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ORIGINAL ARTICLE

Simulation of effects of metal phase in a diamond grain and bonding type on temperature in diamond grinding

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Abstract Manufacturing diamond wheels on various bonds is a relatively high-cost process, requiring high labour and high consumption of expensive diamond grains but yielding relatively low productivity. With better knowledge of the various factors involved in the sintering process, the most efficient combinations can be found, leading to higher productivity. Currently, there are no scientifically based recommendations for the choice of the rational combinations of strength, brand of grain, graininess and concentration with the physical–mechanical properties of bonds. The aim of this research is the development of a technique for the theoretical definition of an optimal combination of strength properties of diamond grains and bond to provide maximum retention of diamond grain integrity during the process of diamond wheel manufacture. This is investigated using 3D simulations of the deflected mode of the sintering area of the wheel's diamond-bearing layer.

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1 Introduction

The manufacture of diamond wheels on various bonds is characterised by high labour and low productivity as well as the high consumption of expensive diamond grains. As a consequence, the additional operational processes of diamond wheels require high cost. It is necessary to attain reliability and improve the quality of diamond-abrasive tool manufacture, since its effective application in production is not possible. The production of diamond-abrasive tools is founded on the establishment of physical and technological regularities of the sintering process of the diamond-bearing layer. Modern trends in the creation of science-intensive products are characterised by the dramatic widening of applied mathematics, in many respects connected with the creation and development of computer aids [1–5]. Currently, there are no scientifically based recommendations for the choice of rational combinations of strength, brand of grain, graininess and concentration with the physical–mechanical properties of bonds. In worldwide practice, one can see the tendency of transition from 2D to 3D computerised simulation to match the advancement in computational power [6–9]. While guidelines are available in the literature concerning the 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 following these recommendations leads to the fracture of diamond grains during the sintering process and thus low productivity of abrasive processing [10, 11].

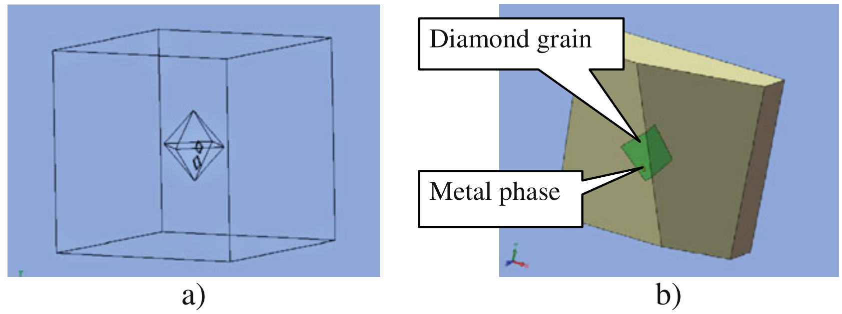

Fig. 1 Computational model (**a**) and 3D model of system "diamond grain-metal phase" (**b**)

2 Research objective

An analysis of recently published research has shown that the problem of increasing the effectiveness of diamond grinding is still topical and that modern methods of mathematical simulation can yield significant results. According to Loladze, during the operation phase of a diamond-abrasive tool, the coefficient of effective utilization of diamond grains does not exceed 5–10%, other grains fail as early as the fabrication stage or fall out during wheel running, see Ref [1]. Therefore, at the initial stage of manufacture of the diamond wheel on various bonds, it is important to define the 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 that diminish the productivity of diamond-grinding process, so that in the future, their effect can be diminished and a high utilization factor of diamond grains can be achieved. The purpose of the present work is the development of a technique for the theoretical definition of an optimal combination of strength properties of diamond grains and bond, in which retention of diamond grain integrity during the process of manufacturing diamond wheels is ensured by using 3D simulations of the deflected mode of the sintering area of its diamond-bearing layer.

3 Simulation

The solution of the problems is based on usage of the software packages COSMOS, ANSYS, NASTRAN, intended for test and evaluation calculations by FEM. As applied to simulation of DCM sintering processes and research of machining area, these packages (in a universal complete set) allow to decide the following classes of the problems: definition of displacement, strains and stress (DM) in system "diamond grains-bond-material to be machined" at static effects (linear statics); definition of DM of system with use of non-linear models (physical, geometrical nonlinearity); DM at contact of deformed solids; DM in system components if cracks are present; analysis of frequencies and mode shapes of self-oscillations of construction; dynamic Fourier analysis and random response—estimation of system behaviour at external polyharmonic or random effect; dynamic transients—calculation of system behaviour in time under condition of non-steady external loading; analysis of fatigue failure of system components; analysis of stationary and transient hydrodynamics; stationary and transient non-linear thermal processes—definition of distribution of heat flows, analysis of temperature fields and strains; definition of responsiveness of outcomes of all aspects of the analysis in respect to changing properties of system components; the multicriteria optimization with use of various type limitations simultaneously, with a capability to control the process flow by the user; adaptive analysis of stress.

The 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 the influence of components of this system on its deflected mode during sintering process. The influence of the properties of metal phase (metal-catalyst) and the percentage of change of internal equivalent stress in diamond grain has been studied. Thus, the process was modelled for several brands of diamond grains, and the

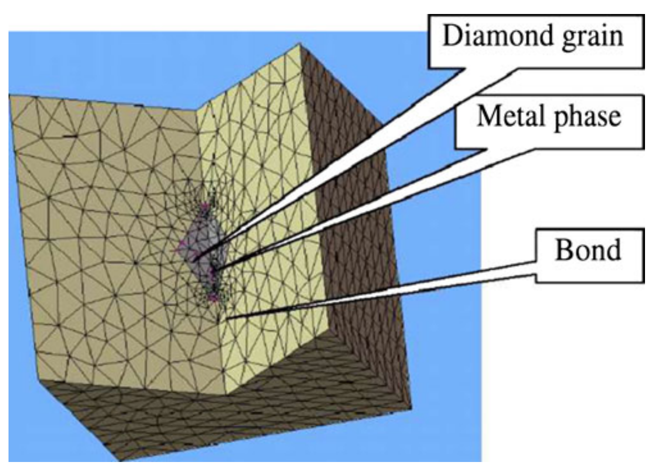

Fig. 2 Generated finite-element mesh in 3D model

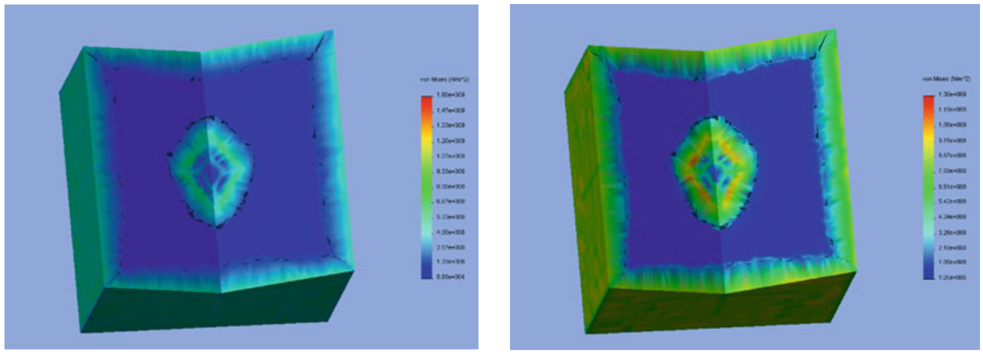

Fig. 3 Effect of temperature on equivalent stress for wheels on metal bonds

obtained results were compared. The influence of the availability of coatings on diamond grains is studied and the coating composition, allowing reduction of equivalent stress in the grain, is defined [12].

In the model, the grain and the bond were considered as elastic continuous bodies. Diamond grains were modelled in the form of octahedrons (see 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 with volume content of approximately 5–10% [13]. 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 varying 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 was carried out using CosmosWorks software.

Since the ultimate tensile strength of diamond is less than its ultimate compression strength, the maximal tensile stress of diamond of various brands and graininess obtained by computation was accepted as the fracture criterion [14].

4 Results and discussion

A finite-element mesh is generated after developing the computational 3D model, and the mesh becomes thicker where diamond grains and metal-catalyst are present (see Fig. 2).

Theoretical research is revealed that the diamond-bearing layer sintering temperature, unlike pressure, has the greatest effect 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 where metal phase is concentrated in the grain. The availability of bundle of metal contamination in crystals

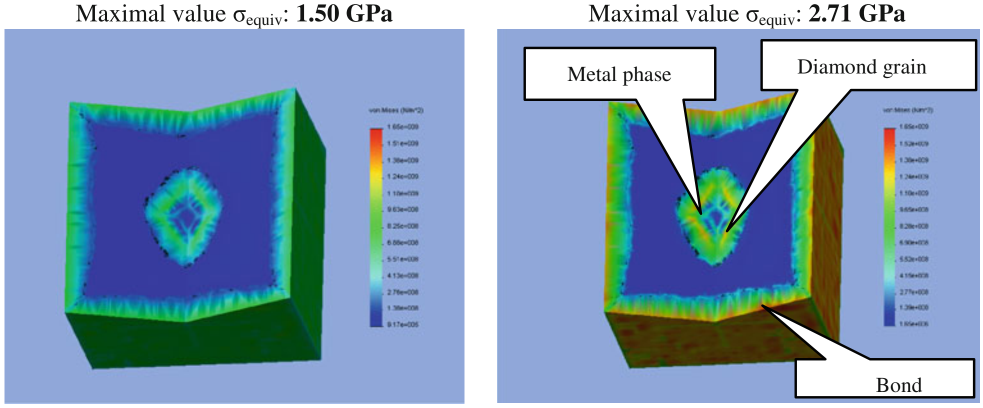

Fig. 4 Effect of temperature on equivalent stress for wheels on ceramic bonds

Table 1 Maximum values of equivalent stress for various components of the system "bond-metal phase-grain" with diamond grain AC100 (200/160)

Bond	Sintering temperature, °C	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

leads to a decrease in their strength and especially thermal stability. It is defined that heating of synthetic diamonds, up to the temperature of 750°C, leads to a decrease of their strength.

The cause of diamond grain cracking is the difference between the coefficients of thermal expansion of the metal phase (the metal-catalyst rests) and the diamond grain. As a rule, the coefficient of thermal expansion of the metal-catalyst is much higher than that of a synthetic diamond. Therefore, fracture of diamond grain when it is heated up initiates from the grain interior. The influence of the sintering temperature of the diamond-bearing layer on equivalent stress change occurring in the grains of diamond wheels [15] is shown in Fig. 3 for a metal bond and Fig. 4 for a ceramic bond.

As follows from the analysis of the carried out calculations, the increase in the temperature of sintering from 400°C up to 700°C leads to the increase of equivalent stress in diamond grain from 1.25 to 2.01 GPa in the bond based on iron and from 1.5 to 2.71 GPa in the wheels on ceramic bond. Having defined a significant role of the temperature factor in the fracture of diamond grains, we next investigated the influence of metal-catalyst properties on diamond integrity retention in the process of sintering the diamond-bearing layer. Four types of metal phase (with the dominating contents of iron, cobalt, nickel and copper) and a bond on the basis of ceramics, titanium, aluminium, iron and bronze were considered. Computational models "bond-metal phase-grain" were set for temperatures of 400°C and 800°C. Thus, the combination of components of a given system was made to define an optimal combination of elements. Simulation of the sintering process of a diamond-bearing layer element was carried out for grain AC100, concentration 200/160. Maximal values of equivalent stress obtained during computation (Table 1) were compared to values of ultimate tensile strength of synthetic diamond. Analysing the results of computations, it is possible to come to the conclusion that combinations of grains and bond are optimal in which the metal phase of grains has a low coefficient of thermal expansion and low coefficient of elasticity, and the bond is sufficiently durable. In addition, the value of the thermal expansion coefficient should be a determining factor when sampling metal-catalyst materials.

The influence of the percentage of the metal phase on the integrity retention of diamond grains was studied with the aid of new 3D model "bond-metal phase-grain" with a content of the metal-catalyst of 20% in diamond grain AC65. From the results, we argue that an increase of metal phase percentage in synthetic diamonds leads to a higher value of equivalent stress in grains. The role of width and the material of diamond grain coatings (copper, molybde-

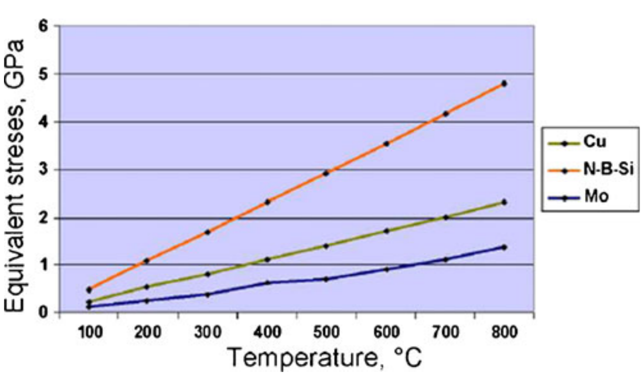

Fig. 5 Dynamics of stress rise in system "grain-metal phase-coating-bond" with diamond grain AC 100; width of coating 15 μm

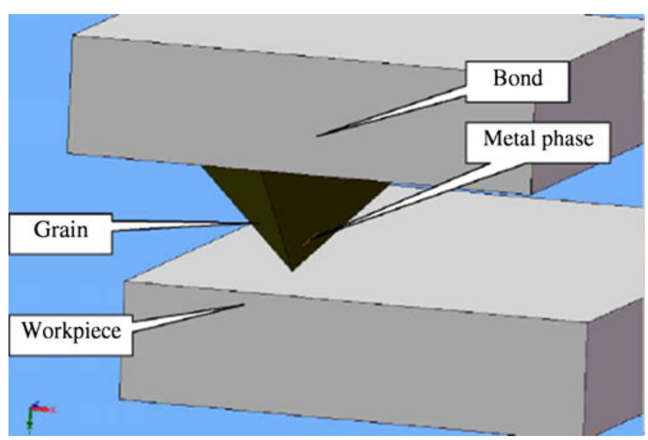

Fig. 6 3D model "bond-grain-metal phase-workpiece" with finite-element mesh

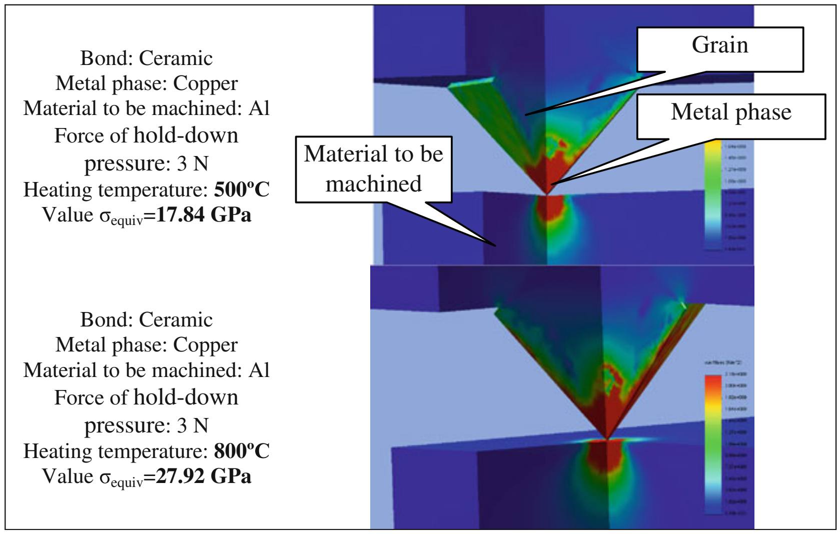

Fig. 7 Stress distribution at increase in temperature of diamond grain

num, sodium-borosilicate glass) was studied and the positive influence of the coatings on diamond grain integrity retention at fabrication stage of diamond wheel is confirmed (Fig. 5). It is established that molybdenum coating of diamond grains is most effective to ensure retention of their integrity in the course of sintering of the diamond-bearing layer.

The process of exploitation of diamond grinding wheels has been simulated at the second stage of research. The influence of metal phase presence in synthetic diamonds during abrasive and single-point machining is studied. Maximum values of equivalent stress are found with an increase in force of hold-down pressure of the grinding wheel and with an increase in temperature in the cutting area. Simulation of the grinding process was carried out according to a similar technique indicated in the first part of the paper, using the software SolidWorks and Cosmos-Works. A 3D model "bond-grain-metal phase-material to be machined" was developed. The ceramic bond, cobalt metal phase (5% of diamond grain volume), diamond grain and workpiece from aluminium were used in the initial model. The workpiece and a fragment of the bond were represented as plates, and the diamond as a fragment with octahedron geometry. During the numerical experiment, the model was loaded with normal force from 0.5 to 4 N, modelling the force of hold-down pressure of a diamond grinding wheel during abrasive processing (see Fig. 6).

A significant influence of temperature in cutting area on the deflected mode of diamond grain was found. This phenomenon is explainable by the influence of temperature factor on the behaviour of the metal-catalyst in the diamond grain. Already at the temperature of 500°C and a force of 1 N hold-down pressure, there can be loads exceeding the maximal value of stress by 5% without heightened temperature. The metal-catalyst has a considerably greater coefficient of thermal expansion compared with diamond, and with an increase in stress there is a superposition of stress fields caused by temperature loads (see Fig. 7). It is shown from the results of calculations that at the same hold-down pressure of the wheel to the sample (3 N), the

Table 2 Computational and experimental values of specific consumption of diamond wheels depending on wheel characteristics

Grain	Modulus of elasticity of bond, GPa	Graininess, μm	Computational value of specific consumption of wheel carat/carat	Experimental value of specific consumption of wheel carat/carat
AC2	40–52	50/40–63/50	30	32
AC4	44–70	50/40–80/63	28	29
AC6	77–95	50/40–100/80	25	26
AC15	86–100	80/63–100/80	20	19
AC32	98–110	80/63–125/100	15	13
AC50	102–119	100/80–160/125	12	11
AC80	143–173	125/100–250/200	10	9
AC100	165–210	125/100–315/250	8	11
AC125	190–260	200/160–315/250	7	8
AC160	210–320	250/200–500/400	5	4

increase in temperature in grinding area from 500°C to 800°C leads to increase in stress in diamond grain from 17.84 to 27.92 GPa.

Carried out computation of grain volumes which fractured and fell out of the bond lets us predict theoretically a value of specific consumption of diamond wheels. Experimental validation of obtained theoretical results when grinding synthetic diamond is given in Table 2.

5 Conclusions

This study of the 3D deflected mode of the system "material to be machined-grain-metal phase-bond" in the software package CosmosWorks has allowed us to examine the influence of qualitative composition of metal phase on 3D deflected mode of the grinding area at high temperatures and also to calculate equivalent stress in the examined system. On the basis of the carried out researches, it is established that to support the retention of integrity of diamond grains in the course of sintering of diamond wheels it is recommended to use a bond based on iron, to apply molybdenum coatings on diamond grains and metal-catalyst based on iron. The obtained results are evidence of the rational application of diamond grains with the minimum possible content of metal phase, and the dominating element in its composition should be a metal with a low coefficient of thermal expansion. This allows a considerable increase in the coefficient of utilization of diamond grains and thus increases the profitability of diamond grinding.

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