Novel approaches in manufacturing of multicomponent metallic binders for diamond cutting tools

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Abstract. In this study, three approaches for the diamond cutting tool binder improvement are shown. They allow to reinforce the binders and enhance their wear resistance, thus making diamond grain retention in the working layer of the tool more reliable. Mechanical alloying method was used to obtain a homogeneous and nanocrystalline structure of the powder binders. It increases the bending strength of iron- and copper-based binders by 60-100%, to 2500 and 1200 MPa, respectively. The positive effects achieved by adding different types of nanoparticles are summed up during hybrid modification of the binders. It has been verified, both theoretically and experimentally, that hybrid modification with WC and hBN nanoparticles, as well as carbon nanotubes, simultaneously increases binder strength by 20% and improves binder wear resistance during machining of abrasive materials threefold. Doping iron-based binders with adhesively active elements (titanium, chromium, etc.) enhances the diamond retention capacity due to formation of carbide interlayers at the metal–binder interface.

1. Introduction

The wide use of diamond cutting tools in the construction and mining industries, as well as the growing demand for this class of tools, makes it necessary to improve their performance parameters and durability. As reported by the largest manufacturers of diamond tools participating in the Cutting Tool Market Report (CTMR), the volume of the diamond tool market in 2018 in the United States was USD 784.69 million, being 9.6% greater than that in 2017 [1]. Under these conditions, the research focused on improvement of cutting and grinding tools is especially relevant.

Diamond cutting tools are made of a composite material: superhard material (SHM) grains embedded in a metallic, ceramic, or organic matrix (binder). Performance parameters of these tools can be improved by designing either novel SHMs with better properties or new types of binders, which would allow one to use the SHM more completely and ensure operational stability. Nowadays, diamond grains are typically used in cutting tools. Diamond is a unique material in terms of its mechanical and thermophysical properties. Although the researchers have mastered the procedure of synthesizing a number of alternative SHMs (e.g., cubic boron nitride, boron carbide, silicon carbide, etc.), diamond remains the most suitable material for manufacturing cutting and grinding tools.

The lack of alternatives to diamond makes another tool improvement trend (developing novel types of binders that can retain the SHM in the working layer) quite promising. To ensure good performance properties of the diamond cutting tool, the binder must reliably retain diamond grains (with grain protrusion being as high as possible) and be characterized by high abrasive wear resistance. These properties ensure gradual renewal of tool working layer and maximum efficiency of using diamond grains [2, 3].
The correlation analysis measuring the association between diamond retention capacity and binder properties demonstrated that the former parameter is most likely to correlate with strength properties of the binders, since volume strain underlies the grain breakout process. The correlation coefficient between diamond retention capacity and bending or compressive strength is 0.996 and 0.979, respectively. The ductility parameters (impact toughness or relative elongation at deformation) have almost no effect on diamond retention capacity [4].

Another way to improve the efficiency and durability of cutting tools is to enhance the adhesion of a binder to diamond grains. This can be achieved either by cladding of diamond with coatings made of carbide-forming metals or by adding the respective metals to the binder [5,6]. In this case, diamond grains will be retained not only mechanically or via van der Waals forces, but due to chemical interactions as well. The interlayers based on carbide compounds (nitrides and borides for cubic boron nitride) preventing crack propagation upon deformation and compensating for the difference in coefficients of linear thermal expansion of the binder and diamond will be formed at the diamond–grain interface.

For these reasons, specialists engaged in designing diamond tools focus their efforts on developing high-strength and wear-resistant binder compositions and methods for their fabrication. In this work the novel approaches are reviewed – production of mechanically alloyed nanocrystalline binders, hybrid modification with nanoparticles and doping of the binders with adhesion active components.

2. Results and discussion

2.1. Fabrication of multi-component powder binders by mechanical alloying

Chemical co-precipitation of metal hydroxides followed by their reduction has conventionally been the most common method for producing multi-component metal powder binders for diamond tools [7]. Although this technique ensures uniform component distribution, it is rather complex and requires expensive equipment and proper safety precautions. Mechanical alloying of elemental powders in planetary ball mills (PBMs) is one of the alternative methods for fabricating powder binders that is devoid of these shortcomings and very process-flexible [8, 9]. Mechanical alloying makes it possible to produce alloy powders from elemental metallic powders via particle deformation and cold welding, followed by mutual diffusion of the components [10]. The material being alloyed receives energy as a result of multiple high-speed collisions with grinding bodies (steel balls). This process is extremely convenient because single-phase materials with a homogeneous structure can be produced in multicomponent systems. The limitations to mutual solubility of the components usually have no effect on this process, so it can be used to obtain thermodynamically unstable phases. An additional benefit of mechanical alloying is that it gives rise to materials having an ultrafine and nanocrystalline structure.

Several types of mechanically alloyed binders for diamond tools have been designed. The compositions based on the Fe-Ni, Fe-Co-Ni, Fe-Ni-Mo, Cu-Ni, and Cu-Fe-Co-Ni systems are best-known [9, 11–14]. Binders produced by consolidation of mechanically alloyed powders via hot pressing are known to be superior to their analogues produced using the conventional procedures by 60–100%. Thus, the bending strength of iron- and copper-based binders was as high as 2000–2500 and 1200 MPa, respectively. The key mechanisms ensuring the excellent mechanical properties of mechanically alloyed binders include solid solution strengthening, nanocrystalline structure formation, and the high density of dislocations and point defects in the crystal lattice. High-energy processing in a PBM leads to accumulation of a large amount of crystal lattice defects in powder grains, which impedes stress–plastic strain response. Hot pressing is conducted at relatively low temperatures (< 0.6 Tmel) for a short period of time (3 min), which does not allow complete material relaxation and defect elimination.

2.2. Hybrid reinforcement of binders with refractory nanoparticles

A number of studies demonstrating that metallic binders reinforced with refractory nanoparticles are superior to the conventional ones have been published over the past decade. WC, ZrO2, Al2O3, and
Si₃N₄ nanoparticles, nanodiamonds, carbon nanotubes, etc. were utilized in these studies [15–18]. Each type of nanoparticles added individually can reinforce the binder by 20–30%, increase its strength, reduce the coefficient of friction, and prevent diamond graphitization. Addition of several types of nanoparticles simultaneously allows to summarize this benefits [19].

At the stage of developing the compositions and technology for manufacturing hybrid-reinforced binders, a computer model allowing one to analyze the structure and mechanical properties and justify the choice of the amount of reinforcing additives was built. The finite element model was created and analyzed using the ABAQUS CAE 6.14 and Intel (R) Fortran Compiler 17.0 software packages. The computations were conducted under small-strain approximation for the linear elasticity theory. Computer code generated with Compaq Visual Fortran was used to automatically build 3D computational cells of the nanocomposite. This code is executed as a subroutine in ABAQUS software and generates finite element models with preset parameters. The nanostructured elements in the model were represented in the following form matching the real geometry of particles: WC nanoparticles, as spheres 80 nm in diameter; hBN nanoparticles, as discs 18 nm high and 72 nm in diameter; and carbon nanotubes (CNTs), as cylinders 80 nm long and 4 nm in diameter.

Modeling gave rise to stress distribution maps in the matrix at different strain values $\varepsilon$ (Figure 1). It was found that WC particles are characterized by approximately the same stress as the surrounding matrix and do not generate any noticeable stress concentrations. For the hBN particle lying perpendicular to the loading axis, a narrow zone at the particle boundary is characterized by an increased stress level, but this zone does not propagate deep inside the matrix. The hBN particle lying parallel to the axis of elongation is characterized by the highest stress (up to 800 MPa). This particle is also a source of high-stress zones in the metallic matrix.

For the binder modified with nanotubes, the highest stresses were found in the central portion of the particles oriented parallel to the loading axis. In this case, the localized “plastic zone” emerges at much higher $\varepsilon$ values (0.488 %) than upon reinforcement with WC and BN (0.164 %). Furthermore, no stress concentrations are formed at the CNT/matrix interface, so it is not prone to microcracking.

According to the structural data obtained by modeling, modification with 0.35–1.05 % WC, 0.1–1 % CNT, and 0.05–0.15 % hBN reinforces the Fe-Ni-Mo binders. The strength parameters are especially sensitive to hBN concentration, since hBN particles can act as a stress concentrator. This

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**Figure 1.** Stress distribution in the Fe-Ni-Mo binder reinforced with WC (shown as a sphere in the inset) and hBN (shown as rectangles in the inset) at different strain values $\varepsilon$. Tensile load is applied along the Y axis.

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behavior of Fe-Ni-Mo binders, both the initial and nanoparticle-reinforced ones, was verified experimentally by tensile strength testing (Figure 2).

Next, a series of samples with different nanoparticle content (belonging to the range specified above) was prepared. A set of tests was performed to evaluate their strength properties, hardness, and wear resistance. The samples modified with 1.05% WC, 0.2% CNT, and 0.1% hBN showed the best characteristics. Their strength was 20% higher than that of the initial binder (2000 vs 1650 MPa, respectively), while their wear resistance was threefold higher. The main reason for this phenomenon was that hBN acted as a dry lubricant, thus reducing the coefficient of friction.

2.3. Doping binders with adhesion active components
Doping binders for diamond cutting tools with components that have good wetting properties with respect to diamond and form carbide compounds when contacting carbon-containing materials is another promising trend in their improvement. The enthalpy of formation of carbides is known to decrease for the following series of metals: Ni, Co, Fe, Cr, Nb, Ta, Ti, and Zr [20]. Therefore, the use of metals from the end of this series for doping the binder will enhance the diamond retention capacity due to formation of adhesive carbide interlayers at the metal–diamond interface. Among these metals, titanium and chromium are especially promising due to their availability and low net cost.

Despite its apparent simplicity, this method is nowadays employed for only a few binders. The best-known class of binders containing strong carbide-forming elements is the so-called active brazing alloys. Among these binders, Cu-Sn-Ti, Cu-Sn-Cr, and some others are used most commonly [21, 22]. The presence of titanium and chromium in them plays a crucial role, since these very dopants ensure wetting of diamond single crystals. However, because of poor mechanical properties of the alloys such as Cu-Sn-Ti and Cu-Sn-Cr, their application is limited to monolayer-coated tools intended for grinding and straightening. Today, carbide-forming additives are almost never used in binders for the tools intended for cutting and drilling of large items made of concrete, stone, and other abrasive materials. The main reason is that it is quite difficult to achieve uniform distribution of these alloys over the binder volume, which would guarantee that they contact diamond with high probability. Another reason is the formation of unwanted intermetallic phases causing strength degradation. Most of the commercially available powders of titanium, chromium, and some other carbide-forming metals have a coarse average grain size (≥ 30 µm), being an order of magnitude larger than the size of Fe- and Co-based powder matrices conventionally used to manufacture diamond tools, which complicates the fabrication of materials with a homogeneous structure.

One of the ways to solve the problem of manufacturing Fe-based binders alloyed with adhesion active components is to prepare powder mixtures with the target composition by mechanical alloying.

Figure 2. The simulated and experimental stress–strain curves of the Fe-Ni-Mo binders subjected to hybrid reinforcement with nanoparticles
in a PBM. This approach has been successfully used when designing Fe-Co-Ni-Ti binders, which show extremely high wear resistance during machining of abrasive materials [23]. These binders were produced from elemental powders. Titanium was added to the matrix both as a pure metal and as the TiH₂ compound. The tests have demonstrated that binders prepared from powder mixtures with TiH₂ had the best mechanical properties and structure homogeneity. This compound is very fragile, can be disintegrated down to the sub-microsized state during milling in a PBM, and does not form agglomerates in the matrix (Figure 3a). The use of TiH₂ as an adhesion active modifier makes it necessary to slightly adjust the modes of compaction of diamond-containing segments, since heating (in the temperature range of 450–650°C) makes this compound decompose to metallic titanium and hydrogen (Figure 3b). In order to prevent the blocking of gaseous reaction products in the pores and the respective increase in residual porosity, pressure started to be applied during hot pressing only once the temperature of 650°C had been attained. Vigorous titanium diffusion was observed in the temperature range of 650–950°C, up to its complete dissolution in the α-Fe-based matrix. Exposure to the maximum temperature (950°C) caused partial graphitization of the diamond surface due to the catalytic activity of iron and the interaction between carbon and dissolved titanium. As a result, an analysis of the surface of diamond single crystals at segment fractures revealed that a large portion of the surface was coated with titanium carbide, which was enhancing the binder adhesion (Figure 3c).

**Figure 3.** A schematic representation of structural modifications occurring during hot pressing of diamond segments with the Fe-Co-Ni-TiH₂ binder at 20 (a), 650 (b), and 950°C (c).
Along with the obviously higher adhesion achieved via chemical interaction with diamond, doping with carbide-forming elements resulted in significant binder reinforcement (by 50–60%), which gives grounds for expecting that the diamond retention capacity will also be enhanced. Figure 4 shows the plots of bending strength of the Fe-Co-Ni binder as functions of TiH$_2$ and Cr concentration. These additives significantly enhanced strength: by 50 and 65%, respectively. Solid-solution and dispersion strengthening of the matrix were the main mechanisms of reinforcement. High-alloyed solid solutions based on $\alpha$-Fe were formed during milling in the PBM due to intensive plastic deformation of metal powders.

![Figure 4. Plots showing the bending strength of Fe-Co-Ni as functions of TiH$_2$ and Cr concentrations](image)

3. Conclusions
In this study, we have demonstrated three approaches that can be used to improve the binder for diamond cutting tools. These approaches significantly reinforce the binders and enhance their wear resistance, thus making diamond grain retention in the working layer of the tool more reliable.

1. Mechanical alloying of powder mixtures in a PBM produces multi-component binders with a homogeneous and nanocrystalline structure, including the binders based on metals having a limited mutual solubility or being mutually insoluble. The resulting dispersed structure of the binder increases the bending strength of iron- and copper-based binders to 2500 and 1200 MPa, respectively.

2. The positive effects achieved by adding different types of nanoparticles are summed up during hybrid modification of the binders. It has been verified, both theoretically and experimentally, that hybrid modification with WC and hBN nanoparticles, as well as carbon nanotubes, simultaneously increases binder strength by 20% and improves binder wear resistance during machining of abrasive materials threefold.

3. Doping iron-based binders with adhesively active elements (titanium, chromium, etc.) enhances the diamond retention capacity due to formation of carbide interlayers at the metal–binder interface. The uniform distribution of the carbide-forming additive is ensured by its dissolution in the matrix via mechanical alloying.

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References
[1] Yang N 2019 Novel Aspects of Diamond. From Growth to Applications. Springer International Publishing, New York 496 p.
[2] Jackson M J and Hitchiner M P. 2013 High Performance Grinding and Advanced Cutting Tools. Springer-Verlag, New York 100 p.
[3] Konstanty J 2005 Powder Metallurgy Diamond Tools. Elsevier, Oxford 152 p.
[4] Zhao X and. Duan L 2018 Metals-Basel 8(5), 307.
[5] Rommel D, Scherm F, Kuttner C and Glatzel U 2016 Surf. Coat. Tech. 291 62.
[6] Sokolov E G and Ozolin A V 2018 Mater. Today-Proc. 5(12) 26038
[7] Konstanty J 2013 Powder Metall. 56(3) 184
[8] Konstanty J and Romanski A 2012 Mater. Sci. Appl. 3 779.
[9] Romanski A, Konstanty J and Ratuszek W 2013 Appl. Mech. Mater. 431 3.
[10] Suryanarayana C 2001 Progr. Mater. Sci. 46 (1–2) 1.
[11] Loginov P, Sidorenko D, Bychkova M, Petzhik M and Levashov E 2017 Metals-Basel 7 570.
[12] Sidorenko D, Loginov P, Mishnaevsky Jr L and Levashov E 2018 Materials 11 404.
[13] Vorotilo S, Loginov P, Mishnaevsky L, Sidorenko D and Levashov 2019 E Mat. Sci. Eng. A-Struct 739 480.
[14] Loginov P A, Levashov E A, Kurbatkina V V, Zaitsev A A and Sidorenko D A. 2015 Powder Technol. 276 166.
[15] Sidorenko D A, Levashov E A, Kuptsov K A, Loginov P A, Shvyndina N V and Skryleva E A 2017 Int. J. Refract. Met. H. 69 273
[16] Li S, Han Z, Meng Q, Zhao X, Cao X and Liu B. 2018 Appl. Sci. 8(9) 1501.
[17] Tjong S C 2007 Adv. Eng. Mater. 9 639.
[18] Sun Y, Wu H, Li M, Meng Q, Gao K, Lü X and Liu B 2016 Materials 9(5) 343.
[19] Loginov P A, Sidorenko D A, Levashov E A, Petzhik M I, Bychkova M Ya and Mishnaevsky Jr L. 2018 Int. J. Refract. Met. H. 71 36.
[20] Sekulić D P 2013 Advances in brazing: Science, technology and applications. Elsevier, Oxford 600 p.
[21] Li X, Ivas T, Spierings A B, Wegener K and Leinenbach C 2018 J. Alloy. Compd. 735 1374.
[22] Li M., Chen J, Lin Q, Wu Y and Mu D 2019 Diam. Relat. Mater. 97 107440.
[23] Loginov P A, Sidorenko D A, Shvyndina N V, Sviridova T A, Churyumov A Yu and Levashov E A. 2019 Int. J. Refract. Met. H. 79, 69.