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THE DRILL BITS: HISTORY AND MODERN EXPERIENCE

Purpose of the work is a brief historical review of the development of diamond drill bits of various types and the presentation of the prospective ways in this area.

Methodology. Analysis and summary of scientific and technical achievements, literary overview.

Results. Processes of formation of rock cutting tools, namely big diamond drill bits; small diamond drill bits; the bits equipped with synthetic diamonds; the bits armed by composite materials using diamonds are considered. Stages of innovative development and new approaches to drilling technologies are presented.

Novelty and practical value. In the historical context, the necessity of improvement a drilling tool is shown, the new promising ways for the development of diamond drill bits and technologies are presented.

***Key words**: drill bits, diamond drilling, historical review, new drilling technologies*

Introduction

Drilling began in the late Paleolithic and Neolithic (13–7 Millennium BC). Any process of creating holes can be seen as boring or drilling. Drill bits are one of the main types of drilling tools. Modern rock drilling is a high–tech and high–end process and has great importance to ensure the suitable development of national economy and energy self–sufficiency of world countries. Despite the seeming simplicity of construction, modern drilling bits are the high-tech products. There are different types of drilling core bits which apply at rotary exploration drilling. Depending on the type of rock-cutting elements, there are distinguishes between diamond and carbide drill bits. The effectiveness of rock drilling technologies depends on the operational capabilities of drilling tool used.

The history of different types of drilling tools and drilling technologies was considered in number works [1–6]. This paper is focused to the history of drill bits and materials for its. The some results of authors own investigations in this direction are presented.

The brief review of diamond drill bit history

The invention of big diamond drill bit. Note, that a kind of diamond rotary drilling was used 5000 years ago in ancient Egypt to quarry stone. A hollow wooden rod (later metal) hardened by fire was rotated by hand or bow string on loose, hard mineral grains such as granulated rubies or sapphires which were sifted onto the drill surface. Short holes with diameter from 6 to 700 mm were drilled in this way [1]. However, manufacturing diamond drilling tools was developed in the mid 19th century.

The diamond core drill was proposed by George Leschot, a Swiss watchmaker. In 1862, while supervising the blasting operations during the construction of a railway tunnel in the Swiss Alps. Leschot was challenged with drilling of solid granite rocks as drill bits made of high strength tempered steel were worn our very quickly. Leschot first proposed to use a diamond to disintegration granite and mountain rocks. He ordered diamonds for manufacturing several dozens of pilot diamond bits.

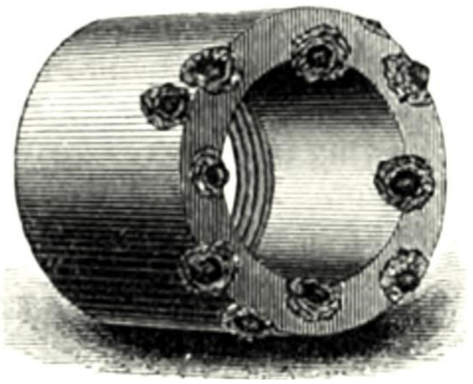


Fig. 1. The diamond core drill was invented by Rodolphe Leschot (picture source: Public Domain)

His son, Rodolfe, together with Piguet, a mechanical engineer, improved the drilling rig and came up with a way to mount the diamonds in the bit. These diamond tools were much more expensive than their steel counterparts, but proved themselves to much more efficient in operation (see Fig.1). The rate of tunnel drilling increased substantially. Being encouraged with the success achieved, Leschot applied a diamond bit in blast hole mining operations in massive marble rocks. Again, the diamond bit displayed its advantages. So, the era of diamond drilling begun.

Initially, the diamonds were fixed on the drill bit with bit's metal. There are several ways to impregnate diamonds in drill bits. The best and most common is the so–called Russian method for diamond impregnation in the drill crown that provides reliable (firm) fixing of diamonds on the body of drill bit and protection of diamonds from damage during operation. This method is characterized by impregnation of diamonds both in lateral surface of the crown and in its cutting face. The large gems are placed on the outer surface of the cutting face, while the small ones are fixed on its inner surface. The diamonds placed on the cutting face of the crown should completely cover it.

The small diamond drill bits. Firstly, large diamonds were used for manufacturing the drill bits. Till the 1930s, Carbonado commonly known as the black diamonds that had finely crystalline structure and low brittleness were exclusively used for the reinforcement of crowns. Weight of single diamond ranges from 0.5 to 2 carats. It is the most expensive industrial diamond. Fine-grained drill bits are allowed to complete a phase of chilled-shot drilling. This method existed as a kind of mechanical rotational drilling. The drilling of hard rock produced by the indentation in the bottom surface of the steel and iron pellets. It was one of the most time-consuming and unproductive types of drilling.

When drilling hard, especially crumbling rocks, the consumption of diamonds increased, with drilling costs rising sharply. Then, small diamonds were offered to be used. Depending on the size, the diamond particles are arranged on the crown cutting face in one layer (single layer crowns), or in several layers (multilayer crowns), or are evenly dispersed within a metal matrix (impregnated crowns).

The single–layer crowns are reinforced with diamonds ranging from 2–5 up to 40–60 pcs/carat. The multi–layer crowns are reinforced with smaller diamond grains, from 60–90 to 90–120 pcs./carat. The impregnated diamond bits are reinforced with diamond particles within the range from 120–500 pcs/carat or even more.

Drill bits with synthetic diamonds. The first attempt to synthesize diamonds was made in 1823, by the founder of Kharkov University Karazin who got superhard solid crystals of unknown substance as a result of wood carbonization at a high temperature. In 1893, Professor Khrushchev, also received a crystal scratching glass and corundum, as a result of rapid cooling of molten silver saturated with carbon. His experiment was successfully replicated by A. Moissone who substituted iron for silver. Later, it was found that the substance synthesized in these experiments was silicon carbide (moissonite), not diamond, which had very similar properties.

In 1879, James Ballantyne Hannay, a Scottish chemist, discovered that alkali metals reacted with organic compounds with carbon released in the form of graphite flakes, and suggested that, under high pressure this carbon can crystallize as diamond. Having carried out a series of experiments in which a mixture of paraffin, bone oil, and lithium was kept for a long time in a sealed red hot steel pipe, he managed to obtain a few crystals that later were identified as diamonds. The scientific world did not recognized his discovery, as at that time, the diamond was believed not to be obtained at low pressure and temperature. The repeated study of Hannay's samples in 1943 with the use of X–ray analysis confirmed that the obtained crystals were diamonds, but Prof. Kathleen Lonsdale, who carried out the analysis, reiterated that the Hannay experiments were a scientific hoax.

Prof. Ovsei Leipunsky published 1939 an article [7] with detailed calculations, graphs, and sheets and accurate and reliable parameters of diamond synthesis. He was an outstanding chemist and physicist widely regarded as the author of the technique for diamond synthesis (1939) used now in industrialized countries. To mark him together with his brother, Acad. Alexander Leipunsky, and sister, Prof. Dora Leipunska, B. Horobets published a book "Three of the Atomic Project: the Secret Leipunskii Physics" (2008). She published 2009the 2nd edition titled The Secret Physics of USSR Atomic Project: the Leipunski Family. This book tells the story of invention by O. Leipunsky and implementation of advanced method for diamond synthesis in Sweden, the USA, and the USSR.

Fifteen years later, Leipunski's theory was verified by experiment in many laboratories by specialists of Allmanna Svenska Elektriska Aktiebolaget (ASEA, Sweden) and General Electric (USA).

In the Soviet Union (1960), at the laboratory of ultrahigh pressures, Leonid Vereshchagin managed to get the first artificial diamonds. Later, the laboratory was transformed into the Institute of High Pressure Physics (IHPP) of USSR, with Vereshchagin being its first director. At the same time, in Kyiv, the Institute of Superhard Materials (director V. Bakul) was established to develop technologies and tools for the diamond application in the industry (grinding and polishing wheels, diamond saws, chisels, drill bits, etc.). In the USSR, the problems related to the synthesis of diamonds were studied at the Institute of High Pressure Physics, the Academy of Sciences of USSR; at the Institute for Superhard Materials for the Academy of Sciences of the UkSSR (Institute for Superhard Materials of the National Academy of Sciences of Ukraine in present time) and at many specialized factories and research institutes.

Diamond drill bits reinforced with composite materials.

There are two types :

a) reinforced with superhard material Slavutich;

b) reinforced with diamond-carbide inserts.

There are some main milestone of diamond drilling in overview [8] are presented. The overview of some successful projects of oil drilling, where synthetics diamonds are used, in work [9] are presented.

Experience of National TU Dnipro Polytechnic (NTU DP) Related to Diamond Drilling.

The Dnipropetrovsk Mining Institute (nowadays, the National Technical University Dnipro polytechnic) was founded in 1899. The Department for Exploration of Mineral Deposits was established in 1929, by Prof. A. Gimmelfarb. However, diamond drilling works started before the creation of the department. In the 1920s, the Professor published a series of articles related to diamonds and their application in the industry, as well as to diamond drilling for extracting coal in Donbass and iron ore in the Kursk magnetic anomaly area. The diamond drilling researches were performed in two directions: the design and the engineering (tech-niques for drilling with the use of diamond bits).

The design direction include the following R&Ds: diamond drill vibration bits; diamond drill bit with asymmetric hydraulic system; detachable diamond drill bits; and rock cutting disc.

In 1984, the SMI and the Tula branch of TsNIGRI designed vibro-absorbing diamond drill bits 01A3-ZhM (01А3-ЖМ) with the natural diamonds and 01A3sv-ZhM (01А3св-ЖМ) with the synthetic ones. The shanks are made of anti-vibration (damping) composite material D30-MP (Д30-МП). The bit diameters are 46; 59; 76; and 93 mm. The bits are designed for rotary drilling of exploration wells with coring in the low abrasive, hard and lowfractured rocks referred to the 4th —

9th categories of drillability. The application of 01A3-ZhM and drill bits instead of 01A3 and 01A3sv bits with steel shanks enables to increase average operating life (durability) by 25—30 % and penetration rates by 10—15 %. Diamond drill bits 01A3-ZhM and 01A3sv-ZhM were manufactured at the Kabardino-Balkarian diamond tools factory.

The team of engaged researchers consists of E.F. Epstein, V.F. Syryk, N.A. Dudlia, N.M. Gavrilenko, A.N. Davidenko, A.V. Varenik. In the course of drilling fluids research, the mechanisms of influence of surfactants on the rocks and on the washing liquid have been understood, with a large amount of materials requiring a separate consideration accumulated.

The NTU DP together with Geotechnics Design Office has developed a technique for hydraulic diamond drilling with the use of high-frequency hammers G59V (Г59В) and G76V (Г76В) with combined reflectors OG59 (ОГ59) and OG76 (ОГ76) located according to SMI recommendations, with intraphase and intracyclic settings.

Acceptance tests of reflectors OG59 (ОГ59) and OG76 (ОГ76) have been made in iron ore deposits of the Kryvyi Rih Exploration Expedition of Company "Yuzhukrgeologia" and Zyryanovskaya Exploration Expedition of Company "Vostkazgeologia". The test results are as follows: increase in penetration rate is 10.3—21.8 %; increase in footage per run is 10.2—42 %; reflector service life is 1150—1400 hours; maximum drilling depth is 2,280 m. The SMI and Company "Yuzhukrgeologia" have designed and implemented a technique for rotary-percussion drilling with the use of high frequency hammers G59V (Г59В) and G76V (Г76В) with and without OGV-MP (ОГВ–МП) reflectors, which ensures an increase in ROP of 7.8—20.8 % and an increase in footage per run of 34 %. The developed technique for rotary-percussion drilling with the use of high-frequency hydraulic hammers with wave reflectors, intraphase and intracyclic settings increases the efficiency and depth of hydraulic percussive drilling. For the first time in the world of drilling practice, a drilling depth of over 2,000 m (2,280 m) has been reached. The hydro-percussive systems GV+OGV (ГВ+ОГВ) have been commercialized.

The NTU DP developed a ZRMA (ЗРМА) device with rubber metallic elastic element that ensured not only vibration damping, but also the operation of drill bit with a variable rotation speed. The use of this device while drilling rocks in the Donbass region significantly reduced the number of accidents and breakdowns of drilling tools and enabled increasing:

1) ROP: by 25 % (with the use of carbide drill bits); by 30 % (with the use of diamond drill bits).

2) footage per run: by 15 % (with the use of carbide drill bits); by 12% (with the use of diamond drill bits).

Thus, R&Ds of the NTU DP Department of Mineral Exploration have been successfully implemented, passed acceptance tests and commercialized. Among them, there are antivibration diamond drill bits 01A3-ZhM, 01A3sv-ZhM-KB3AI and hydro-percussive systems, including high-frequency hydraulic hammer and reflector of hydraulic waves.

While destroying solid and hard rocks, a significant part of energy is spent on the friction of the drill bit on the rock. This energy is converted into heat. The thermal energy of friction can be used to intensify the rock destruction. For this, the temperature in the zone of contact between the cutting elements and the rock should be high enough to heat the face layer of the rock and to weaken it.

In order to utilize the heat energy of friction, the National Mining Academy of Ukraine together with Institute for Superhard Materials of the NAS of Ukraine has designed thermomechanical drill bits with the use of superhard composite materials and diamonds. The bench tests have been conducted for various designs of drill bits made of different superhard materials: polycrystalline diamond, boron carbide, silicon nitride, «geothermal» material, relit, and tungsten carbide powder. For pilot tests, thermomechanical drill bits based on artificial diamonds were used. They differed from the serial bits BS-33 (БС-33) by the presence of one or two wide flushing ports. The bench studies have showed that the specific wear of pilot bits was 1.6—2.4 times lower, as compared with the serial diamond bits, while drilling granite from Kudashevsky deposit having a density of 2.7 kg/m3, porosity 0.98—1.6, tensile strength for axial compression of 140—192 MPa and abrasion of 0.48—0.45 g/cm (Table 1).

Table 1. **Bench tests of Thermomechanical Drill Bits**

Type of drill bit	Penetration rate		Specific wear	
	m/hour	%	mm/m	%
BS-33-59	2.53	100	0.026	100
BS -33-59-TM1/1	2.81	112	0.017	63
BS -33-59-TM2/1	3.24	128	0.011	42
BS 33-59-TM2/2	3.00	118	0.096	369

The results of drilling wells with the use of thermomechanical drill bits under operating conditions are given in Table 2.

Table 2. **Test Drilling of Wells by Thermomechanical Drill Bits**

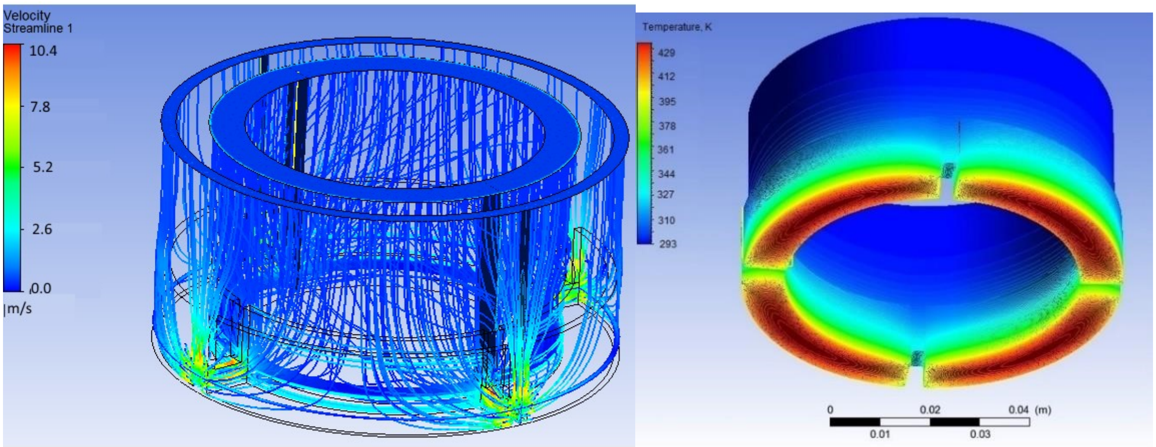
Type of drill bit	Total drilling, m	Footage per drill bit		Penetration rate	
		Depth of drilling, m	m, %	m/hour	%
BS-33-59	14.80	7.40	100	2.99	100
BS-33-59-TM1/2	17.90	8.95	121	3.75	125
BS-33-59-TM2/1	18.64	9.32	126	3.60	120

Due to the utilization of heat energy of friction, the penetration rate increases 1.20–1.25 times and the footage per run increases 1.21–1.26 times.

Currently, scientists of the NTU DP continue to work in this direction. A great attention is paid to the physical processes on the working face of borehole at diamond drilling. In particular, the idea of using friction heat to improve drilling efficiency is very promising. This idea is a basis to drilling with pulse flushing [10]. Supply of cleaning agent with a variable flow rate ensures a deeper heating of rock due to a full manifestation of the internal friction between the mineral grains constituting the rock, and between the atoms, ions, and molecules within crystal lattices, on the one hand. On the other hand, the presence of non-stationary temperature field entails an increase in fragility of the rock. This approach is seems promising to deep well drilling. For example for deep geothermal well drilling, where rotary diamond drilling is normally used. With increase of the well depth and mining rock temperature, the performance of rotary drilling method drops drastically. Proposed method could be alternative drilling technology in complicate conditions, in which mechanical power losses increase with the depths of drilling [11].

A number of mathematical models for research have been developed. The numeric study of fluid mechanics and heat transfer processes on the working face of the borehole during the process of drilling using diamond drilling bits was represented in the works [12]. The outcomes of the modeling (examples see in Fig. 2) were used for determination to establish the resource and power saving modes of drilling operations. The theoretical study of interrupted flushing impact to weakening of rock formation in the course of diamond core drilling using diamond bits in work [13] was conducted. The study revealed that under the pulse mode of drilling fluid supply there are conditions for thermal decomposition of rock formation.

The researchers from NTU DP and Oles Honchar National University (DNU) considered the prospects of further enhancement of diamond drilling bits' designs in order to increase the heat impact onto the drilled mining rock. The influence of the design particulars of drilling bits onto the junction contact temperature was studied herein. A new design of diamond drilling bit was proposed (Fig. 3).



a b

Fig.2. Results of numerical modeling heat transfer and fluid mechanics processes on working field of bit (b)

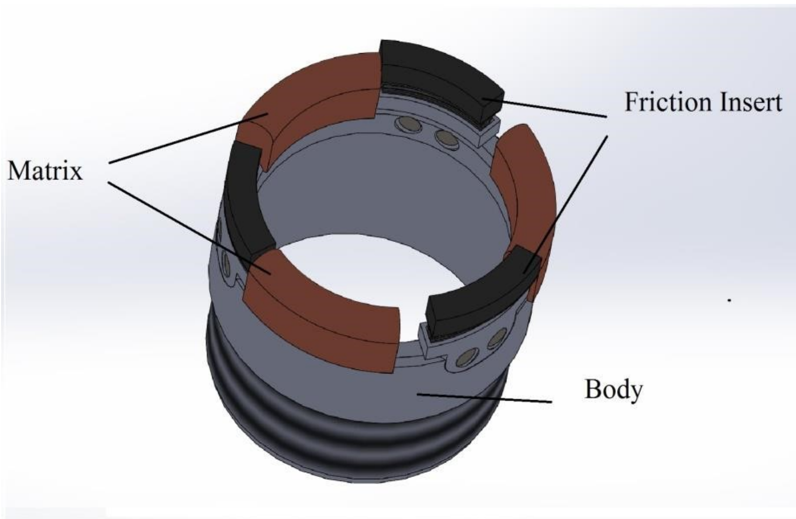


Fig.3. General view a new design of thermal mechanical drill bit

This design has a special friction insert in order to enhance the thermo-cyclical effect. Inserts implementing the heat-resistant friction materials, provide the intensive friction heat generation rate in the bottom-hole area. The difference between rock surface and drilling fluid is increasing. Thus, the rock is weaking because the tensile tensions are grow, and microfractures are propagate.

The brief overview of the history of the creation of carbide drill bits

Hard metals are composite materials of a special class, which has high hardness, wear resistance and durability that are stored at high temperatures (600°C to 800°C). These properties are particularly useful in the drilling of wells. You can briefly define them as a composition consisting of refractory compounds, typically carbide, and a relatively low-melting binder material. Firstly, Henri Muassanom (Henri Moissan) synthesized tungsten carbide in 1893 when he fused tungsten with carbon in his electric furnace.

The next step towards the creation of carbide tools considered by a work of American engineer Frederick Winslow Taylor (Frederick Winslow Taylor). It belongs to the priority development of high-speed steel, which he shared with his compatriot White. On the basis of the known tool steel "Midvale, Taylor and Monsel' white (Maunsel White) applied high temperature quenching, provided her with high hardness and heat resistance, as well as improved the original.

Created by Taylor and white tool material based on tungsten, had a high resistance at high cutting temperatures and allowed to raise the cutting speed to 5 times, so it was named "high speed steel". Reached the speed of 40 m/min at the time was considered fantastic, and represented a real revolution in metalworking. In 1900 at the world exhibition in Paris created by Taylor and White steel won a gold medal. In 1907 d. Englishman Jelvudom Heyns (by Elwood Haynes) was patented "Stellite" (from Latin stella is a star)-cast solid cobalt based alloy, used not only for the manufacture of cutting tools, but also for welding machine parts and tools with a view to durability improvement (United States Patent 873745). Then there were the alloy carbides tungsten for welding on drilling as a wear-resistant coating. The first alloy carbides were part of more porous.

German inventor Hugo Lohman (Hugo Lohmann) in 1913-1914 Gg. tried to improve the properties of the alloy carbides due to grinding in a thin powder, pressing and heating the preforms formatted (dragged) to near the melting point. The most famous of its development was hard alloy containing tungsten carbide and named "lomanit". This alloy was distinguished by exceptionally high hardness, approaching to the hardness of diamond, but like "Stellite" was extremely fragile, besides expensive, which has not received much spread. In the future, Lohman continued its development and made a number of inventions, on the various solid alloys, the most interesting of which singled out Meyer (J.R. Mejer).

Unfortunately, we could not in the databases of WIPO data, the EPO and Germany to find a mention of the issued in the name of Lohmann patents for carbide bits for drilling. Unfortunately, we could not in the databases of WIPO data, the EPO and Germany to find a mention of the issued in the name of Lohmann patents for carbide bits for drilling.

Thus, significantly called the creator of the first carbide bits is not possible. There are more than 90 million patent documents on the database of the European Patent Office (Espacenet). We found out the first issued patent to the core bit, equipped with carbide cutters. With high probability, they can be considered as the core bit, described in the German patent DE335805 issued in the name of Alfred Stapf and Hans Hundrieser. The patent was issued 14.04.1921 stated 26.03.1920. Almost at the same time, namely 16.03.1922 (filing date 22.12.1920) was granted a patent Switzerland CH93763. It does not indicate the inventor and the applicant was made by a German company Berlin-Anhaltische Maschinenbau-Actien-Gesellschaft. However, the design of the tooth described in this patent is almost similar to the previous one, so it is likely that the inventors are the same as in the German patent.

Since 1931, production of hard alloy relit (rare item cast). Note also the produced in the USSR hard alloys sormayt (plant "Red Sormovo", and then plant special steels), shift (Leningrad Institute of metals), Stalin and catch up (plant them. Schmidt), vokar (plant rare elements), drill powder, VZO (Elektrozavod), TAS-hard alloy for drilling blowtorch (plant rare elements). Ignatiev was the world's first self-sharpening carbide-insert bit in the laboratory of self-sharpening tools 1933. Zukhurov (Donbass) has proposed and used bits with a stepped arrangement under the end koromacno ring. However, these developments were not patented.

Outstanding inventor Ignatiev went down in history as the inventor of the first self-sharpening cutting tool and received his patents in the USSR (No. 14451), Germany, USA, France, UK, Italy and Belgium. However, information on the receipt of a patent for a self-sharpening carbide tools, could not be found.

As a result of the patent research database of the Federal Institute of industrial property (Russia) we have found that the first patents for inventions relating to bits are the following two patents (issued in one day, although with a different filing date). Copyright certificate of the USSR 21086 a Method of producing cutters for drill bits. Author Karwacki published 31.07.1931 stated 06.01.1930. USSR patent 21895 Method welding of drill bits of solid carbide. The author is not specified, the applicant State all-Union electrotechnical Association "VEO". Published 31.07.1931 stated 22.03.1930. In these inventions was motivated by the opportunity and suggested a technology of drill bits hard alloy.

Conclusion

The historical review and background of drill bits, materials and technologies of rotary drilling was presented herein. The experience of creating diamond drill bits and drilling technologies in the National mining University (Dnipro, Ukraine) has been analyzed. Developing new technology of rock drilling is very challenging. It is shown that improving the efficiency of rotary drilling is possible in different ways: the use of new materials; changing the operating parameters of drilling and improving the design of drill bits.

Acknowledgment

This article is dedicated to the memory of prof. Anatolii Kozhevnykov.

Целью работы является краткий исторический обзор развития алмазных буровых коронок различного типа и презентация современных исследований в данном направлении.

Методология. Анализ и обобщение научно-технических достижений и литературных источников.

Результаты. Выполнен обзор создания и развития алмазного бурового инструмента: больших и малых алмазных буровых коронок; коронок, оснащенных синтетическими алмазами; коронок, армированных композитными материалами. Показаны этапы развития технологий и новые инновационные подходы к алмазному бурению.

Новизна и практическое значение. В историческом контексте показана необходимость совершенствования бурового инструмента, показаны новые перспективные направления развития алмазных буровых коронок и технологий.

***Ключевые слова**: буровые коронки, алмазное бурение, исторический обзор, новые технологии бурения*

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БУРОВЫЕ КОРОНКИ: ИСТОРИЯ И СОВРЕМЕННЫЙ ОПЫТ

Метою роботи є короткий історичний огляд розвитку алмазних бурових коронок різного типу і презентація сучасних досліджень в цьому напрямку.

Методологія. Аналіз та узагальнення науково-технічних досягнень та літературних джерел.

Результати. Виконаний огляд створення та розвитку алмазного бурового інструменту: великих та малих бурових коронок; коронок, оснащених синтетичними алмазами; коронок, армованих композитними матеріалами. Показано етапи розвитку технологій та нові інноваційні підходи до алмазного буріння.

Новизна та практичне значення. В історичному контексті показана необхідність вдосконалення бурового інструменту, показані нові перспективні напрямки розвитку алмазних бурових коронок і технологій буріння.

***Ключові слова**: бурові коронки, алмазне буріння, історичний огляд, новітні технології буріння*

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