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IMPROVING THE PERFORMANCE PROPERTIES OF DRILL RODS FOR DRILLING AND BLASTING OPERATIONS

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Abstract. The article examines the operating conditions of drilling equipment, particularly drill pipes. The purpose of this study is to develop drill pipes based on the load they experience and the material they are made of. Factors influencing the wear of drill pipes are identified, including friction at pipe joints, thermal wear, abrasive wear, oxidative wear, and others. The working conditions and loads on drill pipes under various drilling scenarios are analyzed, including the maximum loads encountered during the drilling of hard rock using roller bits. The functions of drill pipes are considered, such as transmitting axial force and torque, transporting drilling fluid to the drilling site, removing rock debris from the wellbore. The study justifies and selects materials for drill pipes that balance strength and cost while meeting the requirements of drilling equipment. To achieve this goal, the stress-strain state of drill rods during rotary drilling under operational loads was studied, considering the displacement of working loads or the misalignment of the drill rod and bit axes. Mathematical calculations and data processing are performed using the engineering software package MATHCAD for drill pipes with an outer diameter of DD and an inner diameter of dd, depending on the physical and mechanical properties of the pipe material, axial load on the drill string, and the torque transmitted by the drill pipes. The article provides calculations for drill pipes used in roller drilling of 200 mm diameter wells in hard rock. Connections between drill pipes are analyzed, particularly a specialized locking threaded connection with an increased thread profile height. The study reviews designs used in international practice and domestic drilling equipment manufacturing. A design and calculation of the threaded connection for drill pipes made of 40X steel are presented, along with drawings of the calculated thread profile.

The operating conditions of drilling equipment and factors affecting the wear of drill pipes are examined, and recommendations for extending their service life are provided, which can be utilized in the design of new drilling equipment. Suggestions and structural solutions to enhance the performance characteristics of drill pipes are proposed, allowing the selection of optimal material parameters and structural elements of drill pipes based on the operating conditions of the drill string.

Keywords: drill pipe, drill string, roller drilling, critical loads, threaded connection.

1. Introduction

In open-pit mining, drilling blast holes is one of the most labor-intensive and costly operations. The development of deposits composed of hard and extremely hard rocks necessitates the implementation of drilling and blasting operations.

According to the data, approximately 30% of the total cost of rock excavation is spent on well construction.

The uninterrupted operation of well construction directly affects the seamless functioning of subsequent processing plants. The roller cone drilling method is predominantly used for well construction, accounting for over 80% of all drilling methods. Rotary drilling with cutting tools constitutes approximately 16% of drilling activities, while the remaining 4% is attributed to percussive-rotary drilling, thermomechanical, thermal, and other methods.

The service life of roller cone bits and drill pipes depends on the physical and mechanical properties of the rocks, moisture content, temperature conditions, and other factors.

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One of the primary challenges in open-pit mining is the physical and moral aging of drilling equipment. The choice of drilling method and tools depends on the physical and mechanical properties of the rocks, climatic conditions, and other factors. In most cases, roller cone bits made of various steel grades are selected, which, together with drill pipes, operate under extremely harsh conditions. There are single-, double-, triple-, and quadruple-cone bits, but in the mining industry, triple-cone bits are predominantly used. These bits can be either self-cleaning or non-self-cleaning. To remove crushed rock from the well, water or air is injected. The rock fragments that come into contact with the pipe surfaces cause wear. To extend the service life of drill pipes, the steel grade and the technologies for connecting the pipes are carefully chosen. Additionally, to reduce abrasive wear, innovative anti-corrosion coatings that provide enhanced wear and corrosion resistance must be applied. During well drilling, fluctuations in axial force and torque occur. It is known that the loads on the drilling rig and drill machines due to axial and tangential oscillations can exceed the feed axial force by a factor of 4, and their frequency can be three times higher than the rotational frequency of the drill bit [1]. Therefore, the durability of the equipment is a critical scientific and technical issue, upon which the successful operation of mining production depends.

2. Methods

The reliability of mining equipment is a highly relevant issue. Equipment reliability is defined as the ability to maintain, within specified limits over time, all parameters that characterize its capability to perform required functions under given operating conditions, maintenance, and repairs.

The properties of safety, durability, maintainability, and preserveability.

Durability is the property of the object to maintain a workable state until the appearance of the limit state at the established limit of maintenance and repair.

When designing components, it is essential to understand friction and material wear. A key characteristic of external friction, which occurs on contact surfaces during their interaction, is the process of bond formation between these surfaces, their operation, and eventual destruction.

When external forces act on an object, physical, chemical, and mechanical processes occur in the surface layers of the friction pair.

The processes of friction and wear of contacting surfaces were studied by many researchers [9], but the most comprehensive study was conducted by B.I. Kostetsky [10], who determined that each component and connection undergoes a clearly defined key type of wear, which determines the component's durability during operation

Wear of the first kind, known as adhesive wear, occurs during sliding friction at low relative velocities of the contacting surfaces in the absence of lubrication or a protective oxide film. This wear arises from plastic deformation of the surface layers of the metal components between the friction surfaces. As a result of bond destruction, particles of metal are either detached from the friction surfaces or adhere to them.

When the friction surfaces move relative to each other, there is a metallic bond formed at their contact points.

With continued movement, at the points where adhesive wear occurs, strengthening takes place, and particles of the softer metal are detached from the surfaces, or scratching occurs in the strengthened areas of the contacting surface layer.

In the case of oxidative wear, the material wears down as a result of microplastic deformations in the surface layers and the diffusion (penetration) of oxygen into the plastically deformed volume of the metal (for iron, FeO, Fe2O3, Fe3O4). Oxidative wear can occur both during sliding friction and rolling friction.

Thermal wear occurs when heating, caused by friction, leads to high localized temperatures on the friction surfaces due to high specific pressures and sliding speeds. As a result, the surfaces heat up to elevated temperatures, which can cause processes such as recrystallization, annealing, hardening, or melting. These changes lead to a sharp reduction in the metal's strength and its rapid wear. Thermal wear occurs during sliding friction at high relative sliding speeds.

Abrasive wear shares many similarities with metal cutting processes. In this type of wear, abrasive particles, when they come into contact with the friction surfaces, deform and shear off the surface layer. As a result, numerous scratches appear on the contacting surfaces, leading to material degradation and the eventual destruction of the component, causing changes in its shape and dimensions.

Abrasive particles can include hard inclusions from the material of the component, wear products, or external abrasives that have entered the contact area.

Pitting wear occurs during rolling friction as a result of microplastic deformations and the hardening of surface layers.

Boundary friction and wear in machine joints is the process of mechanical and physico-chemical interaction between the contacting surfaces of solid bodies.

There are several tasks involved in managing the processes of friction and wear, including:

- expansion of the range of mechanical loads and environmental conditions that allow normal friction without causing destruction;
- Optimization of friction forces and minimization of wear rate within the normal friction range.

Another way to reduce wear is alloying the materials of the friction pair to increase hardness. This is achieved by using additives in lubricants.

The use of technological means ensures the maximum resistance to the action of abrasive particles. These methods include the use of special steels and alloys, as well as thermal, chemical-thermal, and other methods of surface hardening treatment. Resistance to abrasive wear is achieved through the application of overlay coatings made from special alloys, which provide high hardness, strength, and toughness of the surface layers of components.

The reduction in the intensity of oxidative wear when friction nodes operate in abrasive environments can be achieved through the use of various strengthening technologies that increase the hardness of the surface layer, thereby facilitating the formation of oxide films. As research has shown, the cause of fatigue wear (spalling) is the plastic deformation of the surface layers. Therefore, to prevent it, contact stresses should not exceed the yield strength of the surface layer of the metal, which is in a special stressed state. A high level of ductility is ensured by using special alloyed steels and strengthening through thermal treatment.

During operation, it is necessary to maintain a temperature regime that preserves the stability of the strength characteristics of the surface layers. Wear reduction in rolling friction can be achieved by limiting the intensity of oxidative processes. For this purpose, four groups of measures can be used:

- Reduction of the plastic deformation size and uneven distribution of the load across the contact area.
- Increasing the hardness of the friction surface to maximum values (VRC 62-64).
- Ensuring a high surface cleanliness grade;
- Coating the rolling surface with a thin layer of ductile metal.

As research has shown, improving the cleanliness grade and coating with a thin layer of ductile metal ensures an increase in the actual contact area and a more uniform distribution of stresses on the friction surface. Increasing the surface hardness leads to a reduction in the depth and intensity of plastic deformation.

During the rotary drilling process, rocks are subjected to destruction by steel or carbide teeth of the rock bits (steel cylinders or cones with teeth or reinforced cylindrical pins) that rotate at high speeds (60–600 rpm) on the drill bit bearings. The rock bits are capable of withstanding pressures up to 2000 Pa. As the rock bits rotate, their teeth create stresses at the contact points with the rock, leading to its destruction through crushing and chipping.

During operation, elements of rotary rock bits are subjected to both static and dynamic loads caused by the impact nature of the interaction between the drill bit's rock-breaking components and the rock to be broken. The cyclical loading of the metal leads to the formation of fatigue cracks and the destruction of both the reinforcement elements and the bearing components of the drill bit.

The drill string acts as a drive shaft from the drilling rig to the rock-breaking tool, transmitting axial force and rotational torque that turns the downhole assembly.

perform the following functions:

- supply drilling fluid to the bottom of the borehole;
- transport drilled rock and serve as a connecting link when extending drill rods as the depth of the well increases.

Drill rods serve to transmit torque and axial force to the drill bit, as well as to supply compressed air to the bottom of the hole for the removal of cuttings from the well. The drill rod set includes one end rod (drill stem) and several main working rods. The nipples of the working rods have internal threads of a smaller diameter for connection with the swivel spindle, through which air and water are supplied. To ensure normal conditions for the removal of drilled rock from the well and to achieve the required upward flow velocity (20–75 m/s depending on the density of the material being removed), the diameter of the rod should be 20–50 mm smaller than the diameter of the drill bit. For example, with a drill bit diameter of 244.5 mm, rods with an outer diameter of 215 mm are used. The rods are made from seamless cold-rolled

(GOST 8734-75) or hot-rolled (GOST 8732-78) steel tubes. Since the rods for drilling wells work under particularly severe conditions, they are made from steels alloyed with molybdenum, nickel, tungsten, and vanadium, which increase the service life up to 10 times compared to rods made from non-alloyed steels.

Mathematical calculations and data processing were carried out using the engineering software package MATHCAD for drill rods with an outer diameter *D* and an inner diameter *d*, depending on the physical and mechanical properties of the rocks, axial load *P* and the torque M_t [5, 8].

Input parameters: $D = 160$ mm, $D = 200$ mm; $P = 1000$ kN; $M_k = 4.2$ kN·m;

$$[\sigma] = 3300\frac{\text{kgf}}{\text{cm}^2} \approx 323.62 \text{ MPa}; \ [\tau] = 2400\frac{\text{kgf}}{\text{cm}^2} \approx 235.36 \text{ MPa};$$

$$\sigma_R = \sqrt{[\sigma]^2 + [\tau]^2} = \sqrt{323.62^2 + 235.36^2} \approx 400.16 \text{ MPa};$$

$$\sigma_R{}^2 = \left(\frac{P}{S}\right)^2 + \left(\frac{M_\kappa}{W}\right),$$

where $S = \frac{\pi}{4}\left(D^2 - d^2\right)$ – cross-sectional area; $W = \frac{\pi}{16D}\left(D^4 - d^4\right)$ – polar moment of inertia of the cross-section.

After substituting $d = D\sqrt{t}$, and other transformations, we will obtain a fourth-order equation:

$$t^4 - \left(2 + \frac{16P^2}{\pi^2 D^4 \sigma_R{}^2}\right)t^2 - \frac{32P^2}{\pi^2 D^4 \sigma_R{}^2}t + 1 - \frac{16P^2D^2 + 256M_k{}^2}{\pi^2 D^6 \sigma_R{}^2} = 0. \quad (1)$$

Let's express equation (1) in the form:

$$t^4 - K(D)t^2 - m(D)t + N = 0, \quad (2)$$

where $K(D)$, $m(D)$ – the coefficients of t, N – the constant term:

$$K(D) \neq 2 + \frac{16P^2}{\pi^2 D^4 \sigma_R^2} \ ;$$

$$m(D)=\frac{32P^2}{\pi^2 D^4 \sigma_R^2};$$

$$N=1-\frac{16P^2D^2+256M_k^2}{\pi^2 D^6 \sigma_R^2}.$$

Substitute the value D=160 mm into equation (2) and solve the equation for «t» in the MatCAD program. The solution has two real positive roots. From them, we choose only the one that corresponds to the substitution $d=D\sqrt{t}$, i.e. $t=\frac{d^2}{D^2}$, and satisfies the condition $0<t<1$, since $D>d$.

We obtain the value of $t\approx 0.876$ for the diameter D, and then using the formula $d=D\sqrt{t}$ we determine $d=160\sqrt{0.876}=149.71$ mm.

Similarly, we obtain the values for d for a diameter $D=200$ mm, where t ≈ 0.92, $d=200\sqrt{0.92}\approx 191.87$ mm.

3. Results and discussion

Calculation of threaded connection. Mechanical properties for steel 40X

$$\sigma_T=569 \text{ MPa}, \ \sigma_{TM}=765 \text{ MPa}.$$

Outer diameter of the ring: Ø=120.3 mm. Inner diameter of the ring: Ø=57.3 mm.

Calculation of the connection for axial load

$$P=F\cdot[\sigma_T]=\left(\frac{3.14\cdot 120.3^2}{4}-\frac{3.14\cdot 57^2}{4}\right)\cdot 56900\approx 515.2\,\text{T},$$

where P is the calculated longitudinal load for the threaded connection, T; F is the cross-sectional area of the drill pipe, mm^2.

Calculation of the connection for the torque:

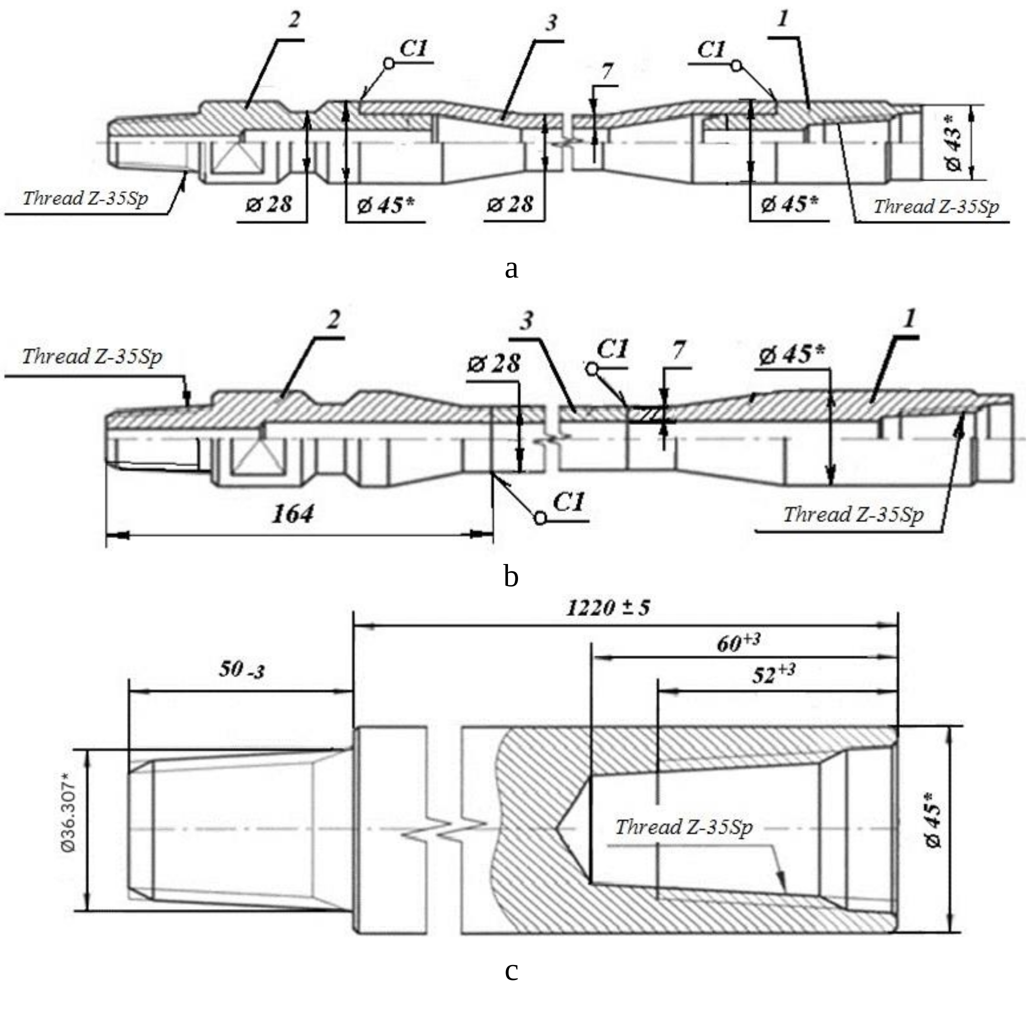
$$M_{conn}=W_\kappa\cdot\tau=0.2\cdot(D^3-d^3)\cdot(0.577\cdot 56900)=0.2\cdot(120^3-57^3)\cdot(0.577\cdot 56900)=$$
$$=0.2\cdot(1728000-185193)\cdot(32831.3)\approx 105.2 \ \text{kN}\cdot\text{m},$$

where W_k – polar moment of resistance of the rod, mm^2.

The proposed special locking thread with an increased profile height, instead of the U-007 profile according to standard 7 ANSI (GOST R 50864), has a strength that is 1.41 to 1.86 times higher than the standard. The described design of the adapter with a removable threaded tip ensures the rotation of the rods in both directions.

These recommendations are applicable for underground drilling of degassing and gas extraction wells in coal mines.

Machine-building plants in Ukraine have mastered the production of drilling rigs for various purposes and technical specifications: well diameters from 100 mm to 1500 mm, well depths from 150 to 1500 m, drive power from 26 kW to 540 kW, and pulling force from 20.0 kN to 1360.0 kN. The drilling rigs are equipped with drilling pipes of various designs and specifications: welded pipes with diameters ranging from 28 mm to 110 mm for drilling with well flushing, solid rods (without internal channels) (здесь точно rod) for creating wells using penetration methods, followed by expansion to the designed diameter using tensioned drilling rods or steel cables. An example of the design of drilling rods is shown in Fig. 1.



a – tube part with welded threaded ends, company Witch Ditch; b – variant of the 28 mm rod with welded threaded ends by friction; c – rod without central channel

Figure 1 – Types of drilling rods

The main threaded connection for rods is the lock cone thread according to the standard API 7 of the American Petroleum Institute. For rods with small diameters (28–54 mm), profile VI according to GOST R 50864 (V-0.05 as per API 7) is used (Fig. 2). Rods of this series were manufactured with special locking threads featuring a Z-30Sp thread profile. The difference in the profile Lies in increased working height, which ensures a 1.76 times increase in the wear resistance of the profile (2.192: 1.242) and an increase in the working life of the locking connection by 1.5 to 1.7 times.

In the technical specifications of drilling rigs for horizontal directional drilling of wells, the values of pull force for the formation of wells are provided. In the practice of creating horizontally directed wells in weak unconsolidated rock formations (sometimes of the "quicksand" type), accidents involving rods occur due to the failure of the threaded ends. Therefore, it is necessary to perform thread quality control and, if necessary, reduce the pulling force.

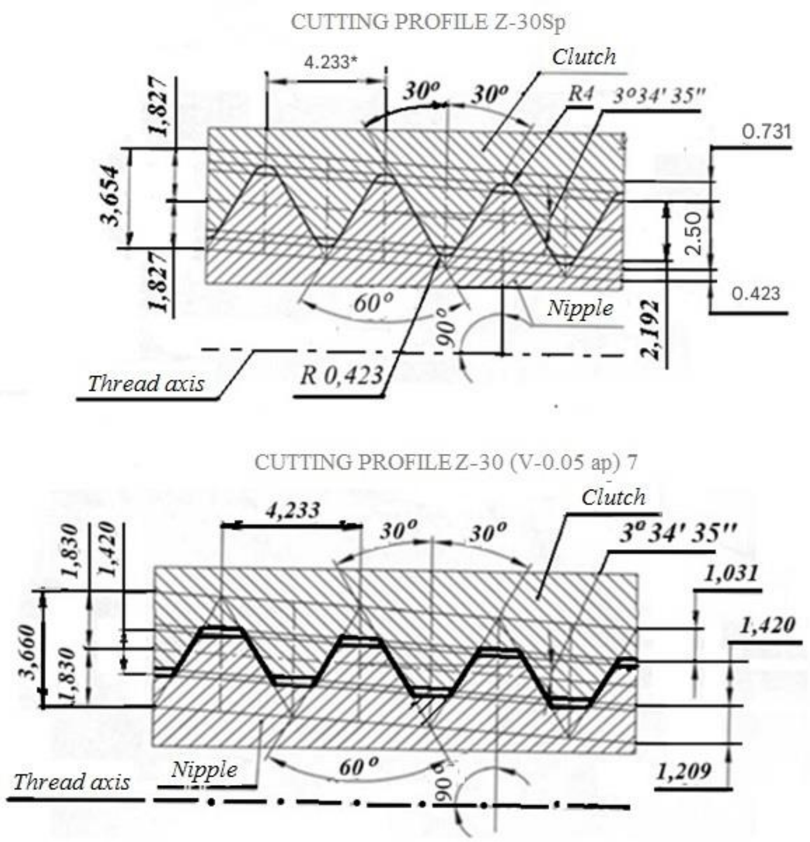


Figure 2 – Types of lock threads

There are known methods for calculating the strength of tapered lock to determine the permissible loads on drill rods. The material for the lock connections is steel grade 40XN according to GOST 4543-71, with heat treatment, based on the following parameters:

Tensile strength limit, MPa 900;
Yield strength from, MPa 700;
Relative elongation % 15;
Brinell hardness HB .... 282.

The methodology for calculating the load that causes shear of thread turns under uniform distribution includes determining the force while considering the thread parameters and the allowable stresses in the material of the threaded connection. The load is determined using the formula

$$Q_{calc} = \pi \cdot d_p \cdot k_s \cdot \tau_c \text{ N},$$

where Q_{calc} – the calculated force of the thread turns in the threaded connection, N; $\pi = 3.14$ – coefficient π; d_p – diameter of the cone circle in the reference plane, mm; $k_s = 0.7$ – coefficient of the completeness of the locking thread; τ_c – calculated shear stress in the threaded connection, MPa.

$$\tau_c = (0.6....0.7) \cdot \sigma_c \text{ MPa.}$$

The diameter of the cone circle in the reference plane is determined by the formula:

$$0.5 d_p = r + \frac{l}{3} \cdot \frac{R+2r}{R+r} \cdot tg\varphi \text{ mm,}$$

where l is the thread length (mm); R is the radius of the large base of the thread cone (mm); r is the radius of the small base of the thread cone (mm); φ is the angle of the thread cone (degrees).

Another dangerous factor for thread failure is the bending of the thread turns. The calculation of the bending stress in the thread turns is performed using the following formula:

$$\sigma_{bs} = \frac{4 \cdot S \cdot Q}{\pi\left(d_0^2 - d_1^2\right) \cdot l} \text{ MPa,}$$

where σ_{bs} is the thread pitch tension, MPa; S is the thread pitch, mm; d_0 is the outer diameter of the thread, mm; d_1 is the inner diameter of the thread, mm.

The shear stresses are determined under the condition of applying the calculated cutting load of the thread. The actual values of the drilling machine travel are lower than the calculated ones.

In addition to using the Z-30Sp thread profile, it is recommended to use interchangeable adapters in drilling machine adapters. The use of interchangeable threaded adapters will significantly extend the service life of the adapter by several times due to the use of replaceable parts. Even when the worn interchangeable adapter is removed, the adapter with the internal unworn thread can still be used, effectively doubling the service life of the adapter.

4. Conclusions

Based on the conducted analysis and the research performed, the main conclusions can be formulated.

Depending on the physicomechanical properties of the rocks being drilled, roller cone bits of various steel grades are selected. There are single-, double-, triple-, and quadruple-cone bits, but in the mining industry, 3-cone roller bits are used, which can be either self-cleaning or non-self-cleaning. Water or air is used to clean the well from the crushed rock. The parts of the rock that come into contact with the surface of the rods cause wear on their surface.

To increase the service life of the rods, the steel grade and the technologies for connecting the rods are selected. Additionally, anti-abrasive coatings are used to reduce abrasive wear. A justification and selection of materials for the drilling rod were made. The chosen material for the drilling rod will ensure an optimal balance between strength and cost and meet the requirements for drilling equipment. Its properties make it a suitable option for manufacturing drilling rods under conditions of applied calculated loads.

Threaded connections are used to join the rods. Improving the efficiency of drilling equipment requires taking into account the operational factors that arise during drilling operations.

Conflict of interest

Authors state no conflict of interest.

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ПІДВИЩЕННЯ ЕКСПЛУАТАЦІЙНИХ ВЛАСТИВОСТЕЙ БУРОВИХ ШТАНГ ДЛЯ ПРОВЕДЕННЯ БУРОВИБУХОВИХ РОБІТ

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Анотація. У статті розглянуто умови роботи бурового обладнання, зокрема бурових штанг. Метою цієї статті є розробка бурових штанг в залежності від навантаження на них та матеріалу, з якого вони виготовляються. Визначені фактори, які впливають на знос бурових штанг, такі як тертя в місцях з'єднання штанг, тепловий знос, абразивний знос, окислювальний знос та інші. Показані умови роботи бурових штанг та навантаження на штанги у різних умовах буріння, а також значення максимальних навантажень, які виникають при бурінні міцних гірських порід шарошковими долотами. Розглянуті функції бурових штанг, такі як передача осьового зусилля, обертального моменту, транспортування бурового розчину на місце буріння, транспортування продуктів руйнування гірських порід за межі свердловини та інші. Виконано обґрунтування та вибір матеріалу бурової штанги, який забезпечить баланс між міцністю та вартістю, при цьому відповідаючи вимогам, що ставляться до бурового обладнання. Для досягнення даної мети виконано дослідження напружено-деформованого стану штанги для обертового буріння за експлуатаційних навантажень в залежності від наявності зміщення робочого навантаження чи осей штанги та долота. Проведено математичний розрахунок та обробку даних в пакеті інженерних програм MATHCAD для бурових штанг з зовнішнім діаметром D та внутрішнім діаметром d в залежності від фізико-механічних властивостей матеріалу штанг осьового навантаження на буровий став та обертального моменту, що передається буровими штангами. Наведений розрахунок бурових штанг для шарошкового буріння свердловини діаметром 200 мм по міцним гірським породам. Розглянуті місця з'єднання бурових штанг зокрема спеціальне замкове різьбове з'єднання з підвищеною висотою профілю. В роботі розглянуті варіанти, які використовуються в закордонній практиці і на вітчизняних заводах бурової техніки. Показано виріб та розрахунок різьбового з'єднання між даними штангами для матеріалу штанг зі сталі 40Х та наведені креслення профілю розрахованої різьби. Розглянуто умови роботи бурового обладнання та фактори, які впливають на знос бурових штанг, запропоновано пропозиції щодо підвищення терміну служби штанг бурового обладнання, які можуть бути використані при проектуванні нового бурового обладнання.

Запропоновано пропозиції та конструктивні рішення для підвищення експлуатаційних властивостей штанг бурового обладнання, що дозволяють при проектуванні нового обладнання вибирати раціональні параметри матеріалів та конструкційних елементів штанг в залежності від умов експлуатації бурового ставу.

Ключові слова: бурова штанга, буровий став, шарошкове буріння, граничні навантаження, різьбове з'єднання.