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Influence of Radiation and Magnetic Pulse Treatment on The Wear Resistance of Carbide Tools

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ABSTRACT

In the mining industry, hard alloy tools with high wear resistance are essential for drilling operations. This study introduces a combined magnetic-pulse treatment method, integrating preliminary gamma irradiation and pulsed magnetic field exposure, to extend the service life of VK8 hard alloy drilling tools. Gamma irradiation utilized ^{60}Co sources with doses from 3.2×10^4 to 5.0×10^8 R, followed by magnetic-pulse treatment using a custom installation with electromagnetic coils, achieving magnetic induction levels of 0.2–0.4 Tesla and pulse durations of 3 µs. The VK8 alloy, comprising 8% cobalt and 92% tungsten carbide, was tested on DZL Ø118 mm blade bits across ten batches. Results showed a 1.7–3.2-fold increase in wear resistance, influenced by treatment parameters, alloy composition, and operating conditions. The hardening effect persisted for 5–6 months after gamma irradiation and over a year after magnetic-pulse treatment. This method offers significant potential to enhance tool performance and durability in rock-destroying equipment.

Keywords: drilling tools, drilling, gamma radiation, magnetic pulse hardening, carbide.

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Introduction

In the mining industry, a variety of hard alloy tools with high wear resistance are extensively used for drilling operations. The efficiency of drilling wells or boreholes, particularly in hard and abrasive rock formations, is largely determined by the operational characteristics of these hard alloy tools. Their service life is significantly influenced by design features, drilling parameters, physical and mechanical properties of the rocks being drilled and by the used type and composition of the hard alloy.

Enhancing the wear resistance of hard alloy tools can be achieved by creating new or modifying existing composite materials. Various methods are used to increase the wear resistance of hard alloy tools, including nitriding, boriding, electro-spark alloying, plasma spraying, rolling, shot peening, isothermal quenching, thermomechanical treatment, and others.

Strengthening of hard alloys is achieved by using the methods of surface and bulk strengthening. However, numerous methods of surface strengthening of metals and hard alloys were not widely used for strengthening hard alloy tools [[1], [2], [3]]. While the positive effect of hardening the surface layer of the working elements of hard alloy tools is undeniable, the efficiency of surface hardening is low, making its practical application impractical.

Some last studies [4] have shown that results in the cryogenic treatment of VK8 hard alloy samples (a mixture of tungsten carbide grains and cobalt, acting as a binder) with a dislocation density 4.8×109 cm-2 results in the during a short-term (20 minutes) strengthening of these samples occurs due to plastic deformation.

Recently researches [[5], [6]] were observed an increase in wear resistance during the investigation of strengthening of TSI (presumably a material or alloy) through prolonged (24 to 36 hours) cryogenic treatment in liquid nitrogen vapors. The hardening effect during thermal shock (T=-196 °C) is explained by changes in the fine crystalline structure of the hard alloy. However, immersing the products in liquid nitrogen significantly increases the brittleness of the metal, since under the cold shock, tensile residual thermal stresses arise in the body of the hard alloy tools, leading in many cases to cracking and tool breakage [[7], [8]].

The modification mechanism of the physical and mechanical properties of drilling crowns during cryogenic treatment is primarily based on substructural hardening due to plastic deformation of the cobalt binder, owing to the significant difference in the thermal coefficient of linear expansion between tungsten carbide and cobalt and due to an increase in dislocation density in the hard alloy [9]. High-temperature treatment of the manufacturing cemented carbides can also significantly alter the properties of hard alloys, since it considerably increases the internal stress in the carbide [10]. For instance, as the temperature exceeds 500 °C, a decrease in the hardness of the VK8 alloy accompanied by an increase in the alloy's ductility and a change in its resistance to cyclic micro-contact loads. Therefore, it is more prudent to perform the strengthening of the finished tool, rather than its individual working elements before the product is manufactured.

The literature analysis has revealed that radiation treatment using gamma rays, which possess high penetrating ability and do not lead to residual radioactivity, is a more promising method [[11], [12]]. When hard alloys are irradiated, the strengthening of the material's structure is determined by the absorbed dose of ionizing radiation. Research results on the effects of gamma irradiation and electron irradiation, as reported in [[12], [13]], showed that with increasing the doses of irradiation, the bending strength limit and deformation increase up to the irradiation dose range from 8×104 - 5×105 R, after which a sharp decrease is observed [13]. The increase in defect density, especially dislocations, according to general views on the nature of substructural strengthening in metals and alloys, leads to changes in their physico-mechanical characteristics. This results in the increase of the wear resistance and strength properties of the material, but at the same time, an excessively high defect density leads to the increasing brittleness, stiffness of products, and consequently, to the decreasing their operational indicators, primarily durability and reliability.

The method of magnetic-pulse treatment is the most effective way for bulk strengthening of cemented carbide tools. The feasibility of using magnetic-pulse treatment for cemented carbide tools is due to the presence of cobalt in the tool composition – a ferromagnetic material with high magnetic permeability. The improvement in the properties of ferromagnetic materials that have undergone magnetic-pulse treatment is achieved through the directed orientation of the free electrons of the hard alloy by an external field, which consequently increases its thermal and electrical conductivity. The interaction between the pulsed magnetic field and the ferromagnetic material is more intense with higher structural and energetic heterogeneity. After processing cemented carbide tools with this method, an increase in their fatigue strength and overall strength, and a reduction in residual thermal stress occur [14]. Utilizing magnetic-pulse treatment notably diminishes the surplus energy in the material, which is linked to the accumulation of internal and surface stresses. Consequently, it was decided to combine two methods of enhancing the wear resistance of cemented carbide materials: radiation and magnetic-pulse treatments.

The goal of this work is to develop a method and optimal regime for the bulk strengthening of cemented carbide tools through the combined application of penetrating gamma radiation and pulsed magnetic field.

Experimental part

For gamma radiation exposure of the samples, a pool-type Gamma Facility of the institute Nuclear Physics, Uzbek Academy of Science (INP UzAS) was used (Figures 1). In so doing, we have used the ^{60}Co sources with average gamma quantum energy of 1.25 MeV and a dose rate of 130 R/s, with an exposure dose ranging from 3.2×10^4 to 5.0×10^8 R. The choice of gamma irradiation is determined by its technological efficiency and high penetrating ability.

Figure 1 - Pool-type Gamma Facility [14]

For the implementation of magnetic-pulse treatment (MPT), a magnetic-pulse facility was constructed (see Figures 2 and 3), featuring a magnetic inductor 2, consisting of two pairs of electromagnetic coils, and a magnetic core 1 on which the electromagnetic coils are mounted.

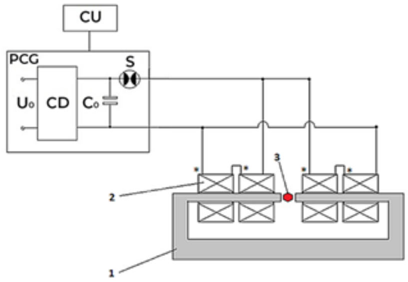

Figure 2 - Block Diagram of the Magnetic-Pulse Installation:
1 - Magnetic core; 2 - Solenoid inductors; 3 - Drill bit; CU - Control unit; PCG - Pulse current generator; CD - Charging device; S - Switching device; C0 - Capacitor bank; U0 - Mains voltage [14]

This design allows carrying out the treatment of entire drill bits and chisels with a pulsed magnetic field, which is a necessary condition for the method of enhancing the wear resistance of finished cemented carbide tools.

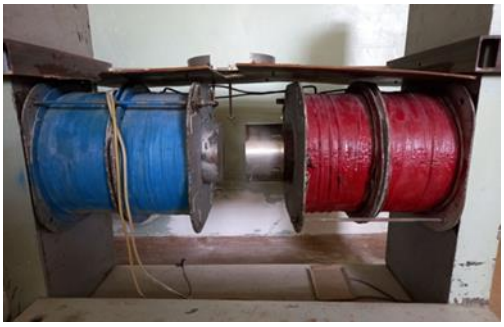

Figure 3 - Magnetic Field Inductors Mounted on a Magnetic Core

The use of cylindrical inductors with a magnetic core is associated with the fact that such a configuration possesses high efficiency and a high-power factor, with the efficiency of an inductor with a magnetic core reaching at least 70-80 %. During magnetic-pulse hardening, as the pulsed electric current flows through the inductor, the magnetic field lines through the magnetic core are concentrated on the hardened sample (drilling tool), which is positioned in the gap of the magnetic core. This induces an eddy current on the surface of the sample, proportional to the changing rate of the magnetic flux through the cross-sectional area of the work piece.

If we take the current strength $I_1 = 10^3$ A, with a coil having N = 10 turns and a length of $l_0 = 0.136$ m, and coil wire thickness a = 0.01 m, we do the calculation using formula

$$H_{1b} = NI_1/l, \tag{1}$$

where N - the number of turns of the inductor coil; I_1 – the strength of the discharge current in the inductor; l - length of the contour, for points located within the inductor in immediate proximity to the turns (length $l=l_0+2a=0{,}156$ m) yields a value for the modulus of the magnetic field strength denoted as H1b, equal to 6.41×10^4 A/m. To study the effect of the magnetic field on the hardening of solid alloys, the treatment of samples of drill bits was conducted using a magnetic-impulse approach with a magnetic induction of 0.2-0.4 tesla and pulse durations of 3 ms. The magnetic-pulse installation allows us to apply the fields with intensities ranging from 10^4 to 10^{11} A/m to the parts being processed, with a pulse duration from 1 to 0.1 ms.

In experiments, the technology of volumetric hardening of rock-destroying tools was applied, using a combination of two types of physical effects: gamma-ray irradiation and treatment in a pulsed magnetic field.

Industrial samples of three-blade drill bits DZLØ118mm, used in the mining enterprises of the Republic of Uzbekistan, were used as test objects. For the rock-destroying assembly of drilling bits, the hard alloy material VK8, which is characterized by strength and wear resistance [15] with an average hardness of 88 HRA (Rockwell), is primarily used. The mentioned hard alloy VK8, used for DZL Ø118mm drill bits, is a composite material belonging to the tungsten-cobalt group with a composition of 8 % cobalt and 92 % tungsten carbide. The chemical composition of the tungsten-cobalt mixture VK8 [16] (mass percentage, %) is: cobalt - 7.5-8.1, oxygen, not more than – 0.5, total carbon - 5.30-5.65, free carbon, not more than – 0.1, iron-0.3. By altering the chemical composition ratio of the alloy, its physic-mechanical properties are regulated. The increasing of the cobalt content in the alloy leads to an enhancement in strength, wear resistance, and a reduction in brittleness (the more cobalt in the alloy, the softer and stronger it becomes). The microstructure of the VK8 alloy is two-phase, consisting of tungsten carbide and cobalt crystals with an uneven distribution throughout the volume of the hard alloy.

The samples were subjected to preliminary treatment with gamma radiation of ^{60}Co in a dose range from $3 \cdot 10^4$ to $9 \cdot 10^6$ R and subsequent exposure to magnetic induction of 0.4 Tesla. Ten batches of nine DZLØ118mm blade drill bits each were processed for the purpose of testing nine batches during drilling, and one batch is used to determine the interval and rate of reduction in strength limit during storage.

Discussion of the results

The measurement of hardness using the Rockwell scale (HRA) showed us an increase in the samples with an increase in the dose of gamma-ray irradiation within the range of $2.5 \cdot 10^4$ to $5.5 \cdot 10^5$ R, and a decrease with a further increase in the irradiation dose.

It was found that processing samples in a magnetic-pulse field increases wear resistance by an average of two times compared to samples without magnetic-pulse processing, which is in good agreement with research data in recent studies [[17], [18]].

The results of drilling with hard alloy bits with VK8 plates on the surface chisels after combined gamma magnetic treatment are presented in Table 1 and Figure 4.

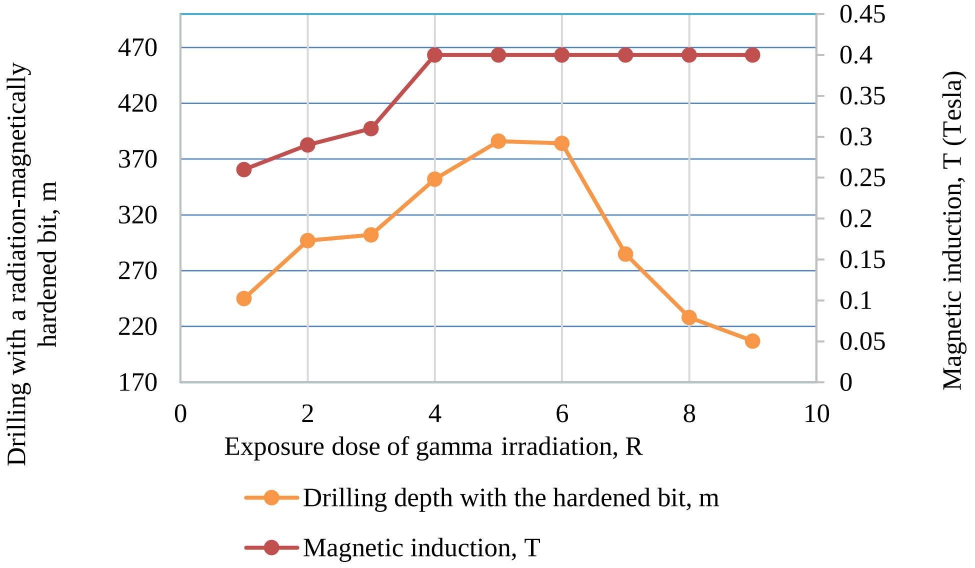

Figure 4 - Test results of drill bits hardened by gamma irradiation and magnetic-pulse treatment

Table 1 - Main quality criteria for core samples

Serial №.	Gamma Radiation Exposure Dose, R	Magnetic Induction, T	Average Penetration per Unhardened Bit, m	Penetration per Bit with Radiation-Magnetic Hardening, m	Increase in Penetration, % / times
1	$3.2 \cdot 10^4$	0.26	120	245	104 / 2
2	$6.5 \cdot 10^4$	0.29	120	297	148 / 2,4
3	$8.9 \cdot 10^4$	0.31	120	302	152 / 2,5
4	$2.4 \cdot 10^5$	0.4	120	352	193 / 2,9
5	$5.5 \cdot 10^5$	0.4	120	386	222 / 2,7
6	$5.6 \cdot 10^5$	0.4	120	384	284 / 3,2
7	$8.9 \cdot 10^5$	0.4	120	285	185 / 2,4
8	$2.2 \cdot 10^6$	0.4	120	228	90 / 1,9
9	$8.9 \cdot 10^6$	0.4	120	207	72.5 / 1.7

The analysis of the data obtained suggests that the use of combined processing of three-blade DZL bits leads to an increase in their durability. Treatment of hard alloy tools within a radiation-magnetic-impulse environment yields a substantial enhancement of the wear resistance, ranging from 1.7 to 3.2 times when contrasted with the untreated counterparts. The increase in the hardening degree of the samples from the absorbed dose of ^{60}Co gamma radiation under the combined effect of the magnetic field has a non-monotonic character (Table 1). From the results of the drilling tests using three-blade DZL drill bits, it is evident that combined radiation and magnetic-pulse treatment significantly enhances the resource of hard alloy tools, and the hardening effect is determined by the dose of gamma irradiation, reaching its maximum value within the absorbed dose range from 2.5×10^4 to 5.5×10^5 R. To monitor the reduction in the hardening magnitude during storage, hardness measurements were conducted after irradiation and after the combined radiation and magnetic-pulse treatment of the samples. [[19], [20]]. It was found that the hardening effect persists after gamma irradiation during 5-6 months and in the case of combined treatment for this effect persists during about 1 year.

Conclusion

A new method of combined magnetic-pulse treatment has been proposed, incorporating preliminary gamma irradiation and the influence of a pulsed magnetic field. This method allows to enhance the service life of drilling tools made from various types of hard alloys.

Using the gamma irradiation of ^{60} Co on hard alloys employed in DZL drilling bits results in the enhancement of the strength of these alloys within the absorbed dose interval ranging from 2.5×10^4 to 5.5×10^5 R.

The degree of hardening of hard alloys for drilling bits is determined by the dose of gamma irradiation and reaches its maximum within the absorbed dose range from 2.5×10^4 to 5.5×10^5 R. Exceeding this dose range results in a decrease in strength, wear resistance, and an increase in the brittleness of hard alloy tools.

Gamma irradiation by using gamma quanta of ^{60}Co within the absorbed dose range from 2.5×10^4 to 5.5×10^5 R, followed by magnetic-pulse treatment with a magnetic induction of 0.2-0.4 Tesla and pulse durations of 3 μs, would increase wear resistance by 1.7 to 3.2 times, depending on the treatment regime, the composition of the hard alloy, and operating conditions.

The hardening effect is retained during 5–6 months after gamma irradiation, and during about 1 year after magnetic-pulse treatment.

Conflict of interest. On behalf of all the authors, the correspondent author declares that there is no conflict of interest.

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Қатты қорытпалы құралдардың тозуға төзімділігіне радиациялық және магниттік импульстік өңдеудің әсері

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ТҮЙІНДЕМЕ

Кен өндіру өнеркәсібінде жоғары тозуға төзімді қатты қорытпалардан жасалған құралдар бұрғылау операциялары үшін маңызды болып табылады. Бұл зерттеу VK8 қатты қорытпасы негізінде бұрғылау құралдарының жұмыс мерзімін ұлғайту мақсатында гамма-сәулелендіру мен импульстік магниттік өріс әсерін біріктіретін магнитті-импульстік өңдеу әдісін ұсынады. Гамма- сәулелендіру ^{60}Co көздерін пайдалана отырып, мөлшерлері $3,2\times10^{4}$-ден $5,0\times10^{8}$ R дейін болды, одан кейін магнитті-импульстік өңдеу арнайы орнатылған электромагниттік катушкалармен жүзеге асырылып, магниттік индукция деңгейі 0,2–0,4 Тесла және импульс ұзақтығы 3 мкс болды. VK8 қорытпасы, құрамында 8% кобальт және 92% вольфрам карбиді бар, DZL Ø118 мм ұстаралы бұрғыларда он партияда сыналды. Нәтижелер өңдеу параметрлері, қорытпа құрамы және жұмыс жағдайларының әсерінен тозуға төзімділіктің 1,7–3,2 есеге артатынын көрсетті. Қатыру әсері гамма- сәулелендіруден кейін 5–6 айға дейін және магнитті-импульстік өңдеуден кейін бір жылдан астам уақыт бойы сақталды. Бұл әдіс тау-кен құралдарының жұмыс көрсеткіштері мен ұзақ мерзімділігін арттыру үшін үлкен әлеуетке ие.

Түйін сөздер: бұрғылау құралдары, бұрғылау, гамма-сәулелену, магниттік импульстің қатаюы, карбид.

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АННОТАЦИЯ
В горной промышленности инструменты из твердых сплавов с высокой износостойкостью необходимы для буровых операций. В данном исследовании представлен комбинированный метод магнитно-импульсной обработки, интегрирующий предварительное, гамма-облучение и воздействие импульсного магнитного поля, с целью увеличения срока службы буровых инструментов из твердого сплава VK8. Для гамма-облучения использовались источники ^{60}Co с дозами от $3{,}2\times10^4$ до $5{,}0\times10^8$ R, после чего проводилась магнитно-импульсная обработка с использованием специализированной установки с электромагнитными катушками, обеспечивающими уровни магнитной индукции 0,2–0,4 Тесла и длительность импульсов 3 мкс. Сплав VK8, состоящий из 8% кобальта и 92% вольфрамового карбида, испытывался на лезвийных сверлах DZL диаметром 118 мм в десяти партиях. Результаты показали увеличение износостойкости в 1,7–3,2 раза, что зависело от параметров обработки, состава сплава и условий эксплуатации. Эффект упрочнения сохранялся в течение 5–6 месяцев после гамма-облучения и более года после магнитно-импульсной обработки. Этот метод представляет собой значительный потенциал для повышения эксплуатационных характеристик и долговечности инструмента в горнодобывающем оборудовании.

Ключевые слова: буровые инструменты, бурение, гамма-излучение, магнитно-импульсное упрочнение, карбид.

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