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3D SIMULATION OF DIAMOND GRINDING PROCESS BY FINITE ELEMENT METHOD

МАМАЛІС А.Г., ГРАБЧЕНКО А.І., ФЕДОРОВИЧ В.О., КУНДРАК Я., БАБЕНКО Є.О. 3D МОДЕЛЮВАННЯ ПРОЦЕСУ АЛМАЗНОГО ШЛІФУВАННЯ МЕТОДОМ СКІНЧЕНИХ ЕЛЕМЕНТІВ
Процес виготовлення алмазних кругів на органічних зв'язках відрізняється високою трудомісткістю і низькою продуктивністю праці, високим рівнем витрати дорогих алмазних зерен і, як наслідок, високою собівартістю подальшого процесу експлуатації алмазного круга. Існує потреба в підвищенні надійності та якості алмазно-абразивного інструменту, без чого нераціонально їх застосування у виробництві. Виробництво алмазно-абразивного інструменту базується на обґрунтованому поєднанні фізичних та технологічних закономірностей процесу спікання алмазоносного шару. На даний момент немає науково обґрунтованих рекомендацій щодо вибору раціональної комбінації сил різання, марки зерна, зернистості круга і його концентрація з фізико-механічними властивостями зв'язки. Метою даного дослідження є визначення оптимального поєднання властивостей алмазних зерен і зв'язки, при якому забезпечується утримання алмазних зерен та їх цілісність. Процесу виготовлення алмазного круга передують теоретичні дослідження процесу спікання з використанням 3D-моделювання напружено-деформованого стану алмазоносного шару.
Ключові слова: алмазне зерно, метод скінчених елементів, 3D-моделювання, алмазний круг, синтетичні алмази, алмазне шліфування.

Процесс изготовления алмазных кругов на органических связках отличается высокой трудоемкостью и низкой производительностью труда, высоким уровнем расхода дорогостоящих алмазных зерен и, как следствие, высокой себестоимостью дальнейшего процесса эксплуатации алмазного круга. Необходимо повышение надежности и качества алмазно-абразивного инструмента, без чего нерационально их применение в производстве. Производство алмазно-абразивного инструмента базируется на обоснованном сочетании физических и технологических закономерностей процесса спекания алмазоносного слоя. На данный момент нет научно обоснованных рекомендаций по выбору рациональной комбинации сил резания, марки зерна, зернистости круга и его концентрация с физико-механическими свойствами связки. Целью данного исследования является определение оптимального сочетания прочностных свойств алмазных зерен и связки, при котором обеспечивается удержание алмазных зерен и их целостность. Процессу изготовления алмазного круга предшествует теоретические исследование процесса спекания с использованием 3D-моделирования напряженно-деформированного состояния алмазоносного слоя.
Ключевые слова: алмазное зерно, метод конечных элементов, 3D-моделирование, алмазный круг, синтетические алмазы, алмазное шлифование.

Process of manufacture of diamond wheels on various bonds is characterized by high labour content and low productivity, high consumption of expensive diamond grains and, as consequence, the high cost price of a further operational process of diamond wheels. It is necessary to attain reliability and quality heightening at diamond-abrasive tool manufacture without which its effective application in production is impossible. Production of diamond - abrasive tool is founded on establishment of physical and technological regularities of sintering process of diamond-bearing layer. Now there are no scientifically based recommendations for choice of the rational combinations of strength, brand of grain, graininess, concentration with the physical-mechanical properties of bonds.
The aim of given research is the development of the technique of the theoretical definition of an optimal combination of strength properties of diamond grains and bond at which ones retention of diamond grain integrity at the process of manufacture of diamond wheel is ensured by using 3D simulations of deflected mode of sintering area of its diamond-bearing layer.
Key words: diamond grain, finite element method, 3d-simulation, diamond wheel, synthetic diamond, diamond grinding.

Problem definition. Process of manufacture of diamond wheels on various bonds is characterized by high labour content and low productivity, high consumption of expensive diamond grains and, as consequence, the high cost price of a further operational process of diamond wheels. It is necessary to attain reliability and quality heightening at diamond-abrasive tool manufacture without which its effective application in production is impossible. Production of diamond - abrasive tool is founded on establishment of physical and technological regularities of sintering process of diamond-bearing layer. Modern trends in the creation of science-intensive products are characterized by the dramatic widening of applied mathematics, in many respects connected with the creation and development of computer aids [1–4]. Now there are no scientifically based recommendations for choice of the rational combinations of strength, brand of grain, graininess, concentration with the physical-mechanical properties of bonds. In worldwide practice, one can see the tendency of transition from two-dimensional (2D) to 3D computerized simulation to match the advancement in computational power [5–8]. Guidelines, available in the literature, concerning application of some combinations of brands of bond and diamond grain, their concentration in grinding wheels on various bonds are of the common character and using of these recommendations leads to the fracture of diamond grains during sintering process and further low productivity of abrasive processing [9,10].

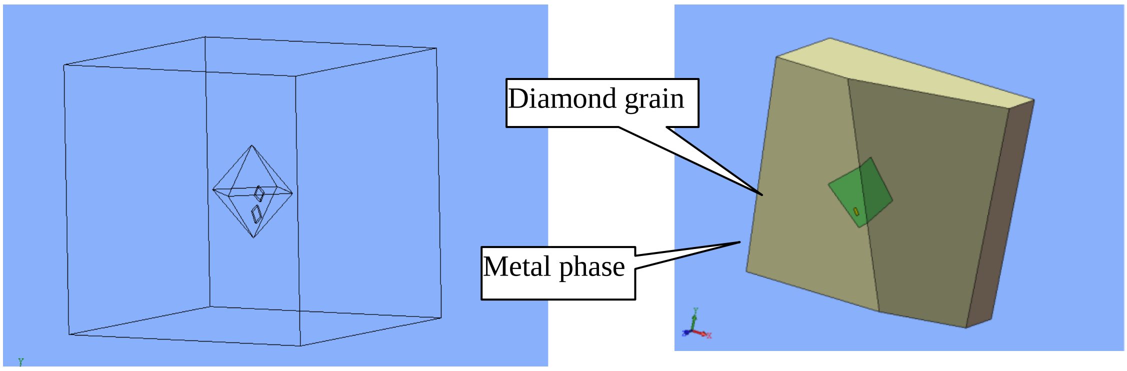
The analysis of last researches and publications has shown that the problem of effectiveness increase of diamond grinding is still topical and modern methods of mathematical simulation can introduce significant results. According to academician Loladze T.N., during the operation phase of diamond-abrasive tool the coefficient of effective utilization of diamond grains does not exceed 5-10 %, other grains fail as early as fabrication stage or fall out during wheel running. Therefore at the initial stage of manufacture of diamond wheel on various bonds it is important to define optimal technological parameters of its manufacture, namely pressure, temperature and sintering time at which integrity retention of diamond grains will be provided. At the next stage of operation of sintered wheels, it is necessary to consider and study the factors diminishing productivity of diamond grinding process that in the future will allow to decrease their influence and to achieve high utilization factor of diamond grains.

Research objective. The purpose of given work is the development of the technique of the theoretical definition of an optimal combination of strength properties of diamond grains and bond at which ones retention of diamond grain integrity at the process of manufacture of diamond wheel is ensured by using 3D simulations of deflected mode of sintering area of its diamond-bearing layer.

Basic research. Sintering process of diamond-bearing layer of grinding wheels has been studied by means of 3D-simulation of this process. The mathematical model "bond – grain – metal phase" was considered taking into account influence of components of this system on its deflected mode during sintering process. The influence of the properties of metal phase (metal-catalyst) and its percentage on change of internal equivalent stress in diamond grain has been studied. Thus the process was modelled for several brands of diamond grains and the obtained results were compared. Influence of availability of coatings on diamond grains is studied and the coating composition, allowing to diminish equivalent stress in grain, is defined [11].

In the model the grain and the bond were considered as elastic continuous bodies. Diamond grains were modelled in the form of octahedrons (fig. 1) with dimensions depending on considered graininess from 50×30×30 to 500×300×300 μm (fig. 1b). The presence of metal-catalyst in diamond grains was modelled by random oriented plates which volume content was 5-10 % [12]. The availability of two metal phases, placed near octahedron faces, was considered. The wheel bond was represented in the form of a cubic fragment with dimensions from 0,5×0,5×0,5 to 3×3×3 mm depending on size and concentration of grains. The model was loaded by static uniaxial uniformly distributed load, in the form of imposed pressure and temperature. The calculated 3D-model has been developed and computation of deflected mode in the model were carried out in the software CosmosWorks.

Since ultimate tensile strength of diamond is less than ultimate compression strength, so maximal tensile stress of diamond of various brands and graininess obtained by computation was accepted as the fracture criterion [13].



a *b*

Figure 1 – Computational model (a) and 3D-model of system "diamond grain – metal phase" (b)

Finite-element mesh has been generated after developing of computational 3D-model, and the mesh becomes thicker in a place of presence of diamond grain and metal-catalyst (fig. 2).

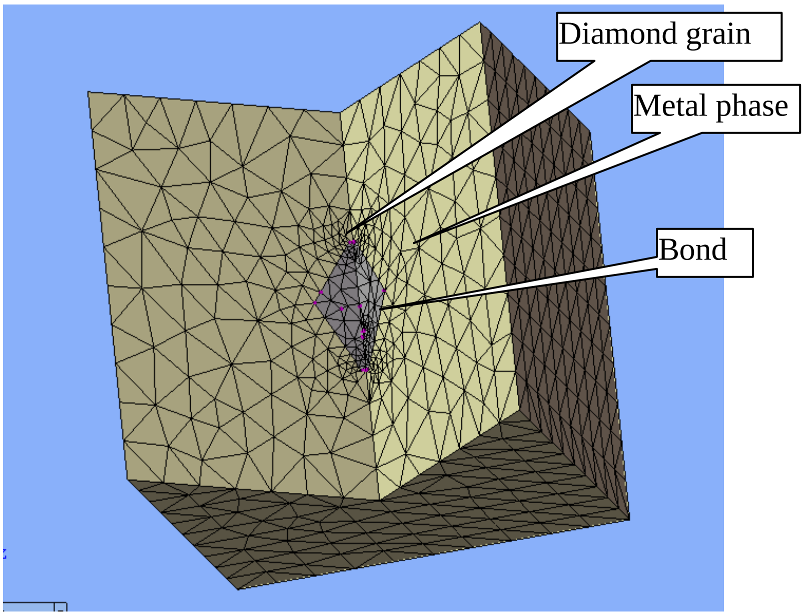


Figure 2 – Generated finite-element mesh in 3D model

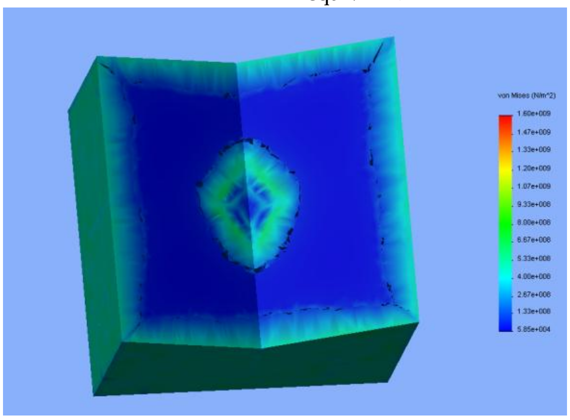
The fulfilled theoretical researches have displayed that diamond-bearing layer sintering temperature, unlike pressure, makes the greatest impact on the deflected mode of the system "diamond grain – metal phase – bond", irrespective of the kind of bond. The increase in stress in grains is observed on a contour of the sphere inscribed in an octahedron, and in places of concentration of metal phase in grain. The availability of bundle of metal contamination in crystals leads to decrease of their strength and especially thermal stability. It is defined that heating of synthetic diamonds, since temperature of 750 °C, leads to decrease of their strength.

The reason of diamond grain cracking is different values of coefficients of thermal extension of metal phase (the metal-catalyst rests) and diamond grain. As a rule, coefficient of thermal extension of metal-catalyst is much more, than for a synthetic diamond. Therefore so-called fracture of diamond grain from within occurs when heating up. Influence of sintering temperature of diamond-bearing layer on equivalent stress change occurring in grain of diamond wheels based on the of various kind of bond [14] is shown in fig. 3 and 4.

Having defined a significant role of the temperature factor in fracture of diamond grains we have passed to studying of influence of metal-catalyst properties on diamond integrity retention in the process of sintering diamond-bearing layer.

Four types of metal phase (with the dominanting contents of iron, cobalt, nickel and copper) and a bond on the basis of ceramics, the titan, aluminium, iron and bronze were considered. Computational models "bond – metal phase – grain" were loaded with temperature 400 and 800 ºC. Thus, the combination of components of given system was made to define an optimal combination of elements. Simulation of sintering process of diamond-bearing layer element was carried out for grain AC100, concentration 200/160. Maximal values of equivalent stress (tab. 1) which were compared to values of ultimate tensile strength of synthetic diamond have been obtained during computation. Analysing results of computations, it is possible to come to the conclusion that such combinations of grains and bond when metal phase of grains has low coefficient of thermal expansion and low coefficient of elasticity, and a bond in turn is enough durable, are optimal. Besides that the value of coefficient of thermal expansion should be determinative when sampling metal-catalyst.

Brand of bond: Fe
Brand of grain: AC50
Graininess: 125/100
Sintering temperature: 400ºC
Maximal value σ_{equiv}: 1,25 GPa



Brand of bond: Fe
Brand of grain: AC50
Graininess: 125/100
Sintering temperature: 700ºC
Maximal value σ_{equiv}: 2,01 GPa

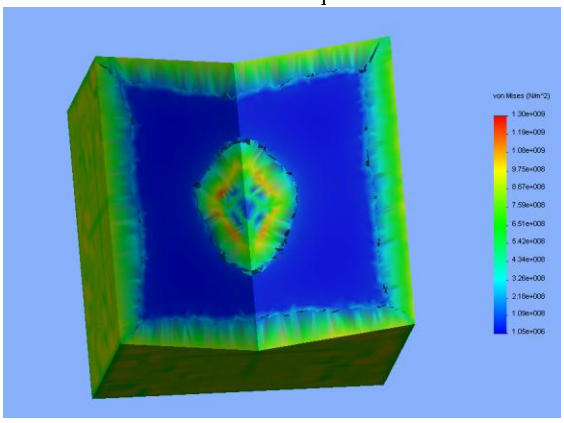
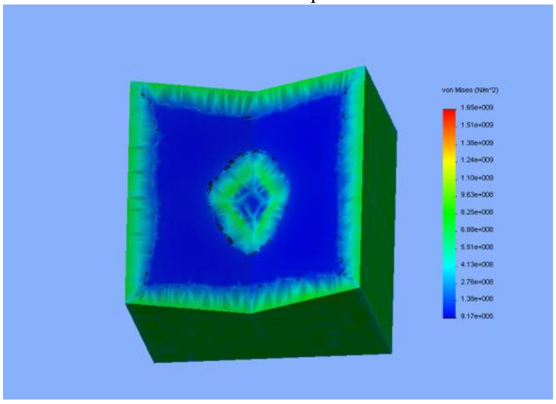


Figure 3 – Dependence of equivalent stress on temperature for wheels on metal bonds

Brand of bond: Ceramic
Brand of grain: AC50
Graininess: 125/100
Sintering temperature: **400ºC**
Maximal value σ_{equiv}: **1,50 GPa**



Brand of bond: Ceramic
Brand of grain: AC50
Graininess: 125/100
Sintering temperature: **700ºC**
Maximal value σ_{equiv}: **2,71 GPa**

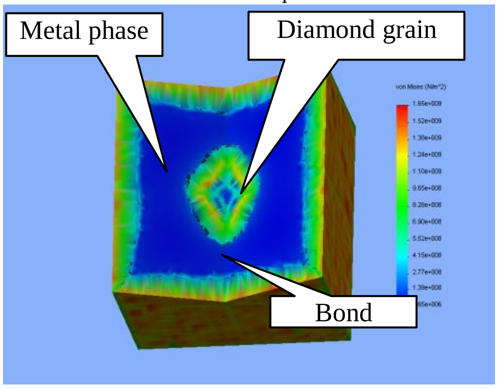


Figure 4 – Dependence of equivalent stress on temperature for wheels on ceramic bonds

Table 1 – Maximal values of equivalent stress at various components of the system "bond – metal phase – grain" with diamond grain AC100 (200/160)

Brand of the bond	Sintering temperature, ° C	Brand of the metal-catalyst			
		Nickel	Cobalt	Iron	Copper
		Equivalent stress, GPa			
Ceramic	400	1,53	1,34	1,24	1,78
	700	2,76	2,41	2,23	3,20
Titanium-magnesium	400	1,53	1,16	1,02	1,82
	700	2,76	2,09	1,84	3,27
Aluminium	400	1,52	1,32	1,19	1,79
	700	2,74	2,38	2,14	3,23

The influence of the percentage of the metal phase on the integrity retention of diamond grain has been studied with the aid of new 3D model "bond – metal phase – grain" with 20 % content of the metal-catalyst in diamond grain AC65. Proceeding from the gained results, it is argued that the increase of metal phase percentage in synthetic diamonds leads to higher value of equivalent stress in grain. The role of width and the material of diamond grain coatings (copper, molybdenum, sodium-borosilicate glass) is studied and positive influence of the coatings on diamond grain integrity retention at fabrication stage of diamond wheel is confirmed (fig. 5).

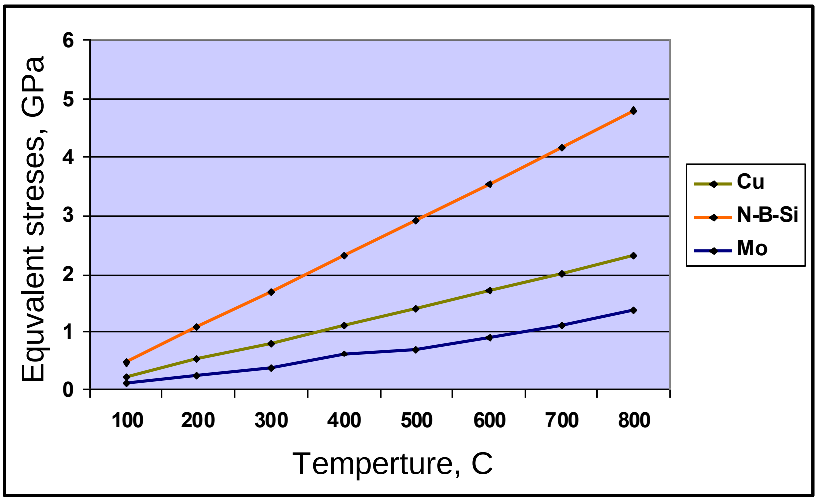


Figure 5 – Dynamics of stress rise in system "grain – metal phase – coating – bond" with diamond grain AC100; width of coating 15 μm

Process of exploitation of diamond grinding wheels has been simulated at the second stage of researches. Influence of metal phase presence in synthetic diamonds at abrasive and single-point machining is studied. Maximal values of equivalent stress are defined at increase in force of hold-down pressure of grinding wheel and at increase in temperature in cutting area.

Simulation of grinding process was carried out according to the similar technique indicated in the first part of the paper. Software products SolidWorks and CosmosWorks were used. 3D model "bond – grain – metal phase – material to be machined" has been developed. The ceramic bond, cobalt metal phase (5 % of diamond grain volume), diamond grain and workpiece from aluminium have been used in the initial model. Workpiece and a fragment of the bond were represented as plates, and diamond as a fragment with octahedron geometry. During calculated experiment the model was loaded with normal force from 0,5 to 4 N, that modelled force of hold-down pressure of diamond grinding wheel during abrasive processing (fig. 6).

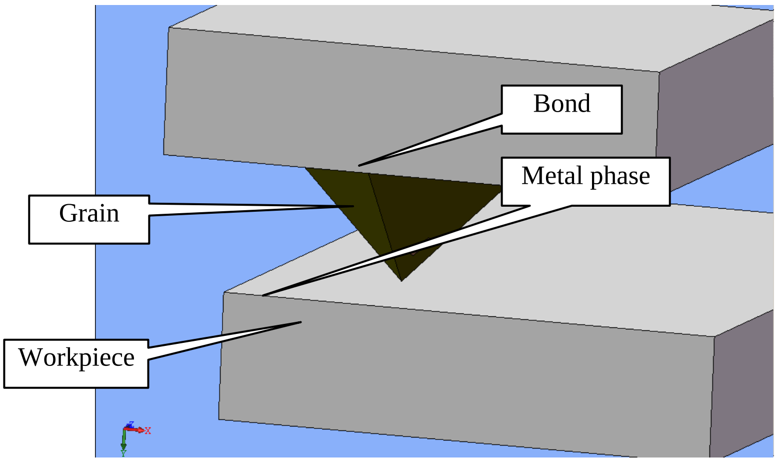
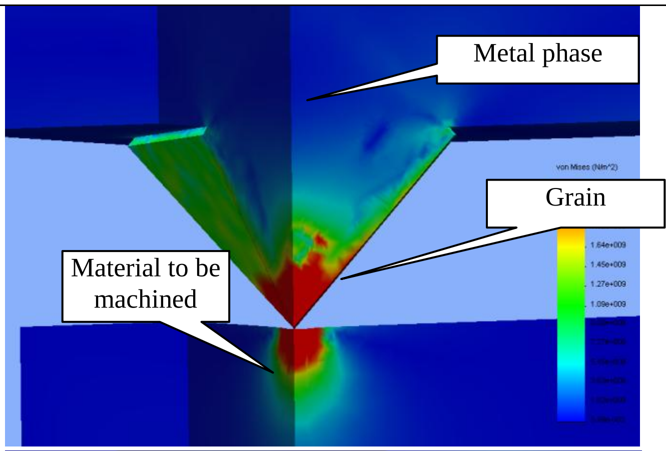


Figure 6 – 3D model "bond – grain – metal phase – workpiece" with finite-element mesh

Significant influence of temperature in cutting area on the deflected mode of diamond grain is defined. This phenomenon is explainable by the influence of temperature factor on behaviour of metal-catalyst in diamond grain. So, already at the temperature 500 ºC and force of hold-down pressure 1 N there can be loads by 5 % exceeding maximal value of stress without presence of heightened temperature. Metal-catalyst has considerably greater coefficient of thermal expansion as compared with diamond, and at increase in stress there is superposition of stress fields caused by force and temperature loads (fig. 7).

Conclusion and further prospects. Theoretical study of 3D deflected mode of the system "material to be machined– grain— metal phase – bond" in problem-oriented software package CosmosWorks has allowed to examine influence of qualitative composition of metal phase on 3D deflected mode of grinding area at high tempetature, and also to calculate equivalent stress in examined system. The obtained results are evidence of application expediency of diamond grains with minimum possible contents of metal phase, and dominanting element in its composition should be a metal with a low coefficient of thermal expansion. It allows to considerably increase coefficient of utilization of diamond grains and to increase profitability of diamond grinding.

Bond: Ceramic
Metal phase: Copper
Material to be machined: Al
Force of hold-down pressure : 3 N
Heating temperature: **500ºC**
Value σ_{equiv}= **17,84 GPa**



Bond: Ceramic
Metal phase: Copper
Material to be machined: Al
Force of hold-down pressure: 3 N
Heating temperature: 800ºC
Value σequiv = 27,92 GPa

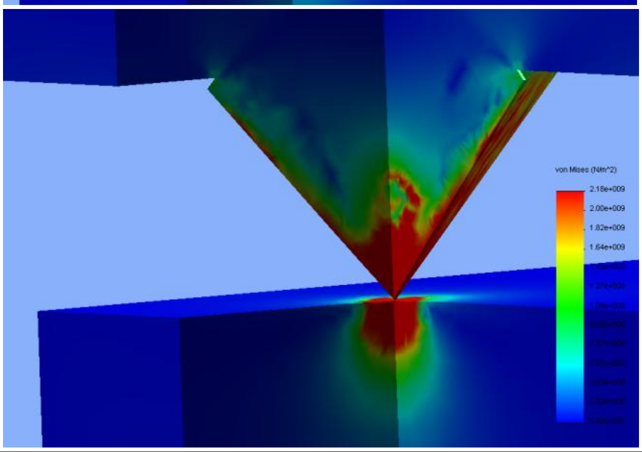


Figure 7 – Stress distribution at increase in temperature of diamond grain

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