в залежності від марки зерна. Зв'язку відтворювали у вигляді призматичних фрагментів з розмірами, в залежності від розмірів і концентрації зерен в алмазоносному шарі. В об'ємі зв'язки в довільному порядку розміщували посадочні поверхні під зерна, кількість яких варіювали в залежності від концентрації алмазів, яку задавали як процентне відношення об'єму зв'язки і загального об'єму АЗ. Встановлено, що визначальним фактором появи критичних напружень при шліфуванні є температура в зоні різання, збільшення якої за наявності включень в АЗ металофази з високим КТР призводить до виникнення руйнуючих напружень в зернах і, як наслідок, їх передчасного руйнування. Доцільним є застосування АЗ з мінімальним вмістом металофази та використання при вирощуванні синтетичних алмазів металів-розчинників з низьким КТР, що дозволить значно збільшити коефіцієнт використання АЗ. В іншому випадку слід здійснювати примусове охолодження зони шліфування.*

Ключові слова: *алмазний круг; оброблюваний матеріал; алмазне зерно; металофаза; зв'язка круга; напружено-деформований стан; метод кінцевих елементів; еквівалентні напруження; самозаточуваність; режими шліфування.*