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Pycnometric-Additive Determining of the Degree of Coating of High-Strength Synthetic Diamond Grinding Powders using the Actual 3D Morphology of their Grains

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Abstract: The methodological components of direct and indirect analytical determining of the degree of coating of synthetic diamond grinding powders are analyzed. It has been established that the weight method most used in practice for determining this technological property of grinding powder is not universal for different methods of applying the coating. More universal in this regard, as the review of publications showed, is the well-known indirect-analytical method based on the pycnometric-additive approach. An improved variant of this method is proposed, aimed at application to high-strength synthetic diamond grinding powders. The method takes into account the peculiarities of the 3D morphology of the grains of such powders. Using the example of grinding powder AC300 500/400, the grains of which were coated with a solution of a mixture of boron oxide, sodium silicate, and titanium carbide, the advantages of using the proposed method are illustrated. The results of a comparison of determining the degree of coating by a known method and its improved variant are presented.

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1. INTRODUCTION

Coating is a common technological operation (procedure) in various industries. Numerous publications in various scientific and technical publications are devoted to the scientific and applied aspects of the coating. They emphasize (state) that the coating is an effective means of influencing the operational properties of products intended for use in mechanical engineering, in chemical and other industries, in the mining industry, and in abrasive tools. Among the main tasks of such influence is the protection of working surfaces from the action of external aggressive environments, mainly from corrosion [1-4], increasing the working life and reliability of parts of machines, devices and abrasive tools, [5-7], ensuring effective storage conditions and ease of use of medical products [8]. In the field of abrasive powders, which is the subject of this publication, coating is one of the effective methods of surface modification of grains of synthetic diamond (SD), cubic boron nitride, and powders of other superhard materials (SHM) [7, 9-12]. The main goal of such a technological operation is aimed at improving the efficiency of using an abrasive tool made using powders modified in this way.

An important characteristic of the coating is its thickness. In the case of abrasive powders, it significantly affects the retention strength of the grinding powder grains in the abrasive tool cutting layer, and hence also on the specific consumption of the abrasive powder. It is because of this that the specific consumption, as a characteristic of the processing process, is classified as one of the main criteria for the effectiveness of abrasive tool [7]. The thickness of the coating also affects the microhardness and crack resistance of the obtained modified surfaces, their structure [13, 14]. At the same time, the greatest positive effect of such a modification is quite often achieved only with the optimal coating thickness [15-18].

Another characteristic of such powders is closely related to the coating thickness of abrasive powders with a modified grain surface, as a sign of their quality, namely the degree of coating [9, 19-21]. Quite often, this technological property is used as an alternative to coating thickness when evaluating the quality of modified abrasive powders [21]. In addition, the degree of coating have an independent value, as an important methodical component of the indirect-analytical determining of the thickness of the coating. This is due to the fact that the degree of coating is included in the list of initial data required when determining the thickness of the coating by known indirect analytical methods [19, 20, 22-26].

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In applied studies, for example [9, 27, 28], the degree of coating (μ) is taken as the ratio of the mass of the coating material to the mass of the initial grinding powder, i.e.

$$\mu = \frac{m_c - m_{sd}}{m_a} \cdot 100 \ , \qquad (1)$$

where m_{sd}, m_c - respectively, the mass of the grinding powder of the initial and after applying the coating to the surface of grain. Note that such a weight method of determining the degree of coating is quite simple in terms of practical implementation. But it can be unconditionally applied only to certain coating methods, in particular to the electrochemical method, which, for example, is devoted to a monograph [27]. This is due to the a priori assumption regarding the fulfillment of the following two requirements. First, the mass increase of the modified grinding powder should occur only at the expense of the coating material, which fully and exclusively settles on the surface of its grains. Secondly, the process of applying the coating cannot be accompanied by a partial loss of mass of either the initial or modified grinding powders. However, in practice, when using other [24, 29-31] coating methods, the specified conditions are not always met. Such methods include, for example, liquid-phase formation of a coating from a solution of heat-resistant compounds and their mixtures [28, 31]. In the process of applying the coating in this way, in addition to the deposition of the coating material on the surface of the grains, its partial crystallization may also occur. In the process of applying the coating in this way, in addition to the deposition of the coating material on the surface of the grains, its partial crystallization may also occur. In particular, it occurs in the case of a saturated solution of a heat-resistant compound. At the same time, the specified increased concentration is desirable in practice, as it allows achieving a sufficient thickness of the grain coating. As our experience [28] shows, the size range of the crystals formed in this case is quite wide, and the size of some of them can be close to the size of the grains of the initial grinding powder. The second condition is not always fulfilled - that there is no loss of powder during its application. For example, such a technological loss of powder, as noted in [29], occurs when coating is applied by sputtering in a vacuum. It is due to the scattering of a certain mass of grinding powder, on which the coating is applied, outside the working area of the installation, where a similar technological procedure is carried out. This leads to a negative increase in the mass of coated grinding powder, which does not allow determining the degree of coating by the traditional weight method. Note that in the case of other known methods of applying coatings, specified in [29, 30], the possibility of such technological losses of powder is also not excluded. These circumstances make it difficult to reliably determine the mass of sanding powder grains with a coating applied to their surface. This is due either to an increase in the number of grains of the initial grinding powder due to the formed crystals of the coating material, or, on the contrary, to their irreversible loss.

Non-fulfillment to meet the above two requirements leads to the appearance of an error in determining the degree of coating, and with it - its thickness. To eliminate the mentioned shortcoming in the work [28], an indirect analytical method of determining the degree of coating of SHM grinding powders was proposed. It does not provide for weighing both initial and modified grinding powders, and therefore is free from the influence of the two factors mentioned above, which are the crystallization of the coating material and the possible scattering of individual grains from the technological area of coating application. The main idea of the proposed method is the transition in formula (1) from mass to volume. This is done by using the, known from physics fundamental pycnometric relation between the mass, volume and density of a solid body and the additive property of the volume itself. Taking this into account, formula (1) was transformed into the following form:

$$\mu = \frac{\rho_c}{\rho_{sd}} \left(\frac{V_{csd}}{V_{sd}} - 1 \right) \qquad (2)$$

where V_c, V_{sd} are the average values of the volumes of the sanding powder grain after applying a coating to the surface of its grain and without coating, respectively, μm^3; ρ_c, ρ_{sd} - density of coating material and SHM grain, respectively, g/cm^3. The volumes V_c, V_{sd} can be calculated based on the results of modern automated diagnostics (for example, using the DiaInspect.OSM device [32]) of the morphometric characteristics of the initial and modified grinding powders and based on the adopted 3D grain model. At the same time, an assumption is also made regarding the similarity of the spatial-geometric shape of the grains of the original and modified powders. In the future, we will call this proposed method pycnometric-additive.

To increase the reliability of indirect-analytical determining of the degree of coating, it is suggested in [28] to carry out a sieve separation of the initial and modified grinding powders with the selection of the main fraction of each of them. The main fraction of synthetic diamond grinding powder according to the Ukrainian standard DSTU 3292 [33] for synthetic diamond powders is from 70 to 80% (by mass). Therefore, it is possible to determine the degree of coating of abrasive powders precisely by this most representative fraction, which is also the most objective expression of the grain composition of the entire abrasive powder. It would be possible to sift out only the small fraction, leaving the main, additional to the main and large fraction. The general algorithm for implementing the method does not change, but the probability that crystals of the coating material will be present in the grinding powder sample obtained in this way increases. The above-mentioned separation of grinding powder can be carried out either by direct sieve separation, or by an indirect method using a computer sieve algorithm [34].

In our opinion, the second option is more effective. Further, a control sample of its grains is taken from the main fraction of the initial grinding powder selected as a result of sieve separation (direct or indirect). Are perform DiaInspect.OSM-diagnosis of morphometric characteristics (maximum and minimum Fere diameters, area and perimeter of grain projection, its height) of this sample, find the average values of the measured parameters. Then, in the same sequence and to the same extent, similar actions (procedures) are performed for grinding powder with a coating applied to its grains. An extrapolation-affinity 3D model of the spatial-geometric shape of the grinding powder grain of the initial and after applying the coating is taken. Well-known studies [22] have proven that the extrapolation-affinity 3D model [35] is the most adequate in terms of determining the average value of the grain volume of SHM powders. Based on this, the average values of the volumes of the grains of grinding powders of the initial and with a coating applied to the surface of its grains are found, and the degree of coating (μ) is calculated according to dependence (2).

The practical application of the pycnometric-additive method proposed in [28] involves replacing each grain of the sample with its extrapolation-affinity 3D model. And this is its essential advantage. But at the same time, such a replacement is carried out for each grain without exception. This applies both to grains of a far irregular (for example, fragmentary) shape, and to grains of clearly pronounced regular shape (for example, ideal regular polyhedra). This non-alternativeness regarding the use of other, different from the extrapolation-affinity, 3D grain models is a certain drawback of this known method. This deficiency is manifested, for example, in the case of diagnosing the degree of coating of high-strength SD grinding powders. Such grinding powders include of high-strength synthetic diamond grinding powders of the grades AC200, AC250, AC300, AC350, AC400 according to the Ukrainian standard [36], synthetic diamond grinding powders from Chinese manufacturers of generally standardized SMD grades for strength (in particular, HWD, HHD, ZND, HFD, etc.). These are also sanding synthetic diamond grinding powders of standardized grades SDB (ElementSix), MBS (General electrik), ISD (South Korea). The grains of such grinding powders are mainly in the shape of octahedra, cubooctahedrons, and truncated octahedra. A rather convincing justification of this fact with reference to well-known publications, in which you can find visual confirmation of such a 3D shape of the grains of high-strength SD grinding powders, was carried out in work [37]. Ibid is also noted that the relative share of grains of the specified shape in such grinding powders is 83-98%. From this follows an important conclusion that when determining the degree of coating of high-strength SD grinding powders, it is advisable to use the combined approach proposed for the first time in [37].

This task is the basis of the new approach proposed in this paper. This approach provides for the possibility of combined use within one calculation scheme of both the extrapolation-affinity 3D model of the grain and its actual (or exclusively actual) spatial shape. For high-strength grinding powders, SD is an octahedron, cubooctahedron, or truncated octahedron. The proposal to use the combined algorithmic scheme described above and the methodical approach based on it, as noted in [37], are completely new for the field of diagnosing the technological properties of synthetic diamond grinding powders, including the degree of their coating. The key to the successful implementation of the mentioned innovation is the availability of methodical means of automated identification and quantitative assessment of the shape similarity of the projection of grains of synthetic diamond grinding powders [38]. The practical application of the proposed innovation will allow obtaining more reliable information about the degree of coating of high-strength synthetic diamond grinding powders.

Another important innovation of our proposed method is as follows. Its use allows you to determine the degree of coating of high-strength synthetic diamond grinding powders in cases where losses of either the coating material or the initial grinding powder occur during the coating process. In the first case, not all the fixed coating material settles exclusively on the surface of the grinding powder grains, in the second case, the mass of the initial grinding powder decreases. In both cases, there will be an incorrect determination of the degree of coating by the known weight method. Eliminating such a methodological gap is the goal of this work.

2. GENERAL METHODOLOGICAL SCHEME FOR DETERMINING THE DEGREE OF COATING OF HIGH-COMPRESSION SYNTHETIC DIAMOND GRINDING POWDER USING THE IMPROVED PYCNOMETRICAL-ADDITIVE METHOD

Analytical analysis shows that the main factor affecting the reliability of the determined indicator of the degree of coating of an individual grain is mainly the accuracy of determining its volume. In turn, the accuracy of determining the volume is closely related to the spatial shape of the sanding powder grain. There are three options regarding the specified shape of grains: 1) all grains of grinding powder are bodies of irregular shape; 2) all grains of abrasive powder are bodies of the correct shape (for high-strength coarse-grained abrasive powders SD is an octahedron, cubooctahedron, truncated octahedron); 3) one part of the sanding powder grains has an irregular shape, the other part has the correct shape. With regard to high-strength SD grinding powders, the third option is the most realistic, which is confirmed, for example, by the data of [37]. In this case, grains of irregular shape, which make up a small proportion of the total number of powder grains, are the main source of negative influence on the reliability of determining the degree of coating. At the same time, the presence of grains of the correct shape in the sanding powder and taking this into account creates potential opportunities to reduce the mentioned negative impact. From this follows an important conclusion that when determining the degree of coating of high-strength SD grinding powders, it is advisable to use the combined approach proposed for the first time in [37]. This approach does not involve the total replacement of every single grain with an extrapolation-affinity 3D model. His innovative idea is that the algorithm for calculating the degree of coating should take into account the presence of both irregular and regular grains in the grinding powder. Known methods of determining technological properties do not provide for such flexibility. When they are used, as already noted, the real grain is completely replaced by its extrapolation-affinity 3D model, regardless of whether its actual spatial form is correct or not. The proposed approach implements the above-mentioned combined calculation scheme.

Note that an approach close to the combined approach proposed in this paper was used in [39] to determine the number of grains in one carat of coarse-grained SD grinding powders. In this work, the authors started from the cubooctahedron as the actual 3D shape of the grain. However, to calculate the indicator of this technological property, they suggest using not this actual shape of the grain, but its 3D models in the form of a sphere and a cube. At the same time, the criterion for choosing a 3D grain model from two possible versions is the orientation of lattices of crystals, which are the grains of coarse-grained, high-strength SD grinding powders. Thus, for crystals with a lattice orientation of 100, it is suggested to use a 3D model in the form of a cube, and for crystals with a lattice orientation of 111 - a sphere-shaped model. Such a transition from the actual 3D shape of the grain to its 3D models has a negative effect on the reliability of the calculation of the number of grains in one carat, since the cube and the sphere are not characteristic 3D shapes of the grains of the high-strength SD grinding powders. In addition, the authors do not stipulate how the orientation of lattices of crystals should be determined. Visual identification is not effective, automated is extremely difficult, if at all possible.

The proposal to use the combined calculation scheme (algorithm) proposed by us and the methodological approach based on it are new for the field of diagnosing the degree of coating of the SD grinding powders considered here. The key to the successful implementation of this innovation is the availability of modern technical means of automated diagnosis of the morphometric characteristics of abrasive powders. Another important guarantee is the mathematical and software tools created and available for use for automated identification and quantitative assessment of the shape similarity of the projection of SD grinding powder grains [38]. The general methodological scheme of the practical implementation of such fractional-averaging diagnostics of technological properties is outlined in [37] and involves a number of separate independent procedures. The first of them is automated diagnosis using modern technical means (for example, the DiaInspect.OSM device or another device similar to it in terms of purpose) of the morphometric characteristics of the grinding powder sample. The second stage is a quantitative analysis of the shape similarity of the projection of each grain of the control sample. This problem is solved by the search-analog method [38]. The third stage is the automated detection (recognition) of grains whose 3D shape coincides with octahedra, cubooctahedrons, or truncated octahedra in a control sample of high-strength synthetic diamond grinding powder. The fourth stage is the virtual division of the control sample of grains into four fractions according to the detected forms of the grain projection and individual morphometric characteristics (in particular, the relative share of the light part of the grain projection in its total area). At the same time, the number of grains in each of the selected fractions is fixed, the weighted average value of the grain volume for each such fraction is calculated, and the degree of grain coating is calculated. At the final stage, weighting factors are determined for each of the selected four fractions and a generalized indicator of the degree of coating of the entire powder as a whole is calculated according to this dependence

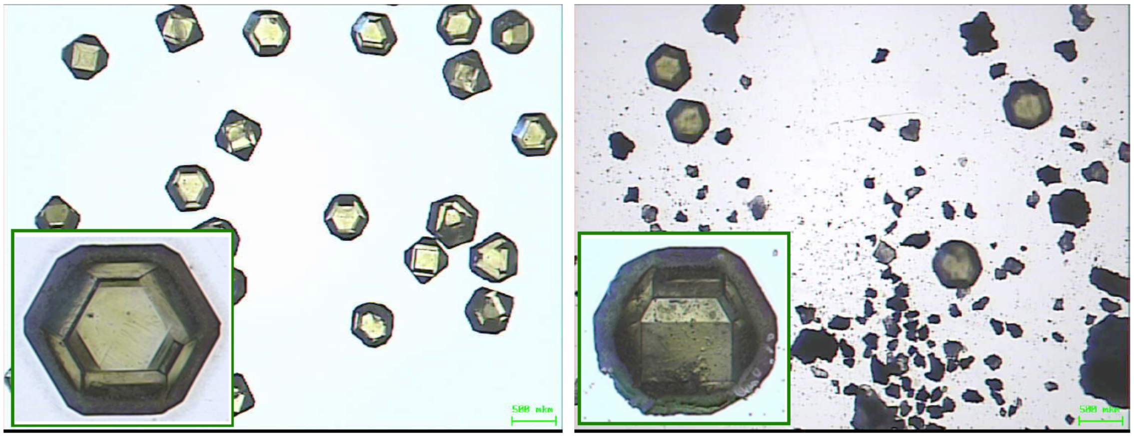
$$\mu = \mu_1 w_1 + \mu_2 w_2 + \mu_3 w_3 + \mu_4 w_4 \quad (3)$$

where μ_1, μ_2, μ_3, and μ_4 are indicators of the degree of coating of selected grinding powder fractions; w_1, w_2, w_3 and w_4 are weighting factors. They are taken as follows: $w_1 = N_1/N$, $w_2 = N_2/N$, $w_3 = N_3/N$, $w_4 = N_4/N$, where N_1, N_2, N_3 and N_4 are the number of grains found in each of the four selected fractions of grinding powder respectively; $N=N_1+N_2+N_3+N_4$ is the total number of grains in their control sample.

3. EXPERIMENTAL AND RESULTS

The application of the proposed methodical scheme will be carried out on the example of standard grinding powder AC300 500/400 according to [33, 36]. The coating was applied by the liquid-phase method from a saturated solution of a mixture of boron oxide, sodium silicate, and titanium carbide. In a porcelain cup, 10 g (50 carats) of grinding powder, 0.5 g each of titanium carbide, sodium silicate, soluble boron oxide, and 5 ml of water were placed. All substances were mixed. In a sand bath with a thermostat, heated to 5-99ºC, the substances in the cup were mixed until boron oxide dissolved. Heating was continued, grinding the mixture in a cup with a porcelain pestle, until drying and obtaining granules. The density of boron oxide was assumed equal to ρ_M = 1.85 g/cm^3, sodium silicate - ρ_M = 2.61 g/cm^3, titanium carbide - ρ_M = 3.21 g/cm^3, diamond - ρ_d = 3.51 g/cm^3. Other initial data included the necessary dimensional and geometrical parameters of the grains. They were obtained by diagnosing the morphometric characteristics of the initial powder using the DiaInspect.OSM device. DiaInspect-photographs of the grains of the control sample of the grains of the initial (without coating) and modified (with applied coating) grinding powders are shown in Figure **1**.

From the entire set of morphometric characteristics diagnosed by the DiaInspect.OSM device, the following are used as initial data: maximum (F_{max}) and minimum (F_{min}) Feret diameters, grain height (H), perimeter (L) and total area (A_t) of grains projection, relative share of the transparent part



(a) **(b)**

Figure 1: DiaInspect photographs of grains of a control sample of initial (uncoated, **a**) and modified (coated, **b**) grinding powders (in the green frame on the background of each photograph of modified grinding powders, DiaInspect photographs of a single (individual) grain are presented on an enlarged scale with a coating of the appropriate material applied to it).

of the grain projection in its total area (*Arealight*, A_{lg}), Feret elongation of the projection (F_{el}), roughness (Rg) and form factor (f_r) of the actual image of the grain projection. More complete information about the geometric meaning of these and other morphometric characteristics, which are diagnosed by the specified device, can be found in the scientific and technical literature [32, 35, 39].

Before applying the coating, sieve separation of the initial grinding powder was carried out. This procedure was carried out by the indirect method [34]. A control sample of 206 grains was taken from the selected main fraction of grinding powder. The DiaInspect.OSM device was used to diagnose the necessary later on morphometric characteristics of this grinding powder control sample. The obtained values of these characteristics were averaged over all grains of this sample. With the use of the obtained data, the automated identification of the geometric projection of the grains of the initial and modified grinding powders was carried out by the search-analog method [38]. The results of the automated identification and quantitative assessment by the search-analog method of the shape similarity of the projection of the grains of the initial grinding powder are presented in the Table **1**.

Quantitative analysis of those listed in the Table **1** the numerical data on the shape similarity of the grain projection of the control sample of high-strength SD grinding powder taken for the study shows that the relative share of projections in the form of a regular hexagon, semi-regular

Table 1: Indicators of Differential ($f_k^{(d)}$, %) Shape Similarity and Error of Shape Change ($\Delta_k^{(d)}$, %) of Projection of Grains of High-Strength Grinding Powder of Synthetic Diamond AC300 500/400 Initial and Modified (Main Fraction)

Basic forms of projection	AC300 500/400			
	initial		Modified (B_2O_3+Na_2SiO_3+TiC)	
	$f_k^{(d)}$, %	$\Delta_k^{(d)}$, %	$f_k^{(d)}$, %	$\Delta_k^{(d)}$, %
Oval-like figures	0.97	16.80	0.00	0.00
Rectangle	4.37	16.26	11.90	16.85
Rhomb	0.00	0.00	0.00	0.00
Isosceles trapezoid	0.00	0.00	0.00	0.00
Square	0.49	8.60	4.76	12.40
Regular pentagon	0.00	0.00	0.00	0.00
Regular hexagon	11.17	10.89	14.29	12.27
Regular octagon	0.97	4.25	2.38	6.31
Triangle	0.00	0.00	2.38	28.48
Parallelogram	0.00	0.00	0.00	0.00
Semiregular dodecagon	76.21	6.53	61.90	7.68
Semiregular octagon	5.83	6.21	2.38	5.33

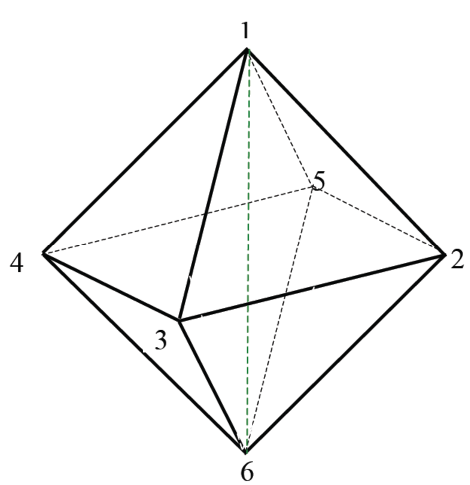
Table 2: Dimensional, Geometric Characteristics, Degree of Coating of Grinding Powder AC300 500/400 Initial (*I*) and after Applying a Coating (*II*) on the Surface of its Grains from a Solution of a Mixture of Boron Oxide, Sodium Silicate, and Titanium Carbide in Equal Proportions

The condition of the grinding powder and the number of grains in the sample, (pcs.)	Combined scheme of using analogues of 3D shape of grains: octahedron (1), cubooctahedron (2), truncated octahedron (3), extrapolation-affinity 3D model (4)					
	allocated fractions of grinding powder		average volume of grains, μm^3		degree of grain coating, μ, %	
	faction number	the number of grains	by factions	of all the powder	by factions	of all the powder
I (206 grains)	1	0	0	62992620	---	---
	2	1	80680860		---	
	3	203	62800580		---	
	4	2	73641000		---	
II (42 grains)	1	0	0	68499500		5,97%
	2	2	104185800		27,86	
	3	38	65160350		3,59	
	4	2	96257000		29,37	

octagon and dodecahedron, which are characteristic of the octahedron, cubooctahedron and truncated octahedron, is 92%. This ratio is consistent with the data of [37] and is a confirmation of the feasibility of using the proposed new method of determining the degree of coating of the specified grinding powders. Then automated detection (recognition) of grains whose 3D shape coincides with octahedra, cubooctahedrons, or truncated octahedra was carried out in a control sample of high-strength synthetic diamond grinding powder. At the final stage, a virtual division of the control sample of grains into four fractions was carried out according to the detected forms of grain projection and individual morphometric characteristics (in particular, according to the relative share of the light part of the grain projection in its total area).

Simultaneously with the shape similarity analysis, virtual separation of the initial grinding powder into the above-mentioned 4 fractions was carried out. The identified shape of the grain projection and the value of the relative share of the light portion of the grain projection in its total area were the criteria for the specified separation. The number of grains in each of the four fractions selected according to these criteria is presented in Table **2**.

The first fraction allocate grains that have a 3D shape of an octahedron (Figure **2a**). The projection of such grains always has the shape of a regular hexagon, and the theoretical value of the indicator of the relative share of the transparent portion of the projection in its total area is A_{lg} = 0.333. In automated recognition, 0.320≤ A_{lg} ≤0.364 was taken. The volume of each individual grain with such a 3D shape is expressed by the well-known formula, where d is the length of the edge of the octahedron. As the analytic-geometric analysis of the orthogonal projection of the octahedron (Figure **2b**) shows, d is expressed through F_{min} by the dependence: $d = F_{min}$. A similar procedure is performed for each grain of this fraction, followed by a summation of the obtained results. The number



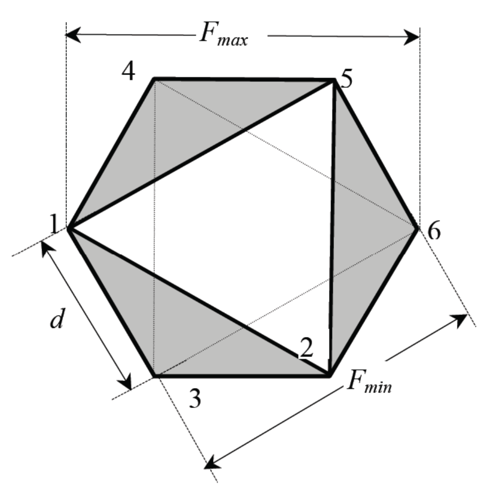


Figure 2: An octahedron as a 3D model of an abrasive powder grain (**a**) and its orthogonal projection in the form of a regular hexagon (**b**).

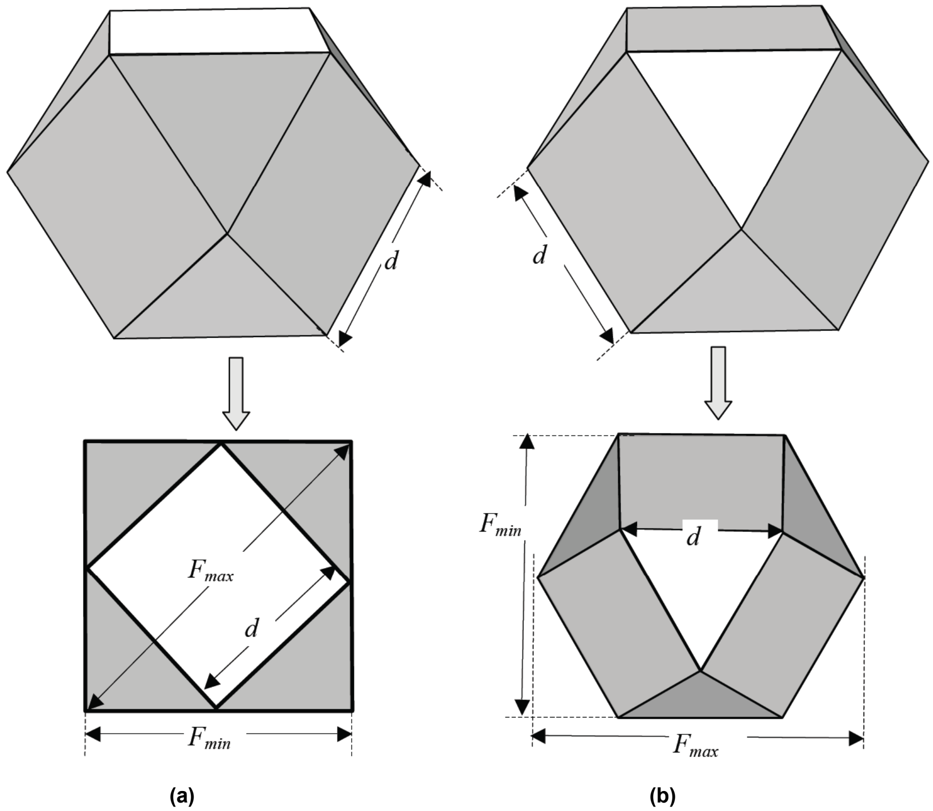


Figure 3: Cubooctahedron as a 3D model of an abrasive powder grain and its orthogonal projections (**a** - when positioned on a face in the shape of a square, the shape of the projection is a square; **b** - when positioned on a face in the shape of a regular triangle, the shape of the projection is a regular hexagon).

of grains that were assigned to this fraction also accumulates. Taking this into account, the average value of the grain volume of this fraction is determined, for which the designation v_{m1} is entered.

The second fraction allocate grains that have the 3D shape of a cubooctahedron (Figure **3a**). The projection of such grains has the shape of a regular hexagon with the theoretical value of the indicator of the relative fate of the transparent portion of the projection in its total area A_{lg} = 0.167 or a square with the theoretical value of the indicator of the relative fate of the transparent portion of the projection in its total area A_{lg} = 0.5. In automated recognition, 0.120≤ A_{lg} ≤0.240 was accepted in the first case and 0.470≤ A_{lg} ≤0.540 in the second. The volume of grains with such a 3D shape is expressed by the well-known formula, where d is the length of the edge of the cuboctahedron. As the analytic-geometric analysis of the orthogonal projection of the cubooctahedron (Figure **3b**) shows, d is expressed through F_{max} by the dependence: $d = 0.5F_{max}$ in both cases. A similar procedure is performed for each grain of this fraction, followed by a summation of the obtained results. The number of grains that were assigned to this fraction also accumulates. Taking this into account, the average value of the volume of grains of this fraction is determined, for which the designation v_{m2} is introduced.

The third fraction allocate grains that have the 3D shape of a truncated octahedron (Figure **4a**). The projection of such grains has the form of a semi-regular dodecahedron with the theoretical value of the indicator of the relative fate of the transparent portion of the projection in its total area A_{lg} = 0.375 or a semi-regular octagon with the theoretical value of the indicator of the relative fate of the transparent portion of the projection in its total area A_{lg} = 0.14286. In automated recognition, 0.350≤ A_{lg} ≤0.390 was accepted in the first case and 0.130≤ A_{lg} ≤0.318 in the second. The volume of grains with such a 3D shape is expressed by the well-known formula, where d is the length of the edge of the truncated octahedron. As the analytic-geometric analysis of the orthogonal projection of the truncated octahedron (Figure **4b**) shows, d is expressed through F_{min} as a dependence in the first case and - in the second case. A similar procedure is performed for each grain of this fraction, followed by a summation of the obtained results. The number of grains that were assigned to this fraction also accumulates. Taking this into account, the average value of the grain volume of this fraction is determined, for which the designation v_{m3} is introduced.

And finally, the fourth fraction is formed by the remaining grains, which have a projection shape different from the three 3D shapes mentioned above. The volume of the grains of this fraction is calculated using their extrapolation-affinity 3D model [35]. The number of grains that were assigned to this fraction also accumulates. Taking this into account, the

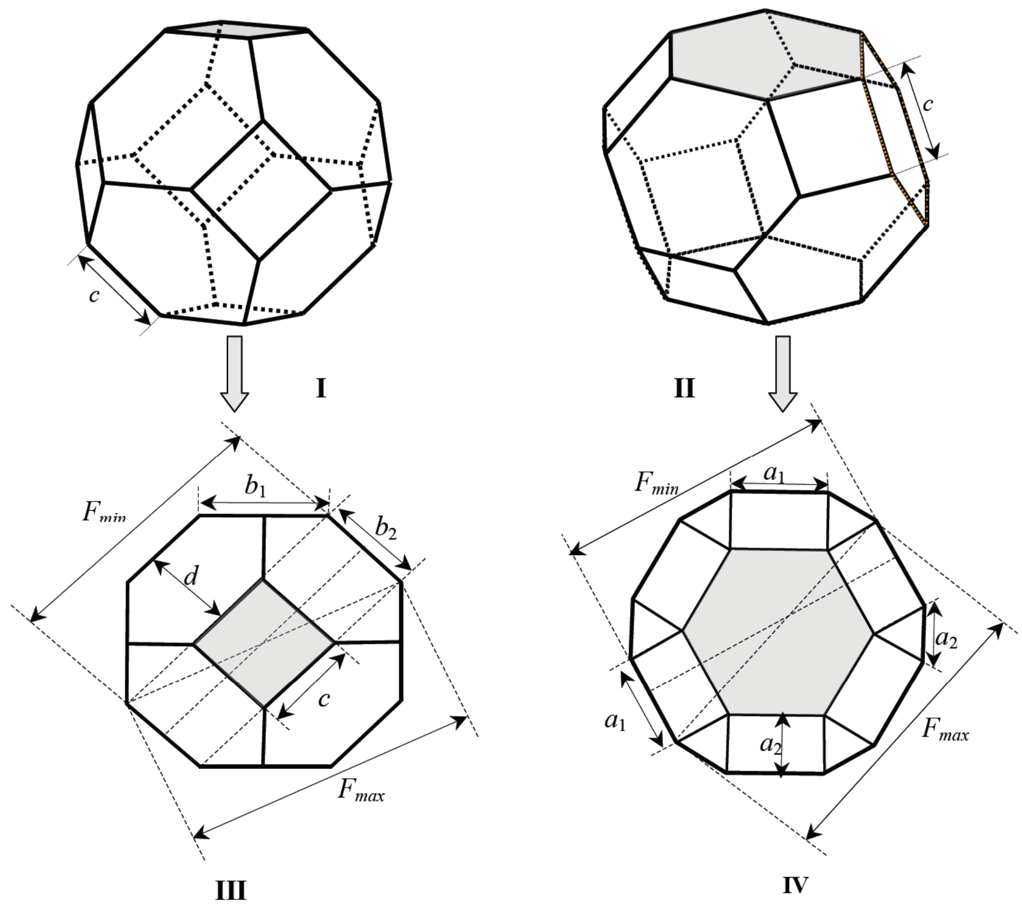


Figure 4: A truncated octahedron as a 3D model of an abrasive powder grain and its orthogonal projections (**I** - when positioned on a facet in the form of a square, the shape of the projection is a semi-regular octagon (**III**); **II** - when positioned on a facet in the form of a regular hexagon, the shape of the projection is a semi-regular duodenum (**IV**)).

average value of the grain volume of this fraction is determined, for which the designation v_{m4} is introduced.

The peculiarity of this allocate is that it is carried out at the level of allocate the results of diagnosing the morphometric characteristics of the control sample of grinding powder into four fractions. In the process of such allocate, four separate files of the results of the initial diagnosis of all grinding powder are formed, that is, a kind of virtual allocate of it is carried out. After completing these procedures, the average value of the grain volume of the initial grinding powder (V_{sd}) is determined by the method of finding the weighted average. At the same time, we proceeded from the volumes v_{m1}, v_{m2}, v_{m3}, v_{m4} and their corresponding weighting factors: $w_1 = N_1/N$, $w_2 = N_2/N$, $w_3 = N_3/N$, $w_4 = N_4/N$, where N_1, N_2, N_3 and N_4 - the number of grains found in each of the four selected fractions of grinding powder, respectively; N is the total number of grains in their control sample. For the initial grinding powder, it was 206 pieces.

Then, in the same order, all the above-mentioned procedures were performed for the modified grinding powder. The number of grains in the selected control sample was 42. According to a similar scheme and using the weighted average as a method of generalization, the average value of the volume of grains of the modified grinding powder (V_{sd}) was determined.

In the future, quantitative analysis of the degree of coating is performed separately for each of the selected four fractions of grains of modified grinding powder, followed by generalization of the results by the method of finding the weighted average. Based on this, the generalized indicator of the degree of coating of the grains of the entire powder as a whole is determined according to this dependence

$$\mu = \mu_1 n_1 + \mu_2 n_2 + \mu_3 n_3 + \mu_4 n_4 , \tag{4}$$

where μ_1, μ_2, μ_3 and μ_4 are indicators of the degree of coating of the selected fractions of the modified grinding powder; w_1, w_2, w_3, and w_4 are weighting factors. The results of the above complex calculations, including the indicator of the degree of coating, which turned out to be equal to 5.97%, are presented in the Table **2**.

The indicator of the degree of coating was also calculated using the pycnometric-additive method proposed in [28], that is, using exclusively the extrapolation-affinity 3D model of the grain. The average grain volume of the initial and modified grinding powders in this case turned out to be equal to

71250000 μm^3 and 75085000 μm^3, respectively. If we compare these values of the average grain volume of the initial and modified grinding powders with the values given in the table (the combined use of both the actual 3D shape of the grain and its extrapolation-affinity 3D model), then they are, respectively, in 1.13 (by 11.59 %) and 1.1 (8.77%) times higher. A similar tendency of the ratio between the actual grain volume and the volume calculated using its extrapolation-affinity 3D model was first discovered in the course of research conducted in [20]. In this work, a parallelepiped was used as a test actual 3D grain shape. The calculated indicator of the degree of coating by the pycnometric-additive method proposed in [28] that is, using exclusively the extrapolation-affinity 3D model of the grain, was 5.15%.

4. DISCUSSION

The conducted studies showed that in the control sample of high-strength synthetic diamond grinding powder adopted for our study, the relative share of projections in the form of a regular hexagon, semiregular octagon, and dodecahedron, which are characteristic of the octahedron, cubooctahedron and truncated octahedron, is 92%. This ratio is consistent with the data of work [37] and is a confirmation of the legality of using the proposed new method of determining the degree of coating of the specified grinding powders. At the same time, the indicator of the degree of coating was also calculated using the pycnometric-additive method proposed in [28]. It turned out to be equal to 5.15%. The comparison shows that its value is 13.74% less than that obtained by the method proposed here. This difference in results can be explained by the combined scheme of using analogues of 3D shape of grains. In the case of high-strength synthetic diamond grinding powders, such analogues are both the extrapolation-affinity 3D model of the grains and their actual 3D shape. This confirms the a priori expected advantage of the method proposed here. Another important conclusion is that the obtained result refers to the method of applying the coating, which does not allow to correctly determining the mass of the grinding powder modified in this way. In combination with the proposal of a combined scheme of using analogues of 3D shape of grains, this provides a significant advantage of the proposed method of determining the degree of coating with high-strength grinding powders of synthetic diamond and constitutes its scientific and methodological novelty.

In this context, it is worth making certain clarifications regarding the scope and methodological features of the application of our proposed new method for determining the degree of coating of high-strength synthetic diamond grinding powders. These clarifications concern, firstly, the objects on which the coating is applied, and secondly, the methods of its application. As for the coating objects, these are exclusively high-strength synthetic diamond grinding powders. According to the size (size) of the grains (up to 1000 μm), such powders can be interpreted as micro-objects. As for the methods of application, these are the methods that are accompanied by the loss of either the coating material or the initial grinding powder. In the first case, not all the fixed coating material settles exclusively on the surface of the grinding powder grains, in the second case, the mass of the initial grinding powder decreases. In both cases, there will be an incorrect determining of the degree of coating by the known weight method. Such potentially wasteful methods include coating by such advanced methods as PVD and CVD. Therefore, the proposed method can be applied to such methods of coating diamond powders. However, in this case, to diagnose the morphometric characteristics of the initial and modified grinding powders, it is necessary to use devices equipped with more powerful microscopes, for example, electronic ones. We used the DiaInspect.OSM device for this purpose, which is equipped with a Nikon ECLIPSE E200 (Japan) optical microscope and a digital video camera JVG (Japan). The need to use electron microscopes is due to the fact that PVD and CVD application methods form thin-layer coatings.

Regarding wear-resistant coatings, protective coatings against corrosion, optical protective coatings, they were not the subject of research in our work. Compared to grains of grinding powders, such objects can be interpreted as macro-objects. Therefore, we did not study and analyze the relevance of determining the degree of coating of such objects. This can be the subject of a separate study and corresponding publication.

5. CONCLUSIONS

A new methodical scheme for indirect-analytical determination of the degree of coating of grains of high-strength synthetic diamond grinding powders has been developed. The practical application of the new methodical scheme allows obtaining more reliable values of the degree of coating. In the case considered in the article, this increase in reliability amounted to 13.74% in comparison with the methodological scheme used in the known method.

An original in meaning and easy-to-use method of indirect-analytical automated identification of the actual 3D shape of grains of high-strength synthetic diamond grinding powders is proposed. The main idea of this method is based on the use of the geometric shape of the grain projection and individual morphometric specific characteristics of the projection, in particular the relative share of the light part of the grain projection in its total area.

The expediency of the combined use in one session of calculating the degree of coating of high-strength synthetic diamond grinding powders of both the actual 3D shape of the grains and their extrapolation-affinity 3D model is substantiated. Thanks to this, an 8.77-11.59% increase in the accuracy of determining the average grain volume of the initial and modified grinding powders, and with it, the accuracy of determining the degree of coating is achieved.

Such an innovation provides a significant advantage of the proposed method of determining the degree of coating of high-strength synthetic diamond grinding powders and constitutes its scientific and methodological novelty.

AUTHOR CONTRIBUTIONS

The manuscript was written through the contributions of all authors. All authors have approved the final version of the manuscript.

HIGHLIGHTS

- Indirect-analytical automated identification of the actual 3D grain shape of high-strength synthetic diamond grinding powders.
- Combined use in one session of calculation of the degree of coating of high-strength synthetic diamond grinding powders of actual 3D shape of the grains and their extrapolation-affinity 3D model.
- 13.7% increase in the reliability of determining the degree of grain coating of high-strength synthetic diamond grinding powders.

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