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Diamond grinding wheels production study with the use of the finite element method

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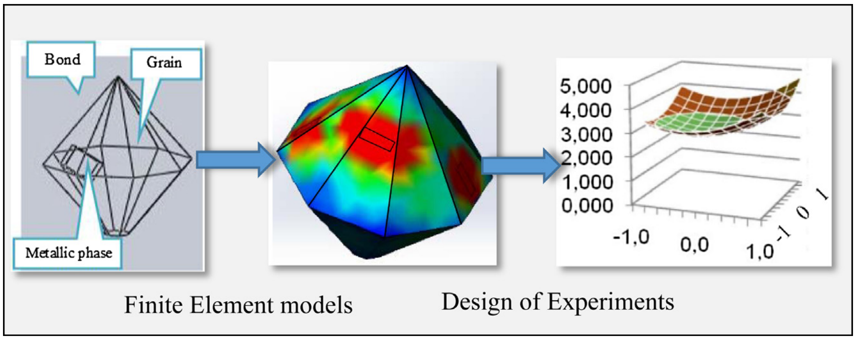
G R A P H I C A L   A B S T R A C T



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A B S T R A C T

Research results on 3D modeling of the diamond grain and its bearing layer when sintering diamond grinding wheels are provided in this paper. The influence of the main characteristics of the wheel materials and the wheel production process, namely the quantity of metallic phase within diamond grain, coefficient of thermal expansion of the metallic phase, the modulus of elasticity of bond material and sintering temperature, on the internal stresses arising in grains is investigated. The results indicate that the stresses in the grains are higher in the areas around the metallic phase. Additionally, sintering temperature has the greatest impact on the stresses of

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the grain-metallic phase-bond system regardless of the type of the bond. Furthermore, by employing factorial design for the carried out finite element model, a mathematical model that reflects the impact of these factors on the deflected mode of the diamond grain-metallic phase-bond material system is obtained. The results of the analysis allow for the identification of optimal conditions for the efficient production of improved diamond grinding wheels. More specifically, the smallest stresses are observed when using the metal bond with modulus of elasticity 204 GPa, the quantity of metallic phase in diamond grain of not higher than 7% and coefficient of thermal expansion of 1.32×10^{-5} 1/K or lower. The results obtained from the proposed 3D model can lead to the increase in the diamond grains utilization and improve the overall efficiency of diamond grinding.

Introduction

Grinding is mainly used as a finishing process but also as a process with high material removal rates, in contemporary industry [1,2]. Its efficiency heavily depends on the quality of the tools used, namely, the grinding wheels. In particular diamond grinding wheels are a large part of the tools used in this process and the quest for better quality tools drives the trends toward the overall improvement of the process.

It is necessary to increase the reliability and quality when manufacturing diamond-abrasive tools, which is indispensable to its effective application in manufacturing processes. The operational efficiency of a diamond grinding wheel is determined in extent by factors such as the quality of production of the diamond-bearing layer and its best performance curve. The production process of diamond wheels on various bonds is rather labor-intensive. Foremost, this concerns the sintering process involved in the production of the wheels [3]. At present, there are no scientifically established guidelines for the choice of rational combinations of strength, brand of a grain, graininess and concentration with physical-mechanical properties of wheel bonds. The guidelines that are available in the literature for the use of various bonds in diamond grinding wheels are of general type [4]. This results in damage to the grains during sintering process, which further leads to lower productivity of the abrasive process.

A way to solve the problem of enhancement of diamond abrasive tool production efficiency is to use the modeling techniques for simulation of their production process. Finite Element Method (FEM) is one of the most frequently used methods for the simulation of manufacturing processes [5–7], including grinding as well [8–10]. The advancements in computer technology have also made 3D modeling available [11–13]. These models, although more complicated and computationally intensive in comparison with 2D models, can be completed in reasonable time and hardware resources with modern personal computers. Additionally, commercial FEM software has further simplified the model building and solving procedure; at the same time these software have made modeling more reliable.

Focusing on the modeling of grinding and grinding wheels, two main trends may be identified [14]. In the first one, the grinding wheel-workpiece interaction is macroscopically examined. The actual grinding wheel is replaced by thermal or thermo-mechanical boundary conditions and chip formation is neglected [9]. In the second approach, being a microscopic one, a grain or a group of grains is modeled and their interaction with the workpiece is investigated [15,16]. These models, usually 3D, use shapes of the grain based on optical observations from actual grinding wheels [17]. However, the action between the grain and the bond is neglected. Furthermore, models such as these, pertain only to the operation of the grinding wheel and not to its production.

As a novelty, the microscopic approach is adopted in this paper to describe a diamond grain of the grinding wheel, at the production stage. The methodology is based on numerical modeling of the deflected mode of diamond abrasive tools such as sintering and grinding zone using the finite element method for the introduction of a 3D model. Simultaneously, it is possible to determine the best composition of the diamond-bearing layer of the wheel, i.e. physical-mechanical properties of wheel bond, graininess and concentration of diamond grains and, if necessary, the rational design of the wheel, for specific process conditions, e.g. for high-speed grinding. These tasks are realized without time- and labor-consuming, costly experimental investigations but by means of design of experiments and statistical analysis. Furthermore, the influence of the quantitative composition of metallic phase in diamond grain and the influence of temperature on deflected mode of diamond-bearing layer, when sintering diamond wheels, are investigated.

Finite element model

The question of efficiency enhancement of the diamond grinding processes is still the subject of active research interest. It is anticipated that modern methods of numerical modeling can produce significant results. It is known that during the operation of diamond abrasive tools the coefficient of efficient use of diamond grains does not exceed 5–10% [3]. The remaining percentage of grains is destroyed at the stage of production or in the course of wheel operation. Therefore, at the initial stage of production of a diamond wheel on various bonds, it is important to determine the optimal process conditions for its manufacture, namely pressure, temperature and sintering time, under which the integrity of diamond grains is not disturbed. At the next stage of operation of the sintered wheels, it is necessary to investigate the factors increasing the efficiency of diamond grinding that from now on will allow achieving high coefficient of use of the capability of diamond grains.

The purpose of this study is to determine, through the use of a 3D model of the sintering zone deflected mode of diamond-bearing layer, the optimum combination of strength properties of diamond grains and bond, which provides the integrity conservation of diamond grains in the process of manufacturing a diamond wheel.

Diamond crystals are synthesized under high pressure and temperature in the presence of iron–nickel alloy catalyst [18]. Impurities, in the form of metal phase inclusions, are identified in the synthetic diamond crystals [19]. In order to investigate the sintering process of the grinding wheels' diamond-bearing layer by 3D modeling, the grain-metallic phase-bond system is considered taking into account the influence of the components of this system on its deflected mode during sintering. The influence of the properties of metallic phase, i.e. the metal-catalyst and its percentage on the change in the internal equivalent stresses in the diamond grains of various brands is investigated, and then the results are compared.

In the proposed model, a grain and the surrounding bond material are considered as elastic solid bodies. Diamond grain is modeled as an octagonal bipyramid [17], as shown in Fig. 1, with the size depending on the graininess under consideration from 50 × 30 × 30 up to 500 × 300 × 300 μm. The presence of a metal-catalyst in diamond grains is modeled by randomly oriented plates, with volumetric content of 6% to 10% [20]. This percentage is interpreted as one to three inclusions of metallic phase, located at the edges of the upper half of the grain, see Fig. 1. The bond material of the wheel (not shown in Fig. 1) is represented as a cubic fragment with size from 500 × 500 × 500 up to 3000 × 3000 × 3000 μm depending on the size and concentration of the grains.

For the 3D model COSMOSWorks is employed. FEM analysis is conducted using SOLID 8-node elements. In the area of the inclusions of metallic phases, selective refinement is performed when creating the mesh of the model. When generating the mesh for metallic phases, elements of the Hex Dominant type are used. Thus, the deformation of the model fragments, taking into account the remoteness of the zones of edge effects, can be simulated accurately enough.

The model is loaded with static, uniaxial, uniformly distributed load, in the form of applied pressure ranging from 0.03 GPa to 0.12 GPa and temperature from 400 °C to 800 °C. Since the ultimate tensile strength is lower than the ultimate compressive strength for diamond, the predicted maximum tensile stresses are compared to the ultimate strength for the diamond; this latter expression serves as a fracture criterion, ranging from 0.12 to 4.45 GPa, depending on the various brands and graininess studied [3].

Modeling of grinding wheels production

The FEM model described in the previous section will be used for the identification of the influence of the quantity of metallic phases in a grain, on the location and magnitude of stresses, with various loadings of the grain. This way, a quantitative and qualitative analysis on the grain and bond behavior in a diamond tool can be observed. The results presented in this section provide the opportunity to get insight and observe details of phenomena that would be impossible to achieve experimentally. Furthermore, the model is used for the investigation of the influence of other parameters connected with grinding wheel production, e.g. sintering temperature, in order to identify optimal production conditions. The modeling at micro-level introduced in this study presents results, e.g. the contours of stresses within the diamond grain and around the metallic phase that cannot be experimentally identified. However, an indirect validation of the model can be provided by comparing the macroscopic behavior of the grains with results presented in the relevant literature; this qualitative comparison, as the conditions are not identical in each case, is provided in each of the following paragraphs of this section.

Effect of the quantity of metallic phases

In order to investigate the influence of the quantity of metallic phase in a grain, models with different percentages of metallic phase are developed. In the reference model, the diamond grain of AC6 brand (graininess 160/125) is considered. In Table 1 the physical properties of the grain-metallic phase-bond system, which were used in the analysis are listed.

After the geometrical construction of the proposed 3D model, the finite element mesh is generated and the mesh is refined in the locations of diamond grain and metallic phase presence. From the stress distribution shown in Fig. 2, it stems that the maximum stresses at heating are concentrated in the areas of the presence of metallic phase. It is obvious that the metallic phase plays a key role in the destruction of the diamond grains during the diamond grinding wheel sintering process. When the metallic phase inclusions are concentrated in close locations, an increase in the stress fields can be observed. In the case of the concentration of all three metallic phase

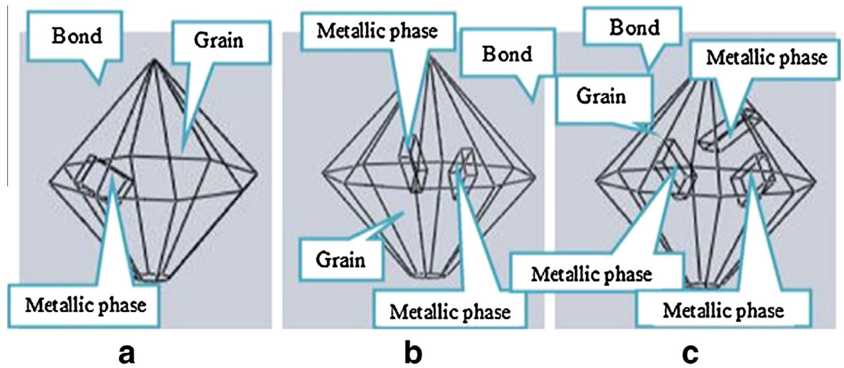


Fig. 1 3D model of diamond grains containing (a) one, (b) two and (c) three inclusions of metal-catalyst.

Table 1 Physical properties of the grain-metallic phase-bond system.

	Grain	Metallic phase	Bond
Modulus of elasticity (GPa)	1060	273	110
Compression modulus (GPa)	360	40	40
Poisson's ratio	0.1	0.2	0.37
Coefficient of thermal expansion (1/K)	0.95×10^{-6}	1.3×10^{-5}	24×10^{-6}
Thermal conductivity (W/mK)	2400	78	390
Specific heat capacity (J/Kg K)	1400	39	390

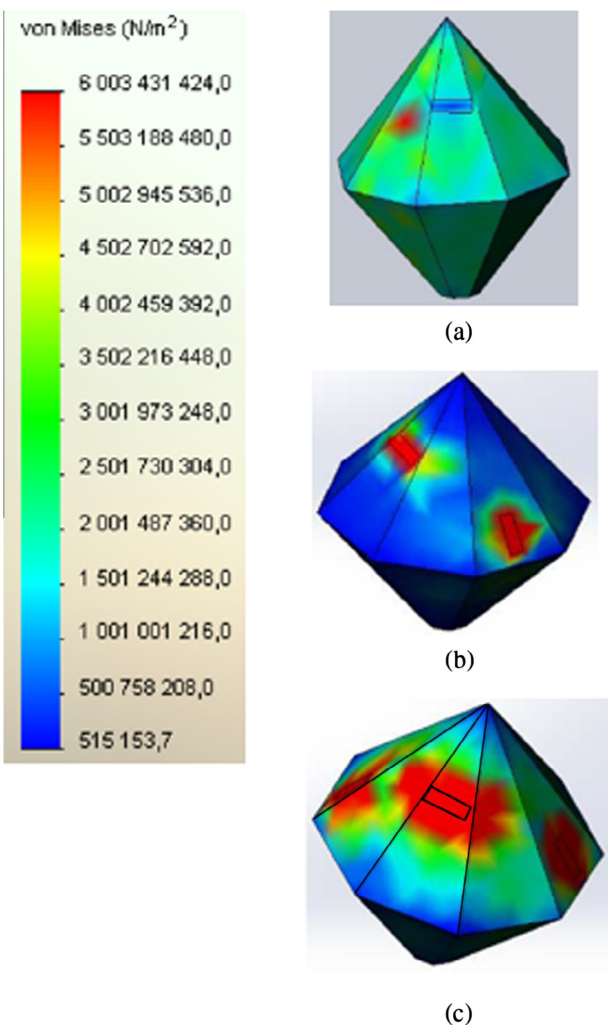


Fig. 2 Stresses in the diamond grain containing (a) one, (b) two and (c) three metallic phase inclusions, for sintering at 400 °C.

inclusions in the top part of the grain, the superposition of stresses can lead to the destruction of a significant amount of diamond grains.

Stresses that exceed the ultimate strength of diamond and are located on the borders of the metallic phase inclusions, cause the development of internal cracks in the grain. The increased values of stresses in the bond have an enhancing action on stresses in the grain; this conclusion is consistent with the low coefficient of efficient use of diamond grains reported in the relevant literature [3,4].

Effect of multiple parameters of the grinding wheel production

A large quantity of metallic inclusions in crystals reduces their strength and especially heat resistance. It is known that heating of the synthetic diamonds, starting from the temperature of 850 °C may lead to a decrease in their strength [21,22]. The reason for the rise in stresses with an increase in temperature is the structural heterogeneity of diamond grains and a substantial difference in the coefficient of thermal expansion (CTE) of diamond and metallic phases that cause the leading expansion of inclusions and the appearance of internal stresses in the grain.

Several model runs are performed for the investigation of the sintering process, and especially the influence of quantity of metallic phase, CTE of metallic phase, modulus of elasticity of bond and sintering temperature on the stresses within the diamond grain. These runs are based on a computer-aided design, i.e. a design generated from a computer algorithm and more specifically, D-optimal design of B4 type [23]. The intervals of values of the factors were chosen in order to cover all conditions of production of diamond-abrasive tools on metal bonds. The values of levels of the factors are listed in Table 2. Table 3 contains the conditions of the required 24 experiments along with the maximum tension in the diamond grains.

Fig. 3 shows the visualization of modeling results according to 24 models carried out. The visualization makes it possible to display in full measure the stresses occurring in the sintering zone when varying simultaneously the above mentioned four factors. Note that for the demonstrativeness of the stresses arising in the neighborhood of metallic phase, the bond is hidden. The results pertaining to CTE of metallic phase, modulus of elasticity of bond and sintering temperature are consistent with results reported in Refs. [16–22].

However, the work presented here, goes further in comparison with previous works, as it provides detailed data of the stress condition inside the synthetic diamond grain and proposes optimal conditions for the production of grinding wheels. More specifically, analysis of results of the planned experiments makes it possible to obtain a refined mathematical model describing the process of sintering of diamond grinding wheels in the presented range of variation of the independent factors:

$$\begin{aligned} Y = {} & 3.71 + 0.58X_1 + 0.18X_2 + 0.03X_3 + 0.31X_4 \\ & - 0.03X_1X_2 + 0.007X_1X_3 + 0.39X_1X_4 + 0.006X_2X_3 \\ & - 0.03X_2X_4 + 0.02X_3X_4 + 0.32X_1^2 + 0.28X_2^2 \\ & + 0.13X_3^2 + 0.12X_4^2 \end{aligned} \quad (1)$$

Table 2 Factors and levels of D-optimal design.

		−1	0	1
% of metallic phase	X1	6	8	10
CTE of metallic phase (1/K)	X2	1.32×10^{-5}	2.24×10^{-5}	3.16×10^{-5}
Modulus of elasticity of bond (GPa)	X3	102	153	204
Sintering temperature (°C)	X4	400	600	800

Table 3 Experimental design using D-optimal design type B4 and its response.

Number of model experiments	X1	X2	X3	X4	Tension in diamond grains (GPa)
1	1	1	1	1	5.74
2	−1	1	1	1	3.85
3	1	−1	1	1	5.49
4	−1	−1	1	1	3.65
5	1	1	−1	1	5.67
6	−1	1	−1	1	4.14
7	1	−1	−1	1	5.38
8	−1	−1	−1	1	3.42
9	1	1	1	−1	3.13
10	−1	1	1	−1	5.28
11	1	−1	1	−1	5.26
12	−1	−1	1	−1	2.53
13	1	1	−1	−1	8.99
14	−1	1	−1	−1	4.00
15	1	−1	−1	−1	6.48
16	−1	−1	−1	−1	3.50
17	1	0	0	0	6.67
18	−1	0	0	0	4.65
19	0	1	0	0	7.59
20	0	−1	0	0	6.06
21	0	0	1	0	5.51
22	0	0	−1	0	5.94
23	0	0	0	1	6.90
24	0	0	0	−1	4.58

Results and discussion

The dependencies of stresses arising in the grain-metallic phase-bond system on quantity of inclusions of metallic phase with the change in modulus of elasticity of bond, at sintering temperature 400 °C, are shown in Fig. 4. It is worth noting that for the examples of this graph the fracture criterion is 4 GPa. The table included in Fig. 4 shows the stresses for various quantities of metallic phase, for three different values of the modulus of elasticity of the bond.

Modeling results indicate that stress in diamond grain increases and can reach the critical value for the specific cases, with the increase in the quantity of metallic phase and with the increase in modulus of elasticity. From Fig. 4 it can be seen that diamond grains will fail during sintering of the wheel when they contain metallic phase more than 6.5 % and the modulus of elasticity of the bond is higher than 200 GPa. Fig. 5 shows the constructed two- and three-dimensional dependencies.

Optimization of the results showed that the optimum conditions for sintering of grinding wheels are the quantity of the metallic phase 7% and modulus of elasticity of bond 204 GPa, which corresponds to case number 12 of Fig. 3.

Fig. 6 shows the dependences of the stresses arising in the grain-metallic phase-bond system on the quantity of metallic phase with the change in sintering temperature. The table included in Fig. 6 shows the stresses for various quantities of metallic phase, for three different values of sintering temperature.

From the analysis of the results, it can be seen that both the temperature of sintering and the quantity of metallic phase make essential impact on the value of stress in diamond grains. However, as the percentage of metallic phase in diamond grains is strictly limited in a narrow range, i.e. 6% to 10 %, the main factor in order to control stress in diamond grains is the temperature of sintering which can vary from 200 °C up to 900 °C, for various bonds.

Conclusions

Carried out studies have shown that the sintering temperature of diamond-bearing layer has the greatest impact on the deflected mode of the grain-metallic phase-bond system regardless of the type of the bond. The increase of stresses in the grains is observed in areas of metal phase concentration. The large quantity of metal inclusions in the crystals reduces

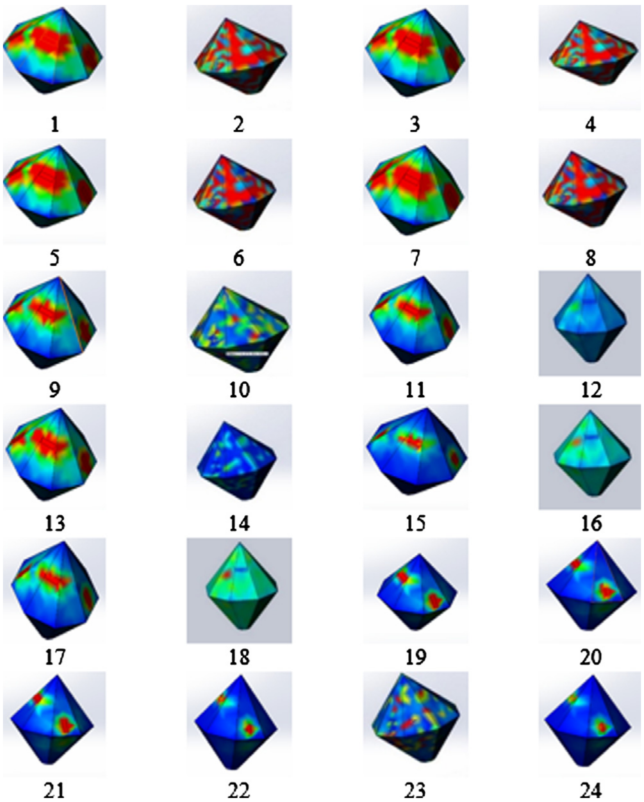


Fig. 3 Visualization of modeling results on the influence of factors on the deflected mode of sintering zone of diamond-bearing layer.

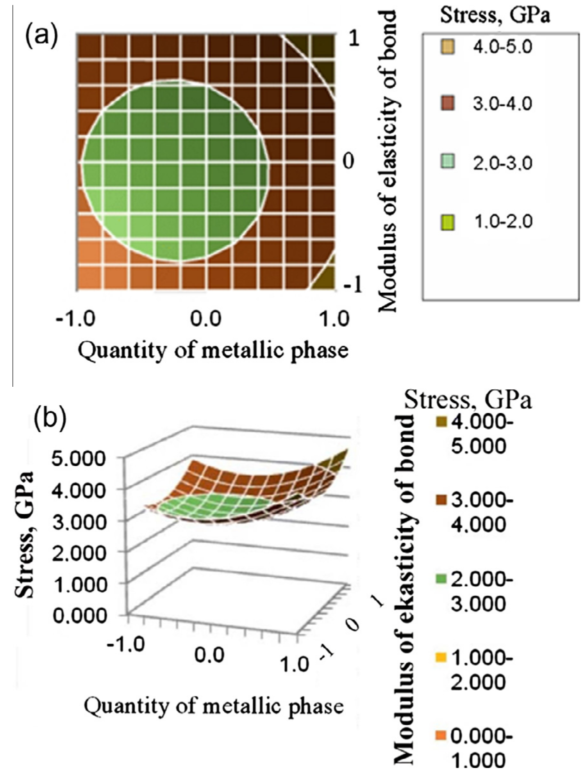
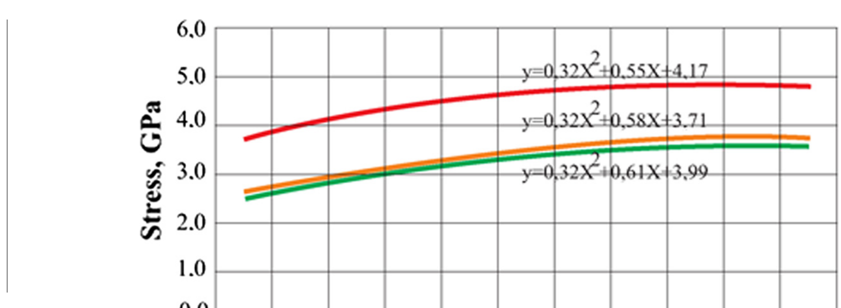


Fig. 5 (a) Two-dimensional and (b) three-dimensional dependences, reflecting the impact of the quantity of metallic phase and modulus of elasticity of bond on the deflected mode of the system.

their strength and especially heat resistance. It is determined that the heating of synthetic diamonds, beginning with the temperature of 750 °C, leads to a reduction in their strength.

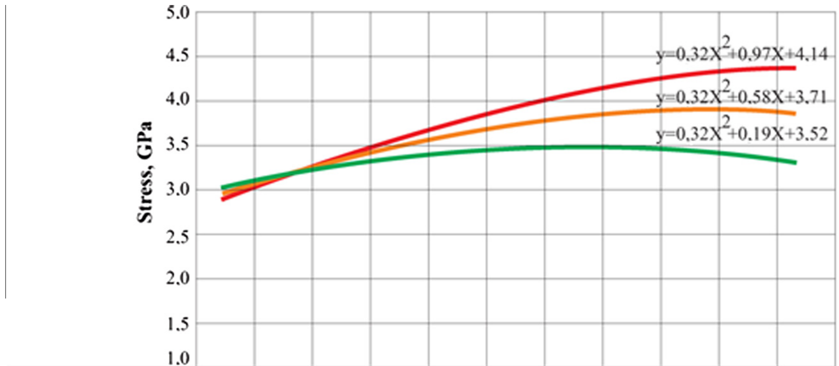
The cause of the cracking of a diamond grain is the different values of the coefficients of thermal expansion of metallic phase and the grain itself. Typically, the thermal expansion coefficient of the metal-catalyst is much higher than that of diamond. Therefore, when heating, the so-called diamond grain rupture from the inside takes place.

It is established that the smallest stresses are observed when using the metal bond with modulus of elasticity 204 GPa. The quantity of metallic phase in diamond grain should not exceed 7% and coefficient of thermal expansion should be no more



Modulus of Elasticity of bond (GPa)	Factor X1	-1.0	-0.8	-0.6	-0.4	-0.2	-0.0	0.2	0.4	0.6	0.8	1.0
	% of metallic phase	6	6.4	6.8	7.2	7.6	8	8.4	8.8	9.2	9.6	10
	204	3.712	3.944	4.151	4.331	4.486	4.615	4.719	4.797	4.849	4.875	4.876
	153	2.815	3.046	3.251	3.430	3.584	3.712	3.814	3.890	3.941	3.966	3.965
	102	2.666	2.895	3.099	3.277	3.429	3.555	3.656	3.731	3.781	3.804	3.802

Fig. 4 The dependence of stresses in the system on the quantity of metallic phase with the change in modulus of elasticity of bond.



Factor X1		-1.0	-0.8	-0.6	-0.4	-0.2	-0.0	0.2	0.4	0.6	0.8	1.0
% of metallic phase		6	6.4	6.8	7.2	7.6	8	8.4	8.8	9.2	9.6	10
Sintering Temperature (°C)	800	2.698	3.028	3.328	3.598	3.837	4.047	4.226	4.374	4.493	4.581	4.639
	600	2.815	3.066	3.287	3.478	3.638	3.769	3.868	3.938	3.977	3.987	3.965
	400	2.867	3.039	3.180	3.292	3.373	3.424	3.445	3.436	3.396	3.326	3.226

Fig. 6 The dependence of stresses in the system on the quantity of metallic phase with the change in sintering temperature.

than 1.32×10^{-5} 1/K. The results obtained indicate expediency of using diamond grains with the lowest possible content of metallic phase, predominant element in the structure of which should be a metal with a low coefficient of thermal expansion. This will significantly increase the coefficient of utilization of diamond grains and improve the efficiency of diamond grinding process.

It has to be noted that strains are also of interest when investigating grinding wheel, in the production stage of the wheel but more importantly in the operation of the wheel. In this paper the main focus is on the production procedure but a paper of similar modeling concept, considering metallic phase, production and operation parameters, where the stress and strain on the diamond grain are investigated under grinding conditions, simulating the actual process at grain level is under investigation.

Conflict of Interest

The authors have declared no conflict of interest.

Compliance with Ethics Requirements

This article does not contain any studies with human or animal subjects.

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