Experimental estimation of drilling energy efficiency and life time of new rotary bits equipped with combined inserts on the basis of superhard composite materials

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Abstract. The article is devoted to the drilling energy consumption and new design of rotary bits, its life time estimation. The feature of the bits is the use of combined cutting inserts based on cubic boron nitride. Tests of the experimental design of mining tools were carried out on a specially designed drilling bench, as well as by Fletcher and Wombat standard drilling rigs.

1. Introduction
Rapid development of technologies in the mining industry, success in the development of materials with unique properties actualize scientific research on the practical application of scientific and technological progress results. Investigations aimed at creating new designs of drill bits with increased wear resistance were carried out by the team of the Federal Research Center of Coal and Coal Chemistry of the SB RAS (FRC CCC SB RAS). FRC CCC SB RAS within the Federal Program framework on the theme: “Development of experimental designs of a combined tool using superhard composite materials for effective rock destruction” [1]. The results of this work are presented in this article.

2. Materials and methods
The most technologically advanced materials capable of replacing tungsten-cobalt alloys in the cutting inserts of rotary bits in the near future are superhard composites based on cubic boron nitride (CBN) and synthetic diamond [2]. And if the experience of using technical diamonds in a drilling tool has been accumulated quite extensively, then the development of designs based on cubic boron nitride has not at present been implemented in principle or was carried out on a non-significant scale [3]. In this regard, the experience of designing drilling bits with cutting inserts based on CBN, as well as their testing represent actual scientific and technical information.

In accordance with the requirement specification, 3 designs of rotary bits with combined cutting inserts were developed, which is a hard alloy coated with a CBN layer. The cutting inserts had circular and semi-circular shape (figure 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 with a diameter of 30 mm with plates made of a standard tungsten-cobalt alloy. Photos of the bits and their designations in the experiment are shown in figures 2 and 3. Geometric and physico-chemical properties of the bit designs are presented in table 1.

The tests were carried out on a specially developed drilling bench, which allows the cutting tool movement, advance force, rotation speed and torque to be recorded. To simulate the rock during the experiments sandy-cement blocks (SCB) were used. Photos of the drilling bench and SCB after the tests are shown in figure 4.
Figure 1. Combined cutting plates used in experimental designs of rotary bits: round shape (a); semicircular shape (b).

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

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 according to Protodyakonov scale of hardness was $f = 8-9$.

Figure 3. 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°        | 35KgGSA/350-390NV                       | CBN                               |
| No.2        | Symmetric         | -15°        | 18°        | 35KgGSA/350-390NV                       | CBN                               |
| No.3        | Symmetric         | -15°        | 16°        | 35KgGSA/350-390NV                       | CBN                               |
| No.4        | Asymmetric        | -2°         | 18°        | 35KgGSL/240-270NV                       | VC8V                              |

Parameters of the drilling mode, the number of tested cutters of each design, as well as the number of blastholes drilled with each sample, are given in table 2.

After drilling 15 blastholes with each experimental design drill bits (Type 1, Type 2, Type 3), the bench tests were completed in connection with obtaining the cutting tool stable characteristics. As a result of the conducted studies, drilling diagrams, recording in time the advance force, the tool movement, the speed of its rotation, and the torque were obtained. Drilling diagrams were recorded for each drilled blasthole. Figure 5 shows one of the diagrams obtained when sample No. 1 of the Type 1 rotary bit was used.

The failure of experimental cutters during drilling at the stand was not registered, and in this connection they were transferred for further rock drilling tests to standard Fletcher and Wombat drilling rigs in the conditions of limited liability company “Alardinskaya Mine” and open joint stock company “UK "Neryungrugol” mine Denisovskaia. Drilling of SCB with cutters with 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.
Figure 5. The drilling diagram obtained at the drilling bench when the sample No.1 of the rotary bit Type 1 was working.

Table 2. Drilling mode parameters.

| 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          |
At the first stage, the sandstone of strength $f = 8-9$ according to Protodyakonov scale of hardness was drilled by the Wombat pneumatic drilling rig with the use of 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 Type 1, 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.

Photos of Type 1, Type 2 and Type 3 rotary bits after the experiments are shown in figures 6, 7.

**Figure 6.** Experimental Type 1 rotary bit after tests.

**Figure 7.** Experimental designs of rotary bits after tests: Type 2 (a), Type 3 (b).

### 3. Results and discussion

The experimental data obtained during the research were statistically processed and allow us to draw the following conclusions.

Figure 8 compares the resource of the developed experimental designs of the rotary bits (Type 1, Type 2, Type 3) with reinforcing inserts made of CBN and a tool with tungsten-cobalt inserts (Type 4), which is widely used in practice.

The drilling tool resource 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 Wombat and Fletcher with pneumatic and hydraulic supply.

It should be noted that in connection with the full-scale resource tests lack, as well as the use of SCB at the bench, the results obtained are of an evaluation nature and are considered preliminary.
It can be seen from the diagram that the life time of the most effective Type 1 experimental design cutter exceeds the life time of the standard rotary bit by more than 9 times.

Other experimental designs (Type 2, Type 3) also have high wear resistance, which indicates the significant prospects of using superhard composite materials for reinforcing rotary bits cutting inserts.

Figure 9 shows the values of the average specific advance rate, which is achieved when drilling with bits of new designs. As can be seen from table 2, the set advance force, as well as the number of revolutions when drilling with Type 1, Type 2, Type 4 cutters were the same. Experimental Type 3 rotary bit in connection with the three-point design required a greater advance force, while the specific advance of such a cutter per revolution was the least.

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 during experimental data processing was determined by the following expression:

\[
\Delta = \frac{L_{av} \times 60}{n \times t_{av}}, \text{ mm/rev.} \tag{1}
\]

Where \(L_{av}\) – average blasthole depth, mm; \(n\) – rotation frequency, rev/min.; \(t_{av}\) – average blasthole drilling time, s.

Figure 10 shows the values of the average drilling speed for bench tests, which was calculated by the expression:

\[
v = \frac{L_{av}}{t_{av}}, \text{ mm/s.} \tag{2}
\]
The drilling speed during rotary bits testing Type 1, Type 2 and Type 4 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.

Figure 11 gives information on the test cutters drilling energy consumption. To calculate the energy consumption, the results of experiments carried out on the drilling bench were used. The value of drilling energy consumption was determined by the work spent on drilling to the destroyed rock volume ratio, while the consumption for the tool advance was not taken into account due to its insignificant share in the total energy consumption.

The following dependencies were used in the calculations:

\[ P = M_{CR} \cdot \omega, \text{ W.} \]  
\[ A = P \cdot t, \text{ J.} \]  
\[ V = \pi r^2 \cdot L, \text{ m}^3. \]

Where \( P \) – the power spent for drilling; \( M_{CR} \) – the torque, N\( \cdot \)m; \( \omega \) is the angular velocity, rad/s.

Where \( A \) is work; \( t \) – drilling time, s.

Where \( V \) is the volume of destroyed rock; \( r \) – radius of the blasthole, m; \( L \) – blasthole, m.

The drilling energy 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 difficulties associated with the removal of the cuttings. The third point presence in the bit design reduces the free space, which leads to densification and re-destruction of the drill cuttings, as a result the specific power consumption for drilling significantly increases.
4. Conclusion
The experimental study results have shown that the use of CBN for reinforcing blades of rotary bits can significantly increase the 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 temperatures up to 900 °C in the cutting zone.

In connection with the lack of full-scale resource tests, the data obtained are indicative and intend to assess the prospects of using the mining tool with reinforcing inserts made of CBN. Further studies will allow us to refine and supplement the results obtained.

References
[1] Dvornikov L T, Klishin V I, Nikitenko S M, Korneyev V A and Korneyev P A 2016 IOP Conf.
Series: Earth and Environmental Science 45 33–42

[2] Nikitenko S M, Kol’ba A V, Anokhin A S, and Kukueva E V 2016 Glass and Ceramics (New York: Springer US) pp 458–464

[3] Nikitenko S M, Anokhin A S, Strel’nikova S S, Kukueva E V, Shipkov A N and Tkachenko V V 2015 Glass and Ceramics (New York: Springer US) pp 290–293