Products Investigation of Contact Interaction of Diamond and a Matrix of Diamond-Metal Composites

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Abstract. Since the strength of the filler-matrix boundaries largely determines the properties of composite materials, the study of the interaction between the filler and the matrix is an urgent task for the development of high-performance composites. The purpose of this work is to study the products of contact interaction between the diamond and the matrix material of wear-resistant diamond-metal composites obtained by explosive pressing with subsequent heat treatment. Composites structure: natural diamond powder in a two-component iron-carbon matrix. Structural and phase studies of the diamond-matrix interface were performed using optical microscopy, scanning electron microscopy, and x-ray analysis. It is revealed that a significant factor contributing to the improvement of the performance properties of experimental diamond composites is the formation of a boron-carbide phase at the interfacial boundary with high values of strength and wear resistance. The scientific novelty of the work is due to the fact that the problems connected with a formation and a state of matrix-filler zones of various composite materials are one of the main ones in the field of fundamental research of the crystalline multiphase state of matter. The obtained data can be used in the engineering practice in the development of new composite materials.

1. Introduction

The current state of theoretical and experimental research in the field of improving the properties of diamond-containing composite materials by creating strong chemical bonds between a matrix and diamond is characterized as a stage of intensive study of various factors that determine the products nature and morphology of the interaction between them, the laws of their influence on diamond retention and wear resistance when using various synthesis methods [1-5]. The method of explosive pressing provides unique opportunities for obtaining tool diamond composites that cannot be provided by traditional methods of powder metallurgy [1]. In particular, the short duration of exposure to high temperatures and pressures allows avoiding graphitization of a diamond component [5-8] which negatively affects diamond retention. Thus, in [9-11] it was noted that the presence of graphite lamellar precipitations in the microstructure of the transition zone "diamond-matrix" is the main cause of premature destruction of diamond materials by the mechanism of intense cracking and loss of diamond grains from the metal binder. In [12], it is shown that the graphitization of diamond particles and the strength of their fixation are also affected by the elements of the matrix material. Carbide-forming elements introduced to the surface of diamond particles from the matrix material increase adhesion, thereby improving diamond retention. At the same time, the study of the "diamond-matrix" border zones that affect the properties of composites obtained by explosive pressing is a complex and poorly studied
area. Currently, work is underway to investigate diamond retention by various methods. The authors of [13] performed a simulation of diamond retention using the Abaqus software and revealed a direct dependence of this parameter on the mechanical and thermal parameters of the matrix material. The combination of hardness and plasticity of the matrix material is conductive to better diamond retention. To meet this difficult requirement, we used two-component matrices made of powders with different hardness and obtained wear-resistant diamond composites by explosive pressing [14, 15]. The purpose of this work is to study the products of contact interaction between the diamond and the matrix material of wear-resistant diamond-metal composites obtained by explosive pressing with subsequent heat treatment.

2. Material and method of experiments
The experimental studies and a justification of the choice of matrix compositions and modes of explosive pressing of cylindrical samples of diamond-metal composites are described in detail in [14, 15]. The obtained data allowed using powders belonging to different classes of iron-based alloys PKH18N9T (relatively soft stainless steel powder with a microhardness of 1800-2200 MPa) and PG-FBKH6 (wear-resistant powder of increased hardness for sputtering; microhardness of 5900-7100 MPa) as a matrix material for further experiments. In the mixtures, the percentage of components was changed: the content of soft powder in them was 20, 30 and 40 %. The initial chemical composition of powder materials is shown in Table 1; the dispersion of powders is ~80 microns. The diamond powder A7K80 500/400 was introduced into matrix powders at the rate of obtaining 100% of their content in a nonporous compact [14].

| Powder       | C          | Si     | Ni | Mn | Cr | Mo | B | Fe | H, MPa |
|--------------|------------|--------|----|----|----|----|---|----|--------|
| PKH18N9T     | 0.05-0.12  | ≤0.2   | 7-10 | -  | 16-20 | ≤0.5 | - | res | 1800   |
| PG-FBKH6     | 3.50-5.50  | 1.0-2.5 | -  | 1.5-4.0 | 32-37 | - | 1.3-2.0 | res | 6900   |

The explosive pressing was carried out according to a cylindrical scheme under two modes that differ in the power of impact, for which the diameter of the explosive substance filling was varied (D_{ES} = 45 and 50 mm). Since a matrix is an iron-carbon alloy, the main calculations of the pressing parameters were performed for this material, taking into account the exclusion of graphitization of diamond particles. The compacted samples were subjected to short-term high-temperature heating at 800°C.

The microstructure of composites was studied using the optical microscope "Axio Observer D1m". The microhardness of phases was measured using the device "PMT-3" at a load of 2 N. The local elemental composition was studied using the scanning electron microscope "Hitachi TM-3030". The X-ray diffraction analysis of composite samples was performed using the high-precise Ultima-IV diffractometer of Rigaku firm. The images were taken in monochromated CoKα radiation at the accelerating voltage of 40 kV and the anode current of 40 mA. A parameter of the crystal lattice was determined by diffraction lines located at large scattering angles. The standard PDF-2 file system was used for the phase analysis.

3. Results and their discussion
As noted above, to obtain a complex of viscoelastic and plastic properties that ensure the wear resistance of a matrix and the rigidity of fixing diamond grains in a binder, a mixture of powders of iron-carbon alloys with different levels of hardness was used in the experimental diamond composites. This choice is a compromise solution that provides a balance between the matrix wear and the diamond retention. If a matrix is too hard, its wear will be slower than the wear of diamonds which will lead to the smearing of a material (a drop in productivity due to insufficient exposure of diamonds). The reduced hardness of
a matrix will lead to its rapid wear and accelerated loss of a diamond component that has not spent its life. As shown in studies [14, 15], the approach used to select the composition of a two-component matrix and the developed modes of explosive pressing provided a significant increase in the wear resistance of diamond composites. According to the results of comparative tests, the wear resistance characteristics of prototype models reach the level of wear resistance of industrial dressing diamonds at half the content of a diamond component. In this regard, the analysis of the diamond-matrix boundaries in the obtained wear-resistant composites is of particular interest.

During explosive pressing, as a result of instantaneous high-intensity exposure to powders, their deformation, compaction and heating occur, this is accompanied by contact formation between particles. On figure 1 it can be seen that after the explosive pressing, the matrix material wraps the diamond particles quite tightly. In addition, high-speed deformation by explosion activates the powder particles. This contributes to the formation of strong chemical bonds between a matrix and diamond during subsequent heat treatment. In other words, it is a fair assumption that the interaction of diamond carbon with the matrix substance during heating will complement the mechanical bond between them with a stronger chemical one.

**Figure 1.** The surface of the diamond composite polished specimen: a – before heat treatment (x500); b – after heat treatment (x5000).

It is known that carbide-forming elements form the strongest bonds with diamond [16-19]. According to the results of micro X-ray spectrum analysis in the border zones of the diamond-matrix of experimental composites, sufficiently high contents of such carbide-forming elements as chromium and boron were detected (figure 2, table 2); when this happens the amount of boron is more than twice its content in a matrix material. Unlike boron, chromium is present in smaller quantities than in a matrix. The results of mapping also confirm the significant presence of boron in the interface areas, and a sufficiently dense and uniform distribution of the boron-containing phase on the diamond surface (figure 3) allows determining it as a quasi-coating. Such coatings on diamond are obtained, for example, to improve the contact properties of diamond-binder composites with a copper matrix [20].

**Figure 2.** The local contents of chemical elements: a – on the diamond surface; b – at the borders of the diamond matrix; c – on the matrix section. Circles show the measurement locations.
Table 2. The results of micro X-ray spectrum analysis of a diamond composite (the composite makeup: 40% of PKH18N9T powder and 60% of PG-FBK6 powder, the explosive pressing at $D_{ES} = 50$ mm).

| Local areas | Co  | Fe  | C   | Cr  | Al  | O   | B   | Ni  |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|
| 1           | -   | 1.07| 93.95| 0.06| -   | 2.01| 2.78| -   |
| 2           | 0.28| 40.06| 17.30| 14.75| 8.71| 8.54| 5.82| 3.86|
| 3           | 0.52| 66.26| 5.19 | 17.63| -   | -   | 2.49| 7.15|

Notes: the location of areas 1, 2 and 3 is shown in Figure 2.

According to x-ray analysis (Table 3), in addition to diamond carbon, carbides of boron, silicon, chromium, and iron are also registered in the diamond-matrix contact zone. As can be seen from Table 3, these results also confirm the predominant amount of boric phase – boron carbide. In [21], in order to obtain the material of “the boron carbide - diamond” system the formation of boron carbide as a result of the interaction and transformation of carbon and boron at relatively high pressures and temperatures is shown. The boron carbide phase educed in diamond composites obtained by the explosive pressing and the heat treatment has the crystal lattice parameters $a = 0.54283$ nm and $c = 1.2203$ nm which allows identifying it as boron carbide $B_4C$. This compound is the most common among boron carbides and ranks third in hardness after diamond and boron nitride, it has high values of strength and wear resistance. It is obvious that the formation of this phase at the diamond-matrix interface is a factor that significantly provided an increase in the strength and wear resistance of the obtained diamond composites. Taking into account the relatively uniform and almost continuous distribution of carbide phase on the diamond surface, we can talk about the formation of boron-carbide coating on it. The increase in the performance properties of the diamond composite in the presence of boron carbide is due not only to improved adhesion between the diamond and the matrix as a result of the formation of chemical bonds in this case, but also in response to the high strength and wear resistance of the boron-carbide phase itself. The issue requires further study using high-resolution methods of research.

Figure 3. A section of the diamond-matrix border (a) of a diamond composite and the map of the distribution of chemical elements in it (b).
Table 3. Main phases in the diamond-matrix border zone and their content.

| Phase                        | Lattice parameters (nm) | Content (%) |
|------------------------------|-------------------------|-------------|
| Carbon (diamond)             | $a = 0.3566$            | 12          |
| Chromium Carbide             | $a = 0.4045$            | 1           |
| Boron Carbide                | $a = 0.5428; b = 1.2203$| 29          |
| Silicon Carbide              | $a = 0.4441$            | 6           |
| Iron Carbide                 | $a = 0.4634; b = 0.4230$| 1           |

4. Conclusion

The structure phase studies of phase boundary «diamond-matrix» of wear resistant diamond-metal composites with two-component iron-carbon matrix obtained by explosive pressing with subsequent heat treatment has showed that a significant factor in increasing diamond retention and functional properties of a material is the formation on the diamond surface of the boron carbide quasi-coating. The increase in the performance properties of the diamond composite in the presence of boron carbide is due not only to improved adhesion between the diamond and the matrix as a result of the formation of chemical bonds in this case, but also due to the high strength and wear resistance of the boron-carbide phase itself.

5. References

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