Rational Characteristics of the Diamond Grinding Wheels

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Abstract. The article presents theoretical studies using finite element modeling, which made it possible to determine the rational characteristics of diamond grinding wheels based on polymer and ceramic bonds. The effect of the parameters of the diamond-bearing layer on the change in the stress-strain state (SSS) of the diamond-bearing layer in the process of microcutting of hard alloys and superhard materials (SHM) has been studied. A scientific hypothesis was put forward and proved the need for an integrated approach when choosing the concentration and grain size of diamond in the diamond-bearing layer of the grinding wheel. Based on the limiting values of equivalent stress σeq in the grinding zone, it has been established that the concentration of grains in the working layer of the wheel must be selected, taking into account their grain size, as well as the group of the processed material. The data on the stress-strain state of the diamond-bearing layer during grinding of hard alloys and superhard materials were obtained by the calculation method using the analysis by the finite element method.

Keywords: Diamond grinding · Finite element · Concentration · Grain size · Superhard materials

1 Introduction

Traditional studies of diamond grinding processes are mainly based on costly and time-consuming experiments. Since the quality of the diamond-abrasive tool largely predetermines the efficiency of the diamond grinding process, then already at the stages of its design and manufacture, it is necessary to theoretically substantiate a rational choice of the structure and physical and mechanical properties of the components of the diamond-bearing layer. Doing this experimentally is very laborious and expensive. At the present stage of the development of computer technology and the appearance of a large number of software products based on the finite element method, it has become possible to increase the efficiency of such studies significantly. The use of computational methods to determine the rational characteristics of diamond wheels at the stage of their design and manufacture will significantly expand the technological capabilities of the diamond grinding process.

V. Tonkonogyi et al. (Eds.): InterPartner 2021, LNME, pp. 151–159, 2022.
https://doi.org/10.1007/978-3-030-91327-4_15

2 Literature Review

Along with the choice of the bond grade, grain, and grinding modes, the choice of the relative concentration of diamond grains and their grain size is of great importance [1–3]. A significant number of studies are devoted to studying the effect of concentration on the specific consumption of diamond, grinding performance, and roughness of the processed surface [4–8]. Most of the recommendations for choosing the concentration of diamond grains in polymer and ceramic bonds apply to the processing of carbide materials, high-speed steels, titanium alloys. Model studies carried out by the authors of [9] indicate that a complex choice of grain size and relative concentration of grains can lead to a significant reduction in stresses at the stage of sintering of the diamond layer. By the calculation method, it is possible to determine the stress-strain state of the diamond-bearing layer not only in the manufacture of diamond-abrasive tools but also at the stage of grinding various groups of materials [10].

Modeling the limiting stress values by the computer-aided design and the finite element method [11–13] will allow avoiding expensive experimental studies and, in the future, create a number of recommendations for a wide range of grinded materials.

The diamond content in the amount of 4.4 carats per 1 cm^3 of the diamond layer is taken as 100% concentration. The actual amount of diamonds in the diamond-bearing layer N_0 is determined not only by the concentration but also by the grain size [9]. So, for example, at a concentration of 100%, 1 cm^3 contains 1522 grains AC6 (State Standard of Ukraine **3292–95)** 63/50, 440 grains AC6 100/80, 68 grains AC6 200/160.

$$N_0 = 0,878K/(100\gamma_a V_z), \tag{1}$$

where: K – relative concentration of the diamonds, %; γ_a – diamond density, g/mm^3; V_z – average volume of one grain, mm^3.

It can be affirmed that the number of cutting edges that actually take part in the grinding process also changes along with the number of grains. Despite this, the existing recommendations are not differentiated for different grain sizes and are focused on the used bond type and operation. Most often, reference manuals indicate the recommended concentration of 100, 150% both in the processing of hard alloy as well as in the processing of SHM [14, 15].

This choice of concentration is explained by the fact that with an increase in the number of working grains, the heat removal from the grinding zone improves [16]. However, it remains unclear how, in wheels on polymer and ceramic bonds, the picture of heat removal changes with a change in the concentration of grains. Considering the structural features of the diamond-bearing layer of this type of wheel, there is a direct relationship between the volumetric content of diamond grains and a filler. Their ratio is constant, and with a decrease in the content of grains, the volumetric content of the filler in the bond increases [17, 18].

Based on the abovementioned, a hypothesis was put forward that it is possible to calculate the optimal ratio of the volumes of diamond grains and the filler in a polymer and ceramic bond using three-dimensional modeling. The choice of a rational concentration of diamond, depending on the grain size, will significantly reduce the number of prematurely destroyed grains and increase the durability of the diamond tool during its operation.

3 Research Methodology

The finite element method's modeling of the diamond grinding process was carried out according to the methodology [19, 20] on a specially supplemented three-dimensional model (Fig. 1). The diamond-bearing layer included the elements “grain” and “filler”, and their ratio varied depending on the chosen concentration.

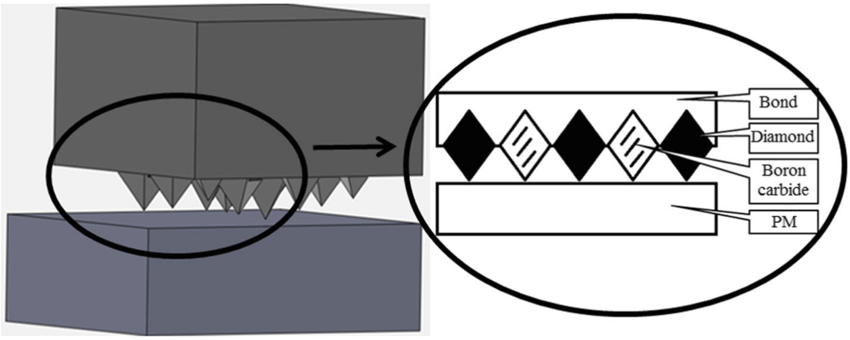

Fig. 1. 3D model of the system “bond–grain–filler–processed material (PM)”, developed to study the effect of grain concentration on the stress-strain state of the system.

As a diamond grain, the “grain” element of AC6 grade 63/50, 100/80, 200/160 was modeled, which contained the inclusion of a Co – Cr-based metal phase. The material to be processed was represented by a hard alloy of the T15K6 grade [11] and a superhard material (synthetic polycrystalline diamond carbonado) of the SPDC grade [6]. Modeling of the grinding process of T15K6 was carried out with the speed of movement of the element “bond–grain” equal to V_{wh} = 25 m/s. When processing the SPDC, the movement of the “bond–grain” element was carried out at a speed of V_{wh} = 30 m/s. The clamping pressure of the wheel was set by the normal load on the “bond–grain” element. When processing alloy T15K6, the normal pressure was 1 MPa, when processing superhard material SPDC – 2 MPa.

In the model study, the physical properties of the polymer bond corresponded to the B2–01 grade, and the K1–01 bond was considered as a ceramic-based bond. Boron carbide is a filler for such bonds [21]. When modeling the volume of diamond grains, the content of the filler was considered. When the proportion of the components was changed, the physical and mechanical property of a diamond or filler was assigned to a solid body in the form of an octahedron [22].

The physical and mechanical properties of the components of the diamond wheel are given in the table (Table 1).

Table 1. Accepted physical and mechanical properties of the modeled materials [23, 24].

Used properties	Bond					Boron carbide
	B2–01	B1–10	B1–13	K1–01	K2–01	
Mass density of the material ρ, g/cm^3	1.67	2.95	3.24	2.62	3.6	2.48
Hardness, HRB	50	53	54 ± 3	95	110	–
Ultimate compressive strength σ_{comp}, MPa	78 ± 10	136 ± 14	213.0	–	–	1800
Impact strength, kJ/m^2	1.0 ± 0.2	2.5 ± 0.3	2.0 ± 0.2	1.96	1.96	–
Ultimate tensile strength σ_{tens}, MPa	2.60	2.99	2.8	–	–	–
Thermal conductivity, W/m·K	0.55	2.09	2.01	1.4	1.4	11.5
Elastic modulus, GPa	20.3	20.8	16.2	63	63	296
TCLE α, $\times 10^{-6}$ K^{-1}	5.3	20.6	16.5	3.75	6.41	4.5

The physical characteristics of the filler were also incorporated into the model properties, which made it possible to realistically display the physical properties of the diamond-bearing layer [25].

4 Results

At the first stage of the research, the effect of the relative concentration on the stress-strain state of the "grain" and "bond" element during grinding of the T15K6 hard alloy was studied. The grain concentration in the model varied from 25% to 200%.

As the calculations shown, when modeling grain grade AC6 63/50 in a bond B2–01 (Fig. 2), the limiting value of σ_{eq} in the grain at the selected grinding modes slightly exceeded the permissible stress only in the range from 25 to 50%.

Thus, the stress σ_{eq} at 25 and 50% was 0.7 GPa and exceeded σ_p = 0.67 GPa only by 20%. With an increase in concentration to 75%, the σ_{eq} value increased to 0.74 GPa, and at the maximum relative concentration, the σ_{eq} value was 1.19 GPa.

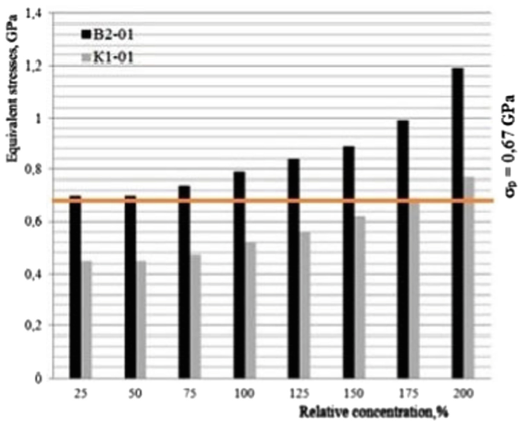

Fig. 2. Calculated limit values of σ_{eq} when grinding hard alloy T15K6. Bond grade – B2–01, K1–01; grain – AC6 63/50. Permissible value σ_p = 0.67 GPa.

The data are consistent with the theoretical calculation of the stress-strain state of the system when modeling the process of hot pressing of polymer bonds, where the calculated permissible concentration for diamonds of this grain size was also 50%. Considering the small mass of a single grain of this fraction and the average number of grains in 1 cm^3, the following can be assumed. At a 25–50% concentration in the diamond-bearing layer, there is an optimal ratio of diamond and filler. In this case, the composition's overall thermal conductivity and rigidity lead to minimizing stresses in the diamond. The calculation for the grade of the bond K1–01 and grain AC6 63/50 showed a similar range of the most effective concentration, which should not exceed 50%.

Comparing the values of the obtained stresses, it can be noted that when using a bond based on ceramics, the values of the excited stresses are ~1.5 times lower. Presumably, this dependence may be associated with the fact that a wheel on a polymer bond has a relatively low thermal conductivity (λ = 0.55 W/m·K), but a relatively high value of the thermal expansion coefficient $\alpha = 5.3 \times 10^{-6} \cdot K^{-1}$. Such a ratio of thermomechanical characteristics can lead to the "clamping" of the diamond grain, which leads to the formation of critical values of σ_{eq}. In addition, the elastic modulus of the ceramic bond is 3 times higher than that of the polymer bond, which is also reflected in the tensile and compressive loads of the diamond composition.

Further studies of the stress fields with a change in the grain concentration in the wheel on the B2–01 and K1–01 bonds showed that for the average fraction AC6 100/80 the range of the smallest values of σ_{eq} is achieved when modeling the relative concentration from 25 to 75% (Fig. 3, a).

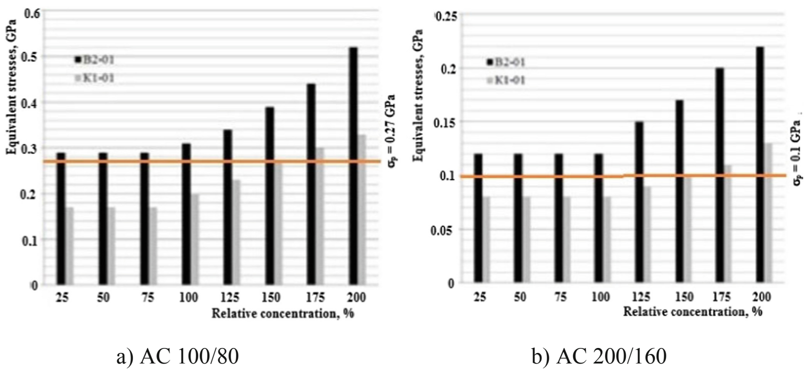

Fig. 3. Calculated limit values of σ_{eq} when grinding hard alloy T15K6. Bond grade – B2–01, K1–01. Permissible value a) σ_p = 0,27 GPa, b) σ_p = 0,1 GPa.

In this concentration range, the given values are minimal and do not exceed the value σ_{eq} = 0.29 GPa, and with a change in the concentration upward, it only increased. In the case of modeling, the concentration of 200% in the B2–01 bond σ_{eq} reached the value of 0.52 GPa, which is 1,9 times higher than the permissible value σ_p = 0.27 GPa. When grinding with grains of grade AC6 200/160, the range of permissible concentrations has expanded from 25 to 100%. When using a 125% concentration in the B2–01 bond, breaking stresses σ_{eq} of more than 1.5 GPa arose, and when the maximum concentration value of 200% was selected, σ_{eq} reached 0.22 GPa (Fig. 3, b). For a bond based on ceramics, the permissible concentration was in the range 25–100%, in which the value of σ_{eq} did not exceed 0.08 GPa.

Analysis of stress distribution in the system (Fig. 4) suggests that the probable reason for exceeding the permissible limit σ_p when choosing an increased concentration is a sharp change in the thermal conductivity of the diamond-bearing layer and especially the working surface of the wheel.

In the case of the value of the volumetric content of the filler, corresponding to the range from 43.75 to 25% of the volume of the diamond-bearing layer, the filler serves as a "separator" of diamond grains and prevents the imposition of temperature and contact stresses. With an increase in the concentration, and hence an increase in the volume of diamond grains contained in the wheel, which replace the filler material, an overlap of stress fields appears.

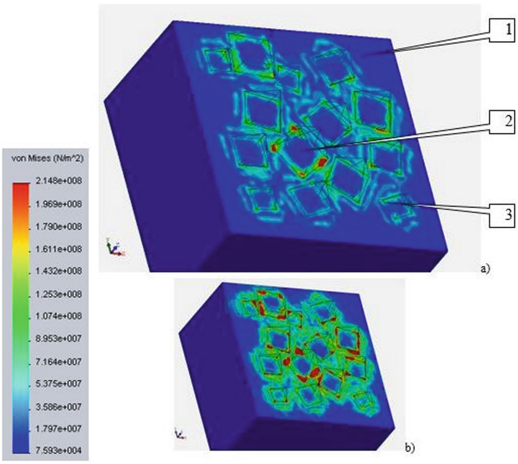

Fig. 4. Stress distribution in the cross-section of the 3D model "bond–grain–filler" when modeling the properties of the concentration: a) 50%; b) 200%; (1 – "bond" element, 2 – "grain" element, 3 – "filler" element); a) σeq = 0.12 GPa, b) σeq = 0.22 GPa; processed material – T15K6; bond – B2–01; grain – AC6 200/160.

At the second stage of the research, the effect of the relative concentration on the stress-strain state of the "grain" and "bond" element when grinding a superhard material of the SPDC grade was studied. Calculations have shown that when grinding superhard materials, a different range of permissible concentrations appears.

Modeling the dimensional and volumetric ratios of the diamond layer for the grain grade AC6 63/50 showed that when using polymer and ceramic bonds, it is possible to use concentrations up to 125%. For example, in wheels on the B2–01 bond, the calculated value of σ_{eq} = 0.34 GPa did not change in the range from 25 to 100% concentration. Only at a concentration of 150–200%, this value increased 1.2 times. A similar dependence was observed for the K1–01 bond based on silicate glass (Fig. 5, a).

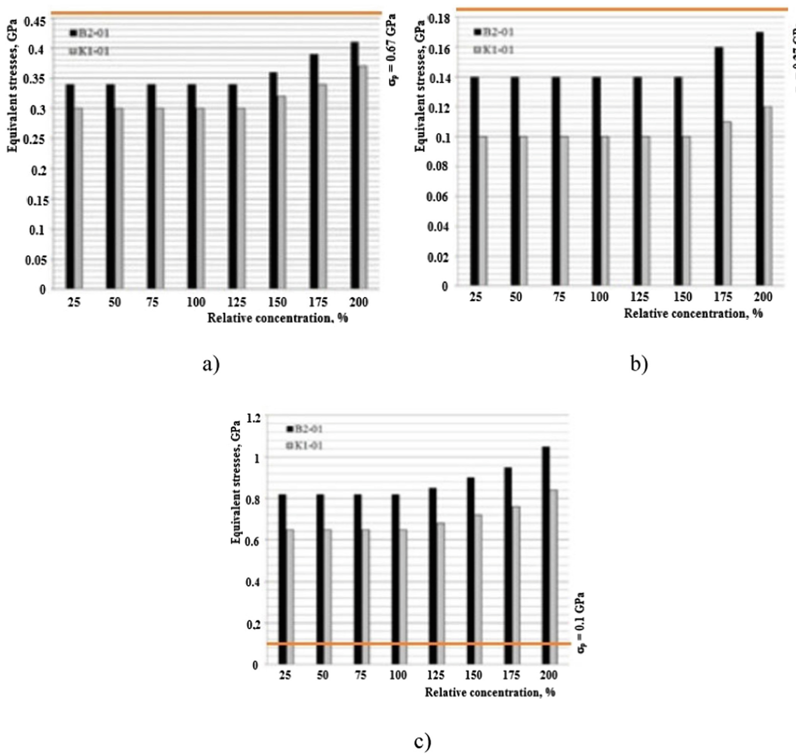

Fig. 5. Calculated limit values of σ_{eq} when grinding SPDC with wheels on polymer and ceramic bond. Permissable values: a) σ_p = 0.67 GPa; b) σ_p = 0.27 GPa; c) σ_p = 0.1 GPa.

In grinding with medium and coarse grains, a more comprehensive range of permissible concentrations was also observed. For AC6 100/80 grain (Fig. 5, b) in B2–01 bond, the limiting value increased only at a concentration of 150%, and in the case of 200% it was σ_{eq} = 0.41 GPa. Under similar conditions in a ceramic bond, the σ_{eq} value was 0.37 GPa. The use of larger grains allows the use of concentrations up to 150%. So, for the interval 25–150%, the value of σ_{eq} did not change and amounted to 0.14 GPa (for the B2–01 bond). As soon as the diamond content was increased to 175%, the stress in the system increased to 0.17 GPa. This value was critical in the case of the value of the maximum safe load (p = 0.1 GPa, which was critical (Fig. 5, c).

The thermal conductivity coefficient of SHM is 10 times higher than the thermal conductivity of the hard alloy, and it can be assumed that a significant part of the heat flux leaves the surface of the processed material. This phenomenon makes it possible to put into operation a more significant number of diamond grains in contact with the SPDC, and the resulting stresses in the grain contact area exceed the permissible values only at a concentration of 150–175%.

5 Conclusions

Thus, it can be argued that the decisive factor in maintaining the integrity of the diamond-bearing layer and the bond as a whole is a comprehensive choice of the concentration and grain size of the diamond grinding wheel. For the first time, the data on the stress-strain state of the diamond-bearing layer during grinding of hard alloys and superhard materials were obtained by the computational method using the analysis by the finite element method. For wheels based on polymer and ceramic bonds, the same tendency of stress changes in the system is observed with varying the relative concentration of diamond grains. Calculations have shown that when processing a hard alloy, the recommended range is a concentration of 25–50% for a grain size of less than 100/80, a concentration of 25–75% for a grain size of 100/80 to 160/125, and a concentration of 25–100% for grains of a coarse fraction 200/160 and more. If these values are exceeded, critical stresses appear in the system, which can prematurely destroy diamond grains. When processing superhard materials, an increased concentration of diamonds is allowed: a concentration of 25–100% for a grain size of less than 100/80, a concentration of 25–125% for a grain size of 100/80 to 160/125, and a concentration of 25–150% for grains of a coarse fraction 200/160 and more.

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