Stability evaluation of cutting edges during operation of composite materials for instrumental purposes based on a metal matrix

A A Fedotov¹, M N Safonova¹ and A S Syromiatnikova²

¹ North-Eastern Federal University, Institute of Engineering & Technology, Applied mechanics Department, Kulakovsky, str, 50, Yakutsk 677000, Russian Federation
² V P Larionov Institute of the Physical-Technical Problems of the North of the Siberian Branch of the RAS, Department of Mechanics and Safety of Structures, Oktyabrskaya STR, 1, Yakutsk 677000, Russian Federation

E-mail: fedot_andrey@mail.ru

Abstract. The development of new, highly informative methodological tools for diagnosing the characteristics and assessing the quality of diamond powders and powders of other superhard materials based on modern technical means of obtaining initial data is an important and relevant scientific and applied task. The direct practical use of diamond powders is preceded by a procedure for establishing the values of their operational properties and characteristics. The results of assessing the stability of the cutting edges of abrasive composite materials are equally important for both powder producers and their consumers. The productiveness of grinding tools is largely dependent on the degree of use of the cutting properties of the grains. Premature loss of grains from the bundle leads to increased wear, and sometimes to a complete loss of tool performance.

1. Introduction

The performance evaluation of grinding tools is carried out by the value of the specific diamond consumption (weighing or counting the number of grains dropped), by measuring the linear and mass wear of the tool, productivity and roughness of the treated surface, which is a very time-consuming and costly procedure. However, it is known that grinding performance and processing quality substantially depend on the stability of the cutting properties of the tool, i.e. stability of the number of active diamond grains during its operation. The stability of the tool is an indicator characterizing the constancy of the cutting properties of a diamond abrasive wheel. Therefore, when developing abrasive composite materials, it is especially important to determine the change in the number of active diamond grains during friction and wear.

Most researchers determine the number of active (cutting) grains by various experimental methods. When deriving an equation for calculating the number of grains on the surface of sintering tools, one of the main characteristics is their shape. The actual shape of the grain differs from the indicated models and depends on the brand of diamonds.

All the described methods for calculating the number of grains are not universal; they are developed for special cases of research, taking into account the peculiarities of manufacturing the objects under consideration [1-8]. Existing calculation methods make it possible to calculate the initial volumetric
concentration of diamond grains in a bond; however, they do not allow determining its change during the operation of the tool.

The content of grains in the working layer is an important characteristic of a diamond tool, significantly affecting its cutting properties, durability and service life, as well as the forces and temperature that arise during the cutting process.

2. Methods
The object of study is a standard bond - tin bronze M2-01 (20 wt. % Tin, 80% copper) with additives from 0-4 wt. % ultrafine natural diamond.

Samples (cylindrical - with a height and a diameter of 1 cm) were made by powder metallurgy by sintering in vacuum (0.1 ∙ 10^{-3} Pa) in an SNVE furnace. Joint sintering ensured the constancy of the process conditions for a given batch of samples. It was empirically determined that the optimal temperature is 700 ºС. The sintering time was 60 minutes.

The calculation and experimental method used to determine the number of active abrasive grains with a statistically uniform distribution in the volume of composite material that was developed in [9] was used. When developing the method, we proceeded from the assumption that abrasive grains are a collection of particles of arbitrary shape and different dispersion, distributed in the bulk of the material statistically uniformly with a random spatial orientation.

It is important to use the shape of abrasive grains as the base model when modeling grinding processes. There are various views on the choice of such models: in the form of a cone with a rounded top, a ball, an ellipsoid of revolution, a cylinder, a cube in the scientific literature. Various models were compared and regulated according to the degree of approximation to the experimental data [10] given these differences.

In a number of cases, the grain located on the plane is located so that the dimensions visible in the plan and taken as the length and width are smaller than the third size, conventionally called the height and visible on the second projection. Therefore, to select a geometric model of the shape of a real diamond grain, it is necessary to most accurately determine the linear dimensions of the grain from volumetric measurements in two projections.

The dimensional characteristics of grains necessary for simulating the control sieve screening procedures were determined from two projections obtained using a SEM XL-20 scanning electron microscope (Philips) in the secondary electron mode. Measurement of the length and width of the projection of grains, their heights were made according to SEM images (figure 1).

![Figure 1. SEM images of grains of diamond grinding powders for modeling grains in two projections.](image-url)
As is known, the shape coefficient $K\phi$ of an individual grain is defined as the ratio of the length of its projection to its width. The isometricity of grains (in percent), following the method of GOST 9206-80 “Diamond powders. Technical specifications” was determined by the formula:

$$u = \frac{u_1}{n} \cdot 100$$ (1)

where $u_1$ is the number of isometric grains, $n$ is the number of measured grains. The number of isometric grains $u_1$ was calculated by calculating the shape coefficient. Grain is considered isometric, the coefficient of form $K\phi$ of which does not exceed 1.3. The thus obtained isometric values of the grains of the powders under study are shown in table 1.

**Table 1. Experimental and calculated data for the selection of a model of diamond grains.**

| Grinding powder (μm) | Rectangular box | ellipsoid | spheroid | cube | octahedron | Isometricity, % |
|----------------------|-----------------|-----------|---------|------|-----------|----------------|
| by GOST              |                 |           |         |      |           |                |
| 50/40                | 0.161           | 0.071     | 0.094   | 0.136| 0.082     | 57.62          |
| 63/50                | 0.178           | 0.081     | 0.121   | 0.143| 0.135     | 56.13          |
| 80/63                | 0.167           | 0.093     | 0.137   | 0.162| 0.114     | 52.14          |
| 100/80               | 0.189           | 0.114     | 0.172   | 0.172| 0.134     | 49.12          |
| 125/100              | 0.183           | 0.27      | 0.163   | 0.191| 0.154     | 55.66          |
| 160/125              | 0.212           | 0.179     | 0.239   | 0.156| 0.167     | 54.31          |
| 200/160              | 0.203           | 0.164     | 0.137   | 0.163| 0.173     | 64.34          |
| 250/200              | 0.251           | 0.189     | 0.275   | 0.196| 0.184     | 59.49          |
| 315/250              | 0.243           | 0.176     | 0.232   | 0.218| 0.187     | 51.37          |
| 400/315              | 0.256           | 0.181     | 0.253   | 0.193| 0.198     | 57.18          |
| 500/400              | 0.269           | 0.193     | 0.271   | 0.237| 0.197     | 61.26          |
| 630/500              | 0.278           | 0.198     | 0.287   | 0.218| 0.181     | 64.23          |

To select a model of the shape of a real diamond grain, it is necessary to most accurately determine the linear dimensions of the grain by volumetric measurements in two projections; according to the results of studies, it is recommended to take an ellipsoid as the base model.

**2.1. Method for determining the relative solids content in biphasic alloys**
Along with methods for calculating the quantity and size distribution of micro particles, there is a point analysis method that does not require geometric modeling of particles and the derivation of the statistical law, and which can be used to establish the volume fraction of the second phase.

The method of point analysis is based on the fact that the proportion of points randomly printed on the micrograph that fall on the images of the phase under study is equal to the volume fraction (or area fraction) of this phase. In order for this principle to be fulfilled, points must be applied randomly to the micrograph. The volume fraction of phase $\alpha$ is given by the fraction of points that fell on the areas occupied by the studied phase.

In practice, it is usually inconvenient to deal with a random set of points and you can use an ordered point system. Figure 2 shows the application of the method of point analysis to determine the volume fraction of the solid phase (diamond particles) in the volume of the composite based on tin bronze (M1) and the study of their changes during friction and wear.

It is assumed that the microstructural components are distributed randomly. This assumption is mainly satisfied for most ordinary microstructures, but it must be remembered in cases where a completely regular arrangement of structural components is observed.
It is very important that the distance between the nodal points in a rectangular grid is large compared to the dimensions of the studied structural components. If this distance is very small, then the condition for the chaotic arrangement of the components is not satisfied, and, therefore, the error in determining the phase volume fraction can significantly increase and become larger than the expected value. In this case, the calculation of the volume fraction of the phase will strongly depend on the location of the point system with respect to the individual particles of the second phase.

Figure 2. The friction surface of composite materials based on M1 is grinding powders from natural diamonds 315/250 microns.

3. Results and Discussion

The isometric values of the grains of the studied powders are shown in table 2.

| Grinding powder | Grain, μm | Geometric model of grain | Isometricity, % |
|-----------------|-----------|--------------------------|----------------|
|                 | By GOST   | Rectangular box | ellipsoid | spheroid | cube | octahedron |
| ND I            | 50/40     | 0.18        | 0.11      | 0.12      | 0.123 | 0.13       | 26.3 |
| ND II           | 80/63     | 0.13        | 0.14      | 0.17      | 0.12  | 0.14       | 41.81 |
| ND III          | 125/100   | 0.21        | 0.19      | 0.23      | 0.156 | 0.17       | 49.3 |
| ND IV           | 315/250   | 0.25        | 0.19      | 0.27      | 0.19  | 0.18       | 39.5 |

A visual examination of SEM-images of diamond grinding powders grains showed that the synthetic diamonds grains have a rounded shape, and natural diamonds grains are mainly lamellar and needle-shaped, there are crystals with a clear cut and sharp edges. The variational range of values is wider, the frequency is lower, and its modal value lies in the range of values of the shape factor greater than 1.3 for natural diamond powders. The consequence of this is a significant difference in the isometricity of the grains.

The method developed in [9] was used to calculate the concentration of diamond grains on the working surfaces of samples based on the M1 metal binder with 6% by weight of natural diamond powders with a grain size of 315/250 μm in the initial state and after testing on a friction machine (figure 3). The principle of operation of the machine is the abrasion of a pair of test samples pressed against each other by force P.

The calculation of the number of particles of the k-th size group \( N_k \) was carried out according to the formula obtained using the probability distribution \( F_i \) for cubic particles [9]:
\( N_k = 1 / H_k \{ 2,433 n_{k:1} - 0.971 n_{k:2} - 0.270 n_{k:3} - 0.097 n_{k:4} - 0.044 n_{k:5} - 0.019 n_{k:6} - 0.012 n_{k:7}\) - \\
0.007 n_{k:8} - 0.007 n_{k:9} \} \),

where \( H_k = 1.5 h \) - average cube height if \( h \) is the cube edge (\( h \) was defined as the half-sum of the sides of the rectangle described around the projection of a random grain section [11]).

\[ \text{Figure 3. Friction surfaces of composite materials M1 – grinding powders from natural diamonds 315/250 microns.} \]

The relative change in the number of active grains in the binder during friction and wear \( C = (n_0 - n_e) / n_0 \) x 100% characterizes the stability of the number of active grains in the binder.

Figure 4 shows the size distribution of diamond particles in the metal matrix of the studied tin bronze composite materials with 6% by weight of natural diamond grinding powders with a grain size of 315/250 microns.

\[ \text{Figure 4. The size distribution of diamond particles in the composite on the working surface in the initial state and after a wear test with 6\% by weight of natural diamond grinding powders with a grain size of 315/250 microns.} \]

The volume fraction \( p_\alpha \) of phase \( \alpha \) is determined from the expression:

\[ p_\alpha = n_\alpha / n \]

where \( n_\alpha \) –the number of points located on the phase \( \alpha \), \( n \) – total number of points plotted on the microstructure image.

The standard deviation of the volume fraction depending on the number of points used in the analysis:

\[ \sigma_{p_\alpha} = \left[ p_\alpha (1 - p_\alpha) / n \right]^{1/2} \].

5
This expression is also valid for the analysis of microstructures containing more than two phases. The results of determining the volume fraction of the solid phase (diamond particles) based on a metal binder (M1) are presented in Table 3.

Table 3. Determination of the volume fraction of the solid phase (diamond particles) in the composite based on the metal bond (M1).

| Sample                 | \( n \) | \( n_α \) | \( p_α \) | \( σ_{pα} \) |
|------------------------|---------|-----------|----------|-------------|
| Sample with 315/250 before testing | 59      | 15        | 0.294237 | 0.056688367 |
| Sample with 315/250 after testing   | 36      | 8         | 0.21223  | 0.069289952 |

The method of point analysis, which does not require geometric modeling of particles and the derivation of the distribution law, which is used to establish the volume fraction of the solid phase, can be used as an indirect express method for determining the health of composite materials with superhard materials powders fillers.

4. Conclusions
The results of the studies showed that when testing the samples for friction and wear, the number of active abrasive grains and the relative solids content of grinding powders from natural diamonds with a grain size of 315/250 µm show the stability of the cutting edges in the self-sharpening mode in a metal matrix based on tin bronze.

References
[1] Novikov N V and Bogatyreva G P 2008 Superhard Materials 2 3
[2] Petasyuk G A and Sirota Yu V 2012 Superhard Materials 6 70
[3] Petasyuk G A 2010 Superhard Materials 2 80
[4] Duxiang W, Pequi G, Lei Z and Zhenjie Z 2012 Applied Mechanics and Materials 474 229
[5] Lis J, Vollstaedt H and Frenzel J 2008 5th Zhengzhou Int. Superhard Materials and Related Products Conf. Retrieved from: http://www.vdiament.de/EN/files/particles-per-carat.pdf
[6] Engels A 2003 Industrial Diamond Review 63(2) 39
[7] Lavrenenko V I, Bogatyreva G P, Il’inskaya G D, Petasyuk G A and Smokvina V V 2011 Rock-cutting and metalworking tools - equipment and technology for its manufacture and use 15 484
[8] Zhuo Z, Xia S, Bai Q and Zhou B 2018 Journal of Materials Science 53(4) 2844
[9] Safonova M N, Syromyatnikova A S and Shitz Yu 2007 Friction and wear 5 84
[10] Safonova M N, Petasyuk G A and Syromyatnikova A S 2013 Computer-analytical methods for diagnosing the operational characteristics of diamond powders and composite materials based on them (Novosibirsk: Publ. House of the Siberian Branch of the Russian Academy of Sciences)