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EXPERIMENTAL DESIGNS OF A COMBINED TOOL USING SUPERHARD COMPOSITE MATERIALS FOR EFFECTIVE DESTRUCTION OF MINE ROCKS*

The paper presents a combined tool using superhard composite materials used for boreholes (small diameter holes) drilling aimed at coal pre-fracturing intensification process studies results obtained in the project framework of the Federal target program on the topic: "Technology development for the effective coal deposit mining with a robotic complex using controlled release of the under-roofing layer" (Agreement No. 14.604.21.0173). The superhard composite material properties are considered. New designs of rotary bits are proposed, one of their features is the use of combined cutting plates made of superhard composite materials.

The experimental design mining tools bench test results are given, as well as the results of their use for drilling mine rock at Fletcher and Wombat standard drilling rigs. The article gives an estimation of the service life, drilling rate and drilling energy consumption by experimental design rotary bits. Conclusions and recommendations on the experimental design mining tool using possibility at significant temperatures in the cutting zone are formulated.

Key words: *mine rock destruction, drilling power consumption, rotary bit, superhard composite materials, tool enforcement, tool service life, drilling rate*

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Introduction

Mine rock destruction effective ways predetermine technological and economic prospects of all mining production development, as well as the prospects of the processing branches using the mining enterprise activity results. The mechanical method of rock destruction was the world's most widespread in the conduct of the main production processes in the mining industry both in underground and open pit mining, as well as in the process of underground structures building. At the same time, the mechanical destruction method leads to the intensive tool wear. That is why the problem of rock massif destruction with minimal specific energy consumption has been and remains one of the most important scientific and applied problems in mining.

The idea of an experimental design combined tool developing using superhard composite materials for the effective destruction of rocks involves, as the main work aim, solving four tasks: reducing the energy consumption and increasing the rock destruction process speed, increasing the tool service life and reducing its cost [1–3].

To date, the solution of the above mentioned problems by changing the geometry of the tool, as well as the introduction of various components into the hard-alloy insert composition has reached its limit. At the same time, despite the available technical possibilities for increasing the drive power of rotary drilling machines, the limitations caused by the structural strength of tungsten-cobalt inserts hinder the use of new high-performance modes of rock destruction. Thus, the currently used mining instrument based on classical hard alloys is a deterrent inhibiting the increase in the mining sector labor productivity. The new materials use for reinforcing the tool can remove this restriction.

Analysis of the superhard composite materials characteristics and their application possibility in the rotary bit design.

The most technologically advanced materials, which can be used for the mining tool cutting inserts in the near future, are superhard composite materials. Superhard composite materials are divided into two groups: those made on the basis of cubic boron nitride (CBN) and made on the basis of synthetic diamond [4, 5]. A large number of articles on the production of new types of superhard materials at pressures above 10 GPa and a temperature of more than 1700 °C have also been published at the present time, but there are no methods to obtain these substances at industrial scale yet [6].

Diamond composites are the hardest in a series of superhard materials. Composites based on polycrystalline diamond are widely used for the processing of non-ferrous metals and their alloys, as well as in areas related to the extraction of mineral resources [4, 7, 8]. Due to their high hardness, diamond composites are mainly used in those operations where the main cause of tool wear is the abrasive wear. However, polycrystalline diamond has a number of operational limitations that significantly reduce the productivity of the tool. One of such limitations is the inability to use this composite at high temperatures (above 400 °C) [9].

During drilling, two-layer diamond composites obtained at pressures of 6–8 GPa and temperatures of 1400–1600 °C

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are widely used at present. A diamond-containing layer is formed by a Co–WC–C bond, which is infiltrated from a substrate based on sintered tungsten carbide. The high mass content of cobalt in the diamond layer (from 6 to 10%) greatly lowers the heat resistance of the diamond insert. At high cutting speed the temperature on the cutting edge of the composite increases to 700 °C, which results in catastrophic thermal and chemical wear of the cutting inserts and is a significant limitation when selecting the operating mode of the tool [9].

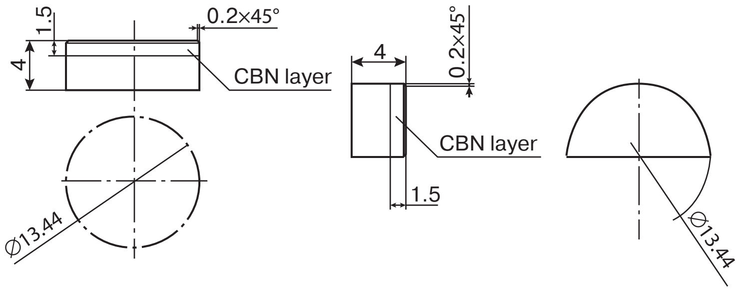


Fig. 1. Combined cutting plates used in experimental designs of rotary bits

Superhard materials based on cubic nitride do not have these limitations and are slightly inferior to diamond composites in hardness. Polycrystalline cubic boron nitride is commercially obtained as monoliths or bilayer composites (cubic boron nitride-hard alloy) by reaction sintering from powder mixtures of different composition at pressures of 4.0–6.0 GPa and temperatures of 1300–1500 °C [6]. For a long time it was believed that cubic boron nitride is not found in nature and can only be obtained by artificial means. In 2013, the International Mineralogical Association (IMA) confirmed the discovery made by geologists from the University of California (Riverside) back in 2009: there is a natural cubic modification of boron nitride, called “qingsongite”. At present, qingsongite is the only known cubic modification of boron nitride, formed in extreme conditions in the Earth interior [10].

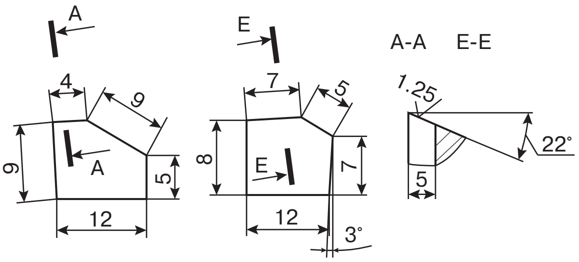


Fig. 2. Cutting plates of standard tungsten-boron rotary bits participating in comparative tests

Composites based on CNB have excellent chemical resistance to iron-containing and nickel alloys, as well as to cast iron, so they are widely used as a cutting tool for processing various parts in the metalworking industry [9]. In addition, recent studies show that on the basis of cubic boron nitride new materials can be created with the hardness exceeding other characteristics of diamond [10–12].

Materials based on cubic boron nitride also have excellent resistance to impact loads and low coefficient of deformation at high temperatures [6], which makes it very tempting to use them for reinforcing the mining tools that operate in conditions of considerable loads. In the course of the conducted research, a composite with a high content (more than 70 mass %) of cubic boron nitride CBN–Al–TiC was obtained and studied by the specialists of OOO “Microbor Composite” (Russia). The initial components used were cobalt boron nitride powders CBN MBR1-3 and commercially available aluminum nano-powders Al and titanium carbide TiC. X-ray diffraction analysis showed that the sintered CBN–Al–TiC composite consists mainly of the phases of cubic boron nitride CBN and titanium carbide TiC, as well as titanium diboride TiB_2 and aluminum nitride AlN [13].

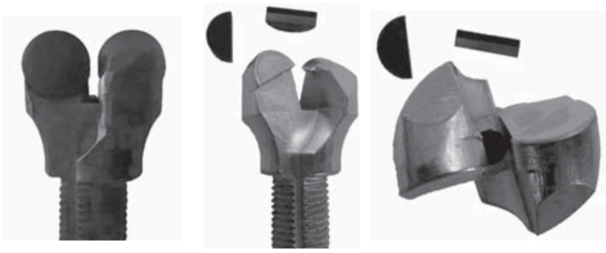
It was also found that the resulting large-sized composite has a homogeneous microstructure and phase composition formed by thermobaric treatment on a cubic press at a pressure of 6 GPa and a temperature of 1450 °C. The microhardness value of the analyzed samples from a large-sized billet is 35.27–37.59 GPa, and that of the elasticity modulus is 502.82–53.3.3 GPa [6]. In this case, the homogeneous properties of a large-dimensional composite are confirmed not only by the values of the microhardness and modulus of elasticity of individual plates, but also by the results of impact turning of hardened steel. External turning with impact was carried out on the multifunctional lathe Puma 240 (“Doosan”, Korea) on the cylindrical CVG (tool alloyed steel) workpiece according to the following conditions: cutting speed 180 m/min, reverse feed 0.3 mm/rev, cutting depth 0.3 mm, the cutting time is 3 min. The wear on all tested plate back surfaces cut from a large-sized composite does not exceed 120 µm, which indicates the possibility of using superhard composites with a high content of cubic boron nitride CBN–Al–TiC as reinforcing inserts when making a mining tool [6, 14].

To ensure the technological process of soldering plates made of superhard composite on the basis of CNB to a billet from tungsten-cobalt hard alloy, the specialists of OOO “Microbor Composite” developed a special copper-titanium solder (Cu–Ti), which provides strong adhesion bonds. Copper-titanium solder was obtained by the method of mechanical alloying in a water-cooled planetary mill. The soldering process with copper-titanium solder was carried out at a temperature of 950 °C in vacuum. Further soldering of the obtained reinforcing inserts to the body of the mining tool was carried out with silver solder PSr-40 using the FKP-250 flux.

Experimental designs of rotary bits and technique of their tests carrying out

In accordance with the requirement specification, 3 designs of rotary bits were developed, which use cutting inserts with CBN layer reinforced sections. The cutting inserts had circular and semi-circular shape and were made of a hard alloy with a CNB layer application (**Fig. 1**). Further, on their basis, cutters were manufactured for 28 mm diameter borehole rotary drilling with two-and three-point designs.

To evaluate the characteristics of the developed rotary bits in comparison with the existing ones, the tests were also carried out for two-point bits RPP-28 with a diameter of 28 mm with plates made of a standard tungsten-cobalt alloy (**Fig. 2**). Photos of the bits and their designations in the experiment are



a *b*

Fig. 3. Experimental designs of two-point rotary bits: with a round insert (Type 1) (*a*); with a semicircular insert (Type 2) (*b*)

a *b*

Fig. 4. Rotary bits: an experimental three-point with a semicircular insert (Type 3) (*a*); standard with cutting inserts made of tungsten-cobalt alloy (Type 4) (*b*)

Table 1. Geometrical parameters of cutting inserts and physics-chemical properties of cutter bodies

Sample type	Cutting edge shape	Front angle	Rear angle	Chemical body composition /body hardness	Cutting plate chemical composition
No. 1	Symmetric	–15°	18°	35KhGSA/350-390NV	CBN
No. 2	Symmetric	–15°	18°	35KhGSA/350-390NV	CBN
No. 3	Symmetric	–15°	16°	35KhGSA/350-390NV	CBN
No. 4	Asymmetric	–2°	18°	35KhGSL/240-270NV	VC8V

shown in **Fig. 3** and **Fig. 4**. Geometric and physico-chemical properties of the bit designs are presented in **Table 1**.

Tests of the developed experimental design rotary bits were carried out by drilling sand-cement blocks (SCB) and mine rock (sandstone). Drilling of SCB was carried out on a specially developed drilling bench, which allows recording the cutting tool movement, advance force, rotation speed and torque. The mine rock drilling was carried out by standard Fletcher and Wombat drilling rigs [15].

To evaluate the physics-mechanical properties of the SCB, samples were taken from each block, which were subsequently subjected to research in the profile laboratory. Each SCB used for testing had storage time of at least 48 days. The results of laboratory studies showed that the average strength coefficient value of Protodyakonov scale of hardness was f = 8–9. Parameters of the drilling modeat the drilling bench, the number of each design tested cutters, as well as the amount of blasthole/meters drilled with each sample, are given in **Table 2**. Drilling mode parameters were chosen according to the recommendations [16].

After drilling of 15 blastholes with each experimental design drill bits (Type 1, Type 2, Type 3), the bench tests were completed as the cutting tool stable characteristics were obtained. As a result of the conducted studies, drilling diagrams were obtained, recording in time the advance force, the cutter movement, the speed of its rotation, and the torque. Drilling diagrams were recorded for each blasthole drilled.

The failure of experimental cutters during drilling at the stand was not registered, and they were transferred for further rock drilling tests to standard drilling rigs Fletcher and Wombat in conditions of operating mines. Drilling of SCB with cutters that have reinforcing hard alloy inserts (Type 4) was stopped after the cutters were worn out.

Further experiments on drilling rock with Fletcher and Wombat rigs were carried out in 2 stages. During the drilling process, the total length of drilled blastholes was registered, as well as the drilling speed.

At the first stage, the sandstone of strength f = 8–9 Protodyakonov scale of hardness was drilled with a pneumatic drilling rig Wombat with the use Type 1, Type 2, Type 3 of rotary bits. At the second stage drilling of sandstone with strength f = 8–9 of Protodyakonov scale of hardness was performed with a Fletcher hydraulic rig using rotary bits Type1, Type 2.

Testing of the Type 3 rotary bit was not carried out due to the rig advance force lack, revealed at the first stage of the rock drilling experiment. Drilling of blastholes in both cases was carried out with water washing.

Experimental design rotary bits test results

The experimental data obtained during the research were statistically processed.

Fig. 5 compares the service life of the developed experimental design rotary bits (Type 1, Type 2, Type 3) with reinforcing inserts made of CBN and that of a widely used in practice cutter RPP-28 with tungsten-cobalt cutting inserts (Type 4).

The drilling tool service life was determined as the average value obtained from the tests results at the drilling bench when drilling SCB and drilling rock with rock hardness ratio f = 8–10 units at industrial drilling rigs Fletcher and WOMBAT.

It can be seen from the diagram at Figure 5 that service life of the most effective Type 1 experimental design cutter exceeds the resource of the standard rotary bit by more than 9 times which indicates the significant prospects of using superhard composite materials for reinforcing rotary bits cutting inserts.

In the course of bench tests, the average value of the specific advance rate for each type of rotary bit was calculated. The advance force, as well as the number of revolutions when drilling with Type 1, Type 2, Type 4 cutters were set the same. Ex-

Table 2. Drilling mode parameters and drilling bench experimental study results

Drilling mode parameters	Sample No. 1	Sample No. 2	Sample No. 3	Sample No. 4	Sample No. 5
Type 1					
Advance force, kN	3,7	3,7	3,7	3,7	3,7
System pressure, MPa	0,2	0,2	0,2	0,2	0,2
Rotation frequency, min^{-1}	280	280	280	280	280
Specific advance, mm/rev	3,8	3,8	3,9	3,7	3,8
Advance speed, mm/s	17,6	17,7	18,0	17,4	17,5
Meters of drilled blasthole	13,2	13,4	13,4	13.2	13,3
Type 2					
Advance force, kN	3,7	3,7	3,7	3,7	3,7
System pressure, MPa	0,2	0,2	0,2	0,2	0,2
Rotation frequency, min^{-1}	280	280	280	280	280
Specific advance, mm/rev	4,8	4,5	4,4	4,5	4,6
Advance speed, mm/s	22,3	21,1	20,7	20,8	21,3
Meters of drilled blasthole	13,5	13,7	13,7	13,6	13,7
Type 3					
Advance force, kN	7	7	7	–	–
System pressure, MPa	0,5	0,5	0,5	–	–
Rotation frequency, min^{-1}	280	280	280	–	–
Specific advance, mm/rev	2,6	2,5	2,5	–	–
Advance speed, mm/s	12,1	11,6	11,7	–	–
Meters of drilled blasthole	13,6	13,7	13,7	–	–
Type 4					
Advance force, kN	3,7	3,7	3,7	3,7	3,7
System pressure, MPa	0,2	0,2	0,2	0,2	0,2
Rotation frequency, min^{-1}	280	280	280	280	280
Specific advance, mm/rev	5,7	5,2	4,5	4,5	5,5
Advance speed, mm/s	26,6	24,2	21,0	20,8	25,5
Meters of drilled blasthole	7,2	7,1	6,2	7,3	6,3

perimental Type 3 rotary bit in connection with the three-point design required a greater advance force, while the specific advance rate of such a cutter per revolution was the least.

The average value of the specific advance rate for the rotary bits Type 1, Type 2, Type 3 and Type 4 was 3.8 mm/rev, 4.6 mm/rev, 2.5 mm/rev and 5.1 mm/rev respectively. It should be noted that the specific advance rate value when drilling with the Type 2 cutter is intermediate between the advance values achieved when drilling with Type 1 and Type 4 cutters, indicating that there are potential opportunities for the performance of the Type 1 cutter improvement. The smaller value of the specific advance rate and, correspondingly, the drilling speed of the Type 1 rotary bit are related to its blades' design, which can be optimized through additional studies.

Specific advance rate when processing the experimental data was obtained through the following expression:

$$\Delta = \frac{L_{cp} \times 60}{n \times t_{cp}} \text{ m}, \qquad (1)$$

where L_{cp} — average blasthole depth, n — rotation frequency, rev/min.; t_{cp} — average blasthole drilling time.

The average speed of drilling with cutters when testing them on a drilling bench was obtained by the expression:

$$v = \frac{L_{cp}}{t_{cp}} \text{ mm/s}. \qquad (2)$$

The average drilling speed at bench tests for rotary bits Type 1, Type 2, Type 3 and Type 4 was 17,6 mm/s, 21,2 mm/s, 11,8 mm/s and 23,6 mm/s correspondingly.

The drilling speed during rotary bit Type 1, Type 2 and Type 4 testing in the working conditions at various rigs was practically the same and reached about 26 mm/s. At the same time drilling with Type 3 rotary bit was not carried out due to the rig used in researches low advance force as it was disclosed at the first stage of mine rock drilling experiment.

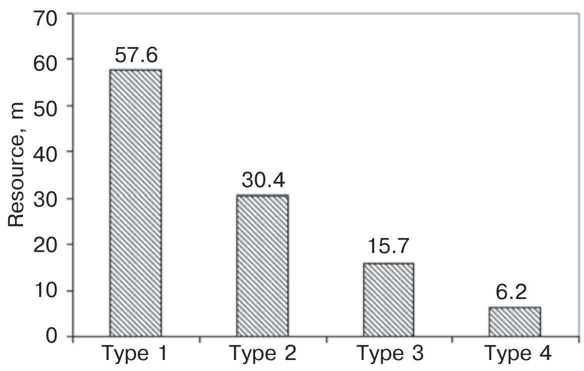


Fig. 5. Rotary bit service life evaluation

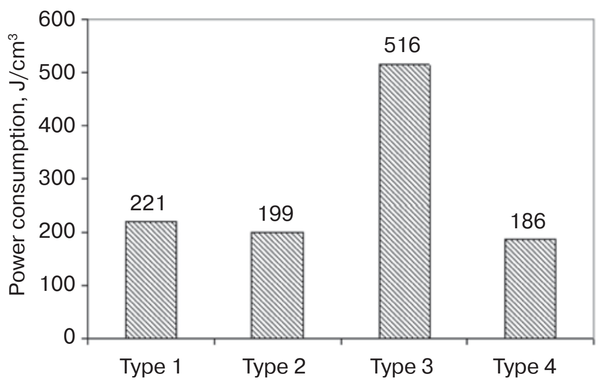


Fig. 6. Drilling power consumption at rotary bits bench tests

Fig. 6 gives information on the test cutters drilling energy consumption.

To calculate power consumption, experiment results carried out on the drilling bench were used. The value of drilling power consumption was determined by the work spent on drilling ratio to the destroyed rock volume, while the power consumption for the tool advance was not taken into account due to its insignificant part in the total power consumption.

The following dependencies were used in the calculations:

$$P = M_{KP}\omega \text{ , W,} \quad (3)$$

where P — the power spent for drilling; M_{KP} — the torque, N·m; ω is the angular velocity, rad/s.

$$A = Pt \text{ , J,} \quad (4)$$

where A is work J; t — drilling time, s.

$$V = \pi r^2 L \text{ , m}^3\text{,} \quad (5)$$

where V is the volume of destroyed mine rock, m^3; r — radius of the blasthole, m; L — blasthole length, m.

The drilling power consumption by means of the rotary bit developed designs Type 1 and Type 2 differs from the similar characteristic of the standard rotary bit Type 4 within the statistical error. At the same time, the blasthole drilling energy consumption with a 3-point experimental rotary bit Type 3 exceeds the specific power consumption for drilling by more than 2 times for each of the tested bits. The most likely reason for the situation is the design imperfection of the experimental rotary bit Type 3.

Conclusion

The experimental study results have shown that the use of CBN for reinforcing blades of rotary bits can significantly increase the service life of a mining tool without its other technological characteristics, such as drilling speed and power consumption worsening. At the same time, the high thermal stability of the CBN allows the based on it mining tool to be operated in combination with high-performance drilling modes at rather high temperatures in the cutting zone.

We must note that because of full-scale service life tests lack, the results obtained are of an evaluation character and are considered preliminary ones.

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