ABSTRACT
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DEVELOPMENT OF EFFECTIVE TECHNICAL AND TECHNOLOGICAL MEANS FOR DRILLING AND DEVELOPMENT OF GEOTECHNOLOGICAL WELLS WITH HIGH PERFORMANCE CHARACTERISTICS

Relevance of the topic. The demand for diamond drilling tools with improved mechanical and operational characteristics for the extraction of minerals in the Republic of Kazakhstan and worldwide is rapidly growing every year. Drilling technological and engineering-geological wells in conditions of complex and variable geological-technical sections requires the continuous improvement of rock-cutting tools. The features of such sections - the alternation of soft and dense rocks, the presence of plastic clays, and the well-developed fracturing of the lower intervals - impose elevated requirements on bits regarding stability, wear resistance, and operational consistency. The most pressing task becomes ensuring the uniform operation of the cutting elements and eliminating the so-called 'sticking' effect of the tool, which leads to a reduction in the mechanical drilling rate and uneven wear of the cutting structure.

For a long time, the main type of drilling tool for such conditions remained carbide blade bits and picobits. They demonstrate satisfactory efficiency when drilling easily destructible rocks in the upper interval of the section, but lose productivity upon transitioning to denser layers. Existing designs of such bits allow for localized wear near the axis, which causes unstable tool operation and intermittent bottom-hole deepening. At the same time, wear in the central zone disrupts the load balance, increases axial vibration, and leads to 'sticking' - a temporary cessation of drilling without withdrawing the tool from the well. This phenomenon is particularly common when drilling plastic, viscous clays and alternating rocks with dense inclusions, where the rock resistance sharply increases as the bit advances.

The emergence and active implementation of bits with polycrystalline diamond cutters (PDC) became an important stage in improving drilling efficiency. PDC cutters possess high wear resistance, maintain cutting ability over long intervals, and provide a significant increase in the mechanical penetration rate. However, standard PDC bit designs were primarily oriented toward homogeneous, low-fractured rocks and a continuous destruction process. Under conditions of variable lithology and high fracturing, the efficiency of such bits significantly decreases. In fractured rocks, where considerable losses of drilling fluid are observed, the conditions for bottom-hole cleaning and heat removal from the cutting elements deteriorate. As a result, PDC cutters undergo localized overheating, thermal aging, and accelerated abrasive wear. Additionally, the sharp change in rock resistance when transitioning from cohesive sections to fractured ones leads to uneven loading of the cutters and the occurrence of vibrations that reduce their service life.

Another problem when drilling fractured rocks is the irregular destruction of the bottom-hole: the cutter may unexpectedly fall into a void (fracture) or sharply collide with a rock protrusion, which causes significant impact and torsional loads. Traditional PDC cutters, especially without additional modifications, tolerate such regimes poorly, since they were originally designed for stable cutting conditions.

Under these conditions, the logical development of design solutions becomes the transition to combined armament of the drill bit, combining carbide and PDC cutters. Such a combination allows for the distribution of functional tasks between different types of cutters: carbide teeth absorb impact and abrasive loads at the periphery, where contact with rock heterogeneities most often occurs, while PDC cutters provide efficient cutting in the central and intermediate zones. However, simply combining cutters of different types does not guarantee the desired result. A rational arrangement of cutters along the radius is required, as well as coordination of the cutting depth, the shape of the seating sockets, the hydrodynamic channels, and the blade profile. Only with a comprehensive approach can combined armament increase the stability of the bit, prevent 'sticking,' and increase the footage per bit.

Particular attention must also be paid to improving the PDC cutters themselves. For equipping tools for drilling rock, composite diamond-containing materials (CDM) based on WC-Co alloys (composites of the $C_{diamond}$ - (WC-Co) system) are used, since they possess a good combination of hardness, wear resistance, strength, and fracture toughness, as well as a number of other useful properties. The drilling speed and the volume of mineral extraction depend on the quality of these tools. Modern drilling tools must not only ensure high operational efficiency but also comply with environmental standards, minimizing negative impact on the environment. The mechanical and operational properties of drilling tools depend on the physical-mechanical and cutting properties of the $C_{diamond}$ -(WC-Co) composites. Sintered CDMs possess properties significantly different from those of each individual component in their composition, while at the same time partially possessing the properties of metal (e.g., plasticity, thermal conductivity) and ceramics (e.g., high hardness, elasticity, and heat resistance). These properties depend on the phase composition, microstructure, and morphology, which in turn depend on the physical-mechanical properties of their components, sintering methods, and technological regimes. Some composites of the $C_{diamond}$ -(WC-Co) system possess mechanical and operational properties unattainable in traditional materials.

However, during the drilling of strong and abrasive rocks, the carbide matrix undergoes intense abrasive, fatigue, and adhesive wear, which limits the practical application of CDMs and reduces their service life. At the same time, on the working surface of the CDM during the drilling of wells in strong and abrasive rocks, physical-chemical processes occur that can lead to irreversible changes in the microstructure of the carbide matrix. In addition, due to weak adhesion between the diamond grains and the matrix, they may completely fall out of the carbide matrix during CDM operation, which significantly reduces the wear resistance of the rock-cutting tool.

The disadvantages of the CDMs under consideration include the graphitization of diamond grains and intensive growth of carbide grains occurring during their sintering, as well as the brittleness of the carbide matrix.

Therefore, improving diamond retention, increasing the strength, reliability, and wear resistance of $C_{diamond}$ -(WC-Co) composites, as well as developing efficient tools based on them, is an important task of science and technology, since it significantly expands their application area and affects mineral extraction.

Significant contributions to the theory and development of technology for obtaining composite materials were made by renowned scientists Skorokhod V.V., Kisly P.S., Novikov N.V., Turkevich V.Z., Aleksandrov V.A., Shilo A.Yu., Lisovsky A.F., Mechnik V.A., Barrer R.M., Clark P.W., Coble R.L., Kingery W.D., Nabarro F.R.N., Nicholas M., Scott P.

Major contributions to the development of equipment and technology for drilling wells of various purposes were made by foreign and domestic scientists and industry practitioners: Vozdvizhensky B.I., Kulichikhin N.I., Shamshev F.A., Bashkatov D.N., Kozlovsky E.A., Pankov A.V., Kvashnin G.P., Bashkatov A.D., Olonovsky Yu.A., Dryagalin E.N., Teslya V.G., Belyakov V.M., Tretyak A.Ya., Dubrovsky V.V., Belitsky A.S., Bessonov N.D., Novikov G.P., Shishchenko R.I., Romanenko V.A., Drakhlis S.L., Fedorov V.S., Epstein E.F., Onishchin V.P., Kozhevnikov A.A., Davidenko A.N., Khomenko V.L., Musanov A.M., Tanatarov T.T., Fedorov B.V., Biletsky M.T., Ratov B.T., Kudaykulova G.A., and many others.

Several approaches exist for improving the properties and reducing the cost of composite materials. One of them is the use of spark plasma sintering (SPS), which allows for the rapid production of materials with a fine-grained structure and enhanced mechanical characteristics due to the high-rate heating of a powder mixture in a vacuum under pressure. Also effective is the introduction of carbides, borides, nitrides, and oxides of transition metals into the composition, which inhibit WC grain growth and increase strength and wear resistance.

The size of the WC grain is of particular importance, as it directly affects hardness and fracture toughness. Additions of ultrafine and nanopowders (e.g., Cr3C2, VC, Al2O3) contribute to its refinement and the improvement of properties, but increase the cost of materials.

For $C_{diamond}$ –(WC–Co) systems used in drilling tools, it is important to study the structure and tribological properties, especially when working in abrasive rocks. Additions of CrB2 and other multicomponent modifiers can reduce the coefficient of friction and wear, however, data on their influence is limited and requires further clarification.

Thus, increasing the wear resistance of composite diamond-containing materials remains a ***relevant task*** associated with the development of efficient rock-cutting tools. A promising direction is the creation of composites of the $C_{diamond}$–(WC–6%Co)–CrB2 system for drilling strong and abrasive rocks.

Aim and objectives of the research. The aim of this work is to substantiate the design parameters of a drill bit with combined armament with high operational characteristics in conditions of a lithologically heterogeneous and fractured section when drilling geotechnological wells.

To achieve this aim, it is necessary to solve the following **objectives**: To analyze the geological-technical conditions of drilling geotechnological wells, using the Budenovskoye deposit as an example of one of the largest sites for the development of uranium raw materials.

To investigate the causes of uneven wear of cutting elements and the occurrence of the 'sticking' phenomenon when using traditional carbide and PDC bits.

To substantiate the principles of forming the combined armament of the bit, combining carbide and PDC cutters, taking into account the load distribution and rock destruction conditions.

To improve the composition and structure of PDC cutters by modifying the matrix material and the geometric parameters of the cutting part to increase heat resistance, wear resistance, and resistance to dynamic loads.

To conduct an analysis of the wear resistance of CDMs and rock-cutting tools manufactured on their basis.

To investigate the effect of CrB2 additive in the range from 0 to 10% on changes in nanohardness H and elastic modulus E in various phases of sintered samples of carbide matrices.

To conduct bench tests of the developed tools when drilling granite and to prepare methodological materials for the application of new tools in industrial practice.

To manufacture pilot samples of the combined bit equipped with inserts of the formed CDMs and to conduct industrial tests of the developed tools under the conditions of the Budenovskoye deposit.

The idea of the work lies in the fact that improving the efficiency of drilling technological wells in conditions of a lithologically heterogeneous and fractured section can be achieved through the development of a drill bit with combined armament, in which carbide and improved PDC cutters work in concert, compensating for each other's weaknesses. The resistance of the bit to dynamic loads, overheating, and uneven wear is achieved not only through the rational arrangement of cutting elements but also through the targeted improvement of the composition and design of PDC cutters made on the basis of composite diamond-containing materials of the $C_{diamond}$ –(WC–Co) system with CrB2 additives, formed by the spark plasma sintering method, which allows them to be adapted to complex geological-technical conditions and to significantly increase the service life of the tool.

Object of research - the processes of rock destruction and wear of cutting elements of the drilling tool when drilling technological wells in lithologically heterogeneous and fractured sections, the design parameters of drill bits with combined armament that affect the efficiency and stability of their operation under the specified conditions, as well as composite diamond-containing materials of the C $C_{diamond}$ diamond-(WC-Co)-CrB2 system.

Subject of research -— the principles of forming and optimizing the combined armament of the drill bit, including the mutual arrangement and functional interaction of carbide and improved PDC cutters, as well as the influence of the composition, structure, diamond retention, and wear resistance of composite diamond-containing materials on increasing the durability and efficiency of the tool in complex geological-technical conditions.

Research methodology. The dissertation is based on a comprehensive approach including theoretical, laboratory, design, and experimental research aimed at creating a drill bit for complex lithological conditions. The main tasks included eliminating 'sticking,' developing combined armament, and modifying PDC cutters.

At the first stage, an analysis was conducted of the geological-technical conditions of drilling and the causes of bit 'sticking,' and design and technological factors affecting the uneven destruction of rocks were identified. Based on the data obtained, requirements for the new tool design were formulated.

At the second stage, a bit was developed with the combined placement of carbide and PDC cutters and optimized geometry that eliminates 'sticking' through the rational distribution of the armament.

In parallel, research was conducted to improve PDC cutters. Using the spark plasma sintering method, WC-Co composites with CrB_2 additives at various concentrations were obtained. Their structure, mechanical, and tribological properties were studied.

Modern analytical methods were applied: SEM and EDS for studying the microstructure, optical profilometry for assessing roughness, microhardness and nanohardness by the Vickers and Oliver–Pharr methods, as well as wear resistance tests according to the 'cylinder-shaft' scheme when processing granite. The wear surfaces were studied using optical microscopy.

The developed bit was implemented as a pilot sample and tested under industrial conditions at a well of the 'Budenovskoye' deposit, where its productivity, vibration resistance, and wear resistance were evaluated.

The practical significance of the work lies in the development and experimental verification of the design of a drill bit for drilling technological wells in complex lithological conditions. The proposed solutions - combined armament (carbide and improved PDC cutters) and optimized geometry that eliminates 'sticking' - make it possible to increase the mechanical drilling rate and wear resistance of the tool.

The scientific results contribute to the development of technologies for obtaining composite diamond-containing materials based on WC-Co matrices by the spark plasma sintering method. The charge compositions and patterns of structure formation and wear of CDMs of the Diamond-(WC-Co)-CrB_2 system have been established, ensuring an increase in their wear resistance.

Composite materials have been developed: $C_{diamond}$ - (66.74WC-4.26Co)-4CrB_2, providing a reduction in wear indicators WR, WV, and WS by up to 2 times compared to the base composition; Diamond-(61.1WC-3.9Co)-10CrB_2, also demonstrating a reduction in wear across all main parameters.

Based on the developed CDM, experimental diamond impregnated bits were manufactured, which, when drilling granite, showed wear resistance approximately 2 times higher compared to the base material.

It has been established that the maximum wear resistance of the bits is achieved at a rotation frequency of 250 rpm and a load of 900 kg, and the minimum - at 750 rpm and 1250 kg.

Implementation of research results. The picobit-type bits developed during the research underwent comparative testing and showed productivity 15-20% higher than previously used picobits.

The PDC cutters developed on the basis of the new CDMs, when drilling granite, are twice as wear-resistant as cutters made from CDMs based on WC-6Co matrices.

Scientific propositions submitted for defense.

1. The optimization of the geometry of the axial part of the drill bit and the redistribution of cutters along the radius eliminate the unevenness of bottom-hole deepening and prevent the occurrence of 'sticking,' thereby ensuring the efficiency of rock destruction and reducing the wear of rock-cutting tools.

2. The combined armament of carbide and PDC cutters ensures uniform distribution of load on the cutting elements when drilling heterogeneous and fractured rocks, which contributes to reducing vibrational instability and increasing the durability of the bit through complete utilization of the armament.

3. The introduction of CrB2 micropowder in the amount of 4% (by mass) into the binder phase composition during the manufacture of PDC cutters formed by the spark plasma sintering method increases their heat resistance and wear resistance through the formation of a thermally stable structure, which is especially relevant when drilling in zones with drilling fluid losses and impeded cooling.

Scientific novelty of the work:

All results presented in the dissertation have been formulated and obtained for the first time, have scientific and practical significance, and contribute to the further development of the scientific foundations for the development of composite diamond-containing materials based on carbide matrices and tools manufactured on their basis with increased wear resistance.

For the first time, it has been established that the cause of the 'sticking' phenomenon of the drill bit when penetrating plastic and dense rocks is not only the physical-mechanical resistance of the rock, but also the irrational geometry of the axial part of the bit, which causes load concentration and localized wear in the central zone, disrupting the uniformity of bottom-hole deepening. This made it possible to substantiate the need for a targeted change in the shape of the blade profile and the redistribution of cutting elements near the axis of bit rotation.

For the first time, the effectiveness of the combined placement of carbide and PDC cutters in a drill bit has been substantiated, based on the different sensitivity of these elements to the type of load and the nature of the rock. It has been shown that carbide cutters effectively absorb impact loads in fractured zones, while PDC cutters provide high productivity in more homogeneous sections.

For the first time, it has been established that the introduction of CrB2 chromium diboride micropowder additive in the amount of 4% into the CDM composition ensures a reduction in the wear rate, which is due to the formation of a fine-grained structure of the carbide matrix, a more uniform distribution of hardness and elastic modulus, an increase in relative density, and an improvement in the adhesion strength of the diamond grains to the carbide matrix. A further increase in the content of CrB2 chromium diboride leads to an increase in the wear rate, which is due to the increased brittleness of the carbide matrix.

Compliance with the directions of science development or state programs: The dissertation corresponds to the key directions of state scientific and technical policy and programs aimed at improving industry, increasing energy efficiency, and ensuring environmental safety. Its content corresponds to the goals of the State Program 'Digitalization of the Economy of the Republic of Kazakhstan,' the State Program 'Development of Science and Technology in the Republic of Kazakhstan,' as well as the State Program 'New Industrial Policy of the Republic of Kazakhstan for 2020-2025.'

Personal contribution of the author. The work presents the results of research with the direct participation of the author in 2023-2026. The main results of the work were obtained by the dissertator independently. The formulation of tasks, discussion of results, and formation of the main conclusions were carried out jointly with scientific consultants. Personally, the author developed the scientific propositions, the selection of starting materials and the preparation of mixtures for forming samples of carbide matrices and composite diamond-containing materials by the spark plasma sintering method, and the principles and methods of theoretical and experimental research. The establishment of the wear patterns of the developed samples of composite diamond-containing materials and impregnated diamond bits manufactured on their basis when drilling strong and abrasive rocks.

From works with co-authors, only those results that were obtained by the author personally are included in the dissertation. The dissertation does not contain ideas and developments belonging to co-authors.

Reliability of results: The reliability of the results of the dissertation is confirmed by the use of modern equipment and certified research methods, a significant amount of experimental data and the application of statistical methods of result processing, and the comparison of the obtained results with the results of other authors.

Approbation of work results and publications.

The main provisions of the dissertation are reflected in a monograph and 6 scientific articles, including 1 publication recommended by the Committee for Quality Assurance in the Field of Science and Higher Education (CQAFSHE), in 2 journals included in the Scopus Analytics database, as well as in collections of international scientific conferences and an international journal.

From December 15, 2024, to January 15, 2025, a scientific internship was completed at the Northeast Petroleum University of China (NEPU, Daqing, PRC) under the supervision of PhD Xiaofeng Zhou.

Within the framework of the work, composite diamond-containing materials and a drill blade bit were developed, for which an application for a utility model was submitted to the National Institute of Intellectual Property of the Republic of Kazakhstan. The main results of the dissertation are reflected in published works.

Scope and structure of the work.

The dissertation consists of an introduction, 5 sections, general conclusions and recommendations, and contains 50 figures, 6 tables, 17 formulas, and a list of references.

The dissertation work was carried out at the Department of 'Geology and Petrochemical Engineering' of the Caspian State University of Technology and Engineering named after Sh. Yessenov.

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