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PERFORMANCE OF DIAMOND CIRCULAR SAWS WITH INNOVATIVE FE-BASED BINDERS

The influence of binder composition on the performance of diamond circular saws in cutting reinforced concrete was investigated. Two different approaches were used to improve Fe-based binder to provide high cutting rate and stable wear rate of the tool. The first approach was built upon doping the binder with titanium, a strong carbide-forming component, which allowed producing titanium carbide layer at the diamond–binder interface, thus improving adhesion. The second approach involved complex modification of the binder with nanoparticles of tungsten carbide, hexagonal boron nitride and carbon nanotubes. These dopants improve the mechanical properties of the binders and provide formation of self-assembling protective WC coatings on the diamond surface. To confirm the benefits of binder modification, we tested diamond circular saws equipped with designed binders in cutting reinforced concrete. The tools with basic binder had the lowest cutting speed, higher wear rate and dulling during the test. The modification by addition of titanium allows this problem to be partially solved due to better diamond fixation in the working layer. The complex modification of the binder with nanoparticles demonstrated the best results as it changed its wear mechanism as well as enhanced its mechanical properties. The simultaneous strengthening with WC particles and carbon nanotubes and provoking of wear of binder microvolumes by boron nitride made it possible to maintain high cutting speed and stabilize the tool wear during machining.

Keywords: *diamond, cutting tool, performance, binder, nanoparticles, strengthening, wear*
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Introduction

For several decades now, diamond cutting tools (diamond circular saws, wire saws, drilling bits, etc.) have been occupying significant niche in operating procedures in mining, process manufacturing and construction industry. The production rate and demand for diamond cutting tools are currently booming [1–3]. According to the estimates made by a number of marketing agencies, the compound annual growth rate of the demand for diamond tools in 2021–2026 will be 4.7–6.7% [4, 5].

The rapid advancement in this industry has become possible due to the fact that the cost of synthetic diamonds was significantly reduced and the tools became more accessible. Along with the advancement in technologies used for the synthesis of superhard materials, there are two other trends: the composition of these materials is also improved and the novel methods for manufacturing metallic binders, which are in charge of diamond retention in the working layer and of the high performance maintenance, are being developed [6–9]. The standard use of single-component metallic [10, 11] and multi-component binders produced by chemical co-deposition from metal hydroxides and further reduction [12] has given way to the modern technique of mechanical alloying (MA) of powder blends [13, 14]. Due to MA, the resulting materials have a homogeneous fine-grained structure that favorably influences the performance of the tools.

MA iron-based binders have been successfully used to produce tools for cutting natural stone [15, 16], concrete [17] and other materials. However, these tools have poor performance and low operational stability sometimes, especially during machining of materials with complex composition and structure (reinforced concrete) or low abrasive capacity (granite or marble). In this case, the working layer gets “glazed”: this effect emerges when the wear rate of diamond is higher than the binder has. Because of the tendency towards glazing, it is impossible to design a tool that could be used for machining of different materials at the same efficiency. The reduced wear rate increases cutting time, which leads to economic losses during production. One of the ways to solve this problem is to modify the binder with components that change the wear mechanism.

In this study, we have produced modified iron-based Fe-Co-Ni binders by adding various dopants to them. Bench tests (cutting reinforced concrete) were conducted for diamond tools with the modified binder, and the features of the effect of the dopants on performance properties of the tools were revealed.

Description

The composition of 75% Fe–15% Co–10% Ni (hereinafter referred to as Fe-Co-Ni; wt. %) used to manufacture diamond tools for cutting concrete was selected as the basic binder [17]. This binder is characterized by high strength (σ_{bend} = 1900 MPa) and ductility. Therefore, grains of the superhard material are reliably retained within the working layer.

Two approaches have been used to improve this binder.

The first approach consisted on doping the binder with titanium, a strong carbide-forming component, which gave rise to an intermediate titanium carbide layer at the diamond–binder interface. This layer increases the binder to diamond adhesion and levels off the difference in the coefficients of thermal expansion of the binder and diamond, so fracture toughness can be increased (**Fig. 1**). Despite the evident advantages of titanium, it is quite rarely used in iron-based powder binders. The reason is that this element is poorly soluble in iron, cobalt and nickel, and tends to form intermetallic compounds, which may make the material brittle at high concentrations. This problem has been solved by using titanium hydride TiH_2 as a precursor [18], so titanium was uniformly distributed over the binder volume and high specific contact area between the grains of the titanium-containing component and diamond was ensured.

The second approach involved complex modification of the binder with nanoparticles of tungsten carbide (WC), hexagonal boron nitride (hBN) and carbon nanotubes (CNTs) [19]. Doping the binder with WC improves its mechanical properties and gives rise to self-assembling protective WC coatings on the surface of diamond single crystals directly during hot pressing (HP) of diamond segments [20]. The hBN particles prevent recrystallization of matrix grains during hot pressing. Carbon nanotubes strengthen the binder via the Orowan mechanism and can contribute to diamond retention by partially inhibiting the graphitization. By performing simultaneous modification of the diamond tool binder with

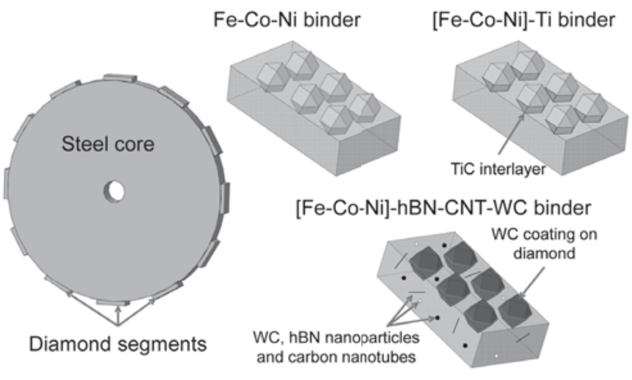


Fig. 1. A schematic diagram of the diamond circular saws (DCS) and diamond segments with binders of different types

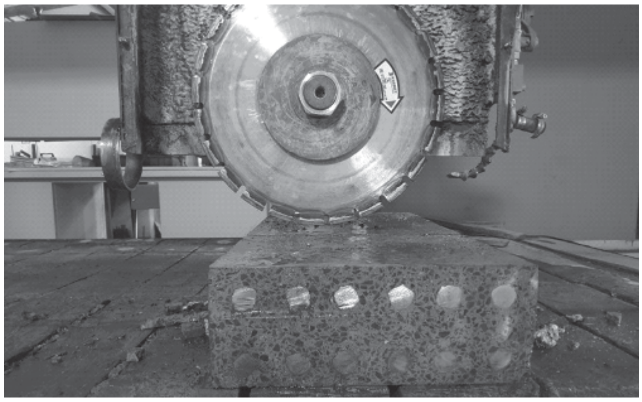


Fig. 2. DCS mounted onto Almaz-3 diamond cut-off machine and reinforced concrete slab

WC, hBN and CNT nanoparticles, it is possible to pool the favorable effects produce by each of these dopants (see Fig. 1).

According to the results of the earlier materials science studies [17–19], we selected the modified binder compositions that were characterized by the optimal combination of mechanical and tribological properties: [Fe-Co-Ni]–3% Ti and [Fe-Co-Ni]-0.1% hBN –0.1% CNT–0.69% WC. These binders were used to manufacture 40×4.2×9 mm segments for diamond saws 400 mm in diameter. Three segmented diamond saws were tested with each binder type.

The tests were performed on an Almaz-3 bridge cut-off machine (Russia) equipped with a water cooling system (10 L/min); the rotation speed was 3000 rpm (**Fig. 2**).

Reinforced concrete slabs 1000×500×150 mm were used as the machined material. Steel rods with cross-sectional diameter of 25 mm acted as reinforcement of concrete. Tool penetration depth per passage was maintained constant (1 mm). The steel ratio of reinforced concrete was 6%. The reinforced concrete slabs were cut in the direction perpendicular to the position of the steel rods.

Wear is determined by the change in the blade diameter; the cutting speed (V, cm^2/h) is calculated using the formula:

$$V = S/\tau, \quad (1)$$

where S is the area of cut, cm^2; and τ is the cutting time, h.

Industrial tests

The results of testing DCSs with different binder compositions are shown in **Figure 3**.

During the running-in stage, all saws were characterized by high cutting speed (1500–1800 cm^2/h) (Fig. 3*a*) and identical degrees of wear until the total surface area of cut became 1000 cm^2 (Fig. 3*b*), which was attributed to significant protrusion of the grains of superhard material above the surface of the working layer.

The difference in performance properties of DCS with different binders increases during testing. The cutting speed of the tool with the unmodified binder decreased to 600 cm^2/h, which is 25% and 50% lower than the cutting speeds of the saws with modified segments [Fe-Co-Ni]–Ti and [Fe-Co-Ni]–hBN–CNT–WC, respectively. The wear observed after the total surface area of cut became 3000 cm^2 were also different.

The tool with the unmodified binder Fe-Co-Ni was characterized by the lowest wear and cutting speed, being caused by glazing of the working layer. This was confirmed by scanning electron microscopy analysis of the surface of worn segments (**Fig. 4**). Most of diamond grains did not protrude above the binder surface and were not involved in cutting.

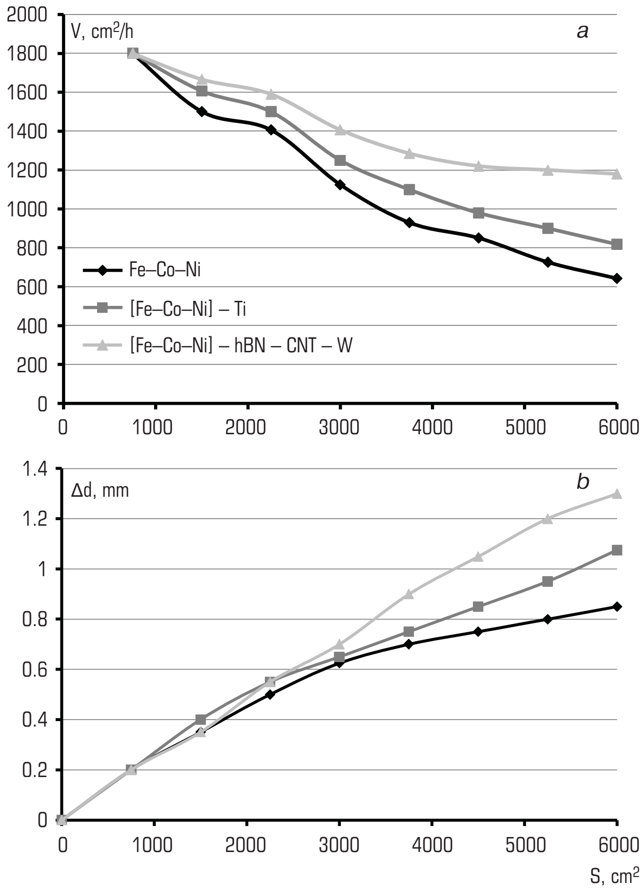
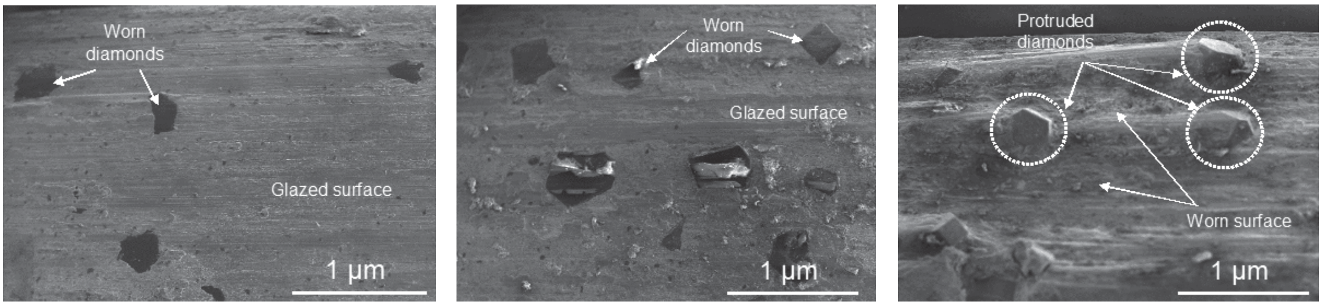


Fig. 3. Change in cutting speed (*a*) and wear (*b*) of DCS in test cutting of reinforced concrete

The analysis of the ratio of exposed, worn and pulled-out diamond grains in the working layer of DCS after the tests showed that the tools with the unmodified Fe-Co-Ni binder were characterized by a small percentage of pulled-out diamond grains (10%), being indicative of good diamond retention. The DCS with the [Fe-Co-Ni]–Ti binder was characterized by a more intense wear and high cutting rate due to the increased ratio between the exposed and pulled-out diamond grains on the working layer of the segment (Fig. 4*d*) caused by the enhanced binder to diamond adhesion.



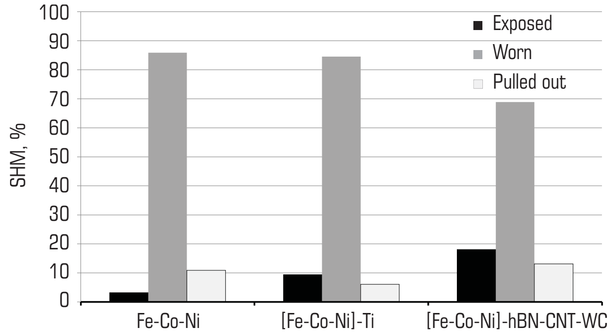


Fig. 4. Surface images of the segments with Fe-Co-Ni (*a*), [Fe-Co-Ni]-Ti (*b*) and [Fe-Co-Ni]–hBN–CNT–WC (*c*); bar chart of exposed, worn and pulled-out diamond grains in working layer of DCS after testing (*d*)

The DCS with the [Fe-Co-Ni]–hBN–CNT–WC binder was characterized by the most stable wear and high cutting speed in the tests. As shown in Fig. 4*d*, the percentage of diamond grains having sharp edges that protruded above the segment surface and were involved in microscratching of the machined material was 18% (the highest one). The increased degree of wear of the binder subjected to complex modification ensures such conditions when the working layer can be renewed and new diamond grains are engaged in the tool work. Despite the low wear resistance, this binder was characterized by excellent diamond retention capacity. This was achieved by dispersion strengthening of the binder by CNT and WT nanoparticles, on the one hand, and increased the binder-to-diamond adhesion due to formation of a tungsten carbide layer on the diamond surface, on the other hand [20].

The hBN dopant has a significant effect on wear resistance of the [Fe-Co-Ni]–hBN–CNT–WC binder. Loginov et al. [19] demonstrated that hBN nanoplates predominantly arranged along the boundaries of binder grains. Upon deformation, hBN particles act as stress concentrators and sources of cracks. Therefore, due to their presence in the binder, the abrasive wear mechanism gives way to pulling out of microvolumes of the material (sometimes along with diamond grains).

Conclusions

Diamond circular saws with metallic binders based on the Fe-Co-Ni alloy (the unmodified binder, the binder modified with titanium [Fe-Co-Ni]-Ti and the binder subjected to complex modification with nanoparticles [Fe-Co-Ni]–hBN–CNT–WC) have been tested in this study. The features of wear of the cutting tools with these binders during machining of reinforced concrete have been studied.

The tool with the [Fe-Co-Ni]–hBN–CNT–WC binder is found to exhibit the optimal performance. Integrated modification of the Fe-Co-Ni binder with WC and hBN nanoparticles and carbon nanotubes makes it possible to maintain high cutting speed, stabilize the tool wear during cutting and ensure operation of the tool in the mode of self-sharpening.

Acknowledgments

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THERMAL MODEL OF CONE DRILL BIT BEARING WITH AIR FLUSHING

Cone drill bits are used in various-purpose drilling in difficult geotechnical conditions, as well as in drilling-and-blasting in open-pit mining. The reliability of the drill bits depends on the rock-breaking source and on the bearing support. One of the causes of low reliability of a drill bit is the failure of the retaining ball bearing due to destruction of roller path and journal of the bearing under high contact and bending stresses. Based on the general provisions of similarity theory, a physical model of the retaining bearing of a roller bit was created. The test data of the bearing on a friction and wear testing machine are presented as the dependences of the bearing temperature, friction moment and clearances on time. The dependence of the bearing temperature on the thermal power is determined. In extreme conditions of lubricant shortage, the contact stresses in the bearing rings and balls and the temperature significantly exceed the permissible values. The methodology is proposed to be used in development of a cone rock bit drilling tool.

The article discusses the method of determining the moment of friction of the bearing of a cone drill bit. The design of bearings without retainers features increased clearances. To determine the moment of friction under these conditions, a simple design of the test bench is proposed, which includes a load and a counterweight connected by a thread thrown over a rolling bearing. The calculations to determine the reduced moment of friction of the rolling bearing in the conditions of the test bench are described.

Keywords: *roller cone bit, drilling bit bearing, thermal conductivity of support elements, heat transfer in leg, ball and roller bearings*
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Introduction

The relatively low penetration rate per drill bit is governed by the difficult operating conditions of the tool as it is to transfer considerable energy to break rocks at bottomhole under essential geometrical constraints. In connection with this, it is rather difficult to provide reliable bearings for drill bits to meet the common standards to ensure the wanted trouble-free life. The main cause of failure of bearing assemblies in drilling in soft and medium-strength rocks is the abrasive wear of roller path as a consequence of bleeding of lubricant because of its heating and due to loss of tightness of bearing cavity. In hard rock drilling, the cause of failures is roller path pitting under high contact stresses. Roller bits are comparatively expensive as they are difficult-to-make, and need special equipment and high-quality constructional materials, including hard alloys. Replacement of drill bits consumes much time and high material inputs. Thus, it is relevant to undertake the research aimed to improve the design of roller bits to ensure their high penetration rate. Many researchers addressed the design development and performance improvement of the roller drill bits [1–6].

S. M. Kuliev, G. G. Gabuzov, B. I. Esman and A. G. Mdivani determined theoretically the temperature of the drill bit bearings [7]. To this effect, they used the heat-balance equation of bottomhole operation of a drill bit. N. N. Zakirov found that the maximum temperature in the friction assemblies of a drill bit may reach 380 °C [8]. These studies show that the heating temperature of drill bits rises with the increasing temperature of the flush fluid, with the higher intensity of friction and with the decreasing thermal conductivity of metal. It is found that the temperature depends on the axial load of a drill bit, its rotation speed, friction factor, physical and mechanical properties of rock, material of the drill bit, rock fracture mechanism (shearing, crushing, cutting), roughness of the contact surfaces and on the bit diameter.

These influence factors of the heating temperature of bearings greatly complicate their analytical correlation. For this reason, it is topical to study thermal burden of a tricone drill bit using an electrothermal analogy.