На сьогодні найуживанішим при проведенні бурових робіт є породоруйнівний інструмент, оснащений ріжучими елементами з полікристалічних алмазів (PDC) та алмазно-твердосплавними пластинами (АТП). Для нього є актуальними дослідження впливу ступеню зношення ріжучих елементів на силові та енергетичні параметри процесу руйнування гірської породи. З метою визначення цього впливу, в лабораторних умовах проведено експериментальні дослідження процесу різання одиничним різцем. Визначено середні значення складових сили різання (колової (P_z) та нормальної (P_y)) при глибинах різання 0,5; 1,0; 1,5; та 2,0 мм за різного ступеню зношення ріжучого елемента (лиска 0, 5,0 та 8,0 мм). Встановлено величину роботи різання та питомої енергії руйнування гірської породи. При глибині різання 0,5 мм зі збільшенням ступеню зношення ріжучого елемента (від 0 до 8 мм) величина роботи зростає від 0,06376 до 0,121 Н·м. При глибині різання 2,0 мм – величина роботи зростає від 0,624 до 3,603 Н·м. Енергоємність процесу руйнування породи при збільшенні глибини різання з 0,5 до 2,0 мм для гострого різця зростає з 3,88 кДж/м^2 до 11,66 кДж/м^2. За результатами досліджень побудовані графічні залежності усереднених значень складових сили різання та її нормальної складової (P_y) від глибини різання та ступеню зношення ріжучого елемента. Одержані результати показали суттєвий вплив розміру лиски зношування на зростання силових параметрів процесу, що є підставою для регламентування ступеню зношення ріжучих елементів в процесі буріння. Визначена тенденція зростання результуючої сили та питомої роботи різання гірської породи ріжучим елементом зі збільшенням ступеню зношення. Це дає можливість за показниками коливань миттєвих значень сили при бурінні свердловин або за зміною потужності визначати ступінь зношення ріжучих елементів та передбачати ймовірність їх руйнування

Ключові слова: руйнування гірської породи при бурінні, буріння свердловин, долота PDC, сила різання

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DETERMINING THE INFLUENCE OF THE CONDITION OF ROCK-DESTROYING TOOLS ON THE ROCK CUTTING FORCE

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1. Introduction

Further development of the oil and gas industry is characterized by the growth of wells drilling [1–3]. In this case, scientists and practitioners solve a series of important tasks to ensure a well's trajectory [4], high technical and economic indicators [5], and safe conditions of drilling [6], as well as the reliability of drilling equipment [7]. Considerable attention is paid to the interaction between the rock-destroying tools and rock aimed at its effective destruction. The new impetus for these studies has been provided by the industrial exploitation of bits equipped with cutting elements made from polycrystalline diamonds (PDC) and diamond carbide inserts (DCI). Studying the impact of wear degree of the cutting element on a change in the strength and energy parameters of the rock destruction process is especially relevant. After all, the wear of the rock destroying tools essentially changes the mechanism of rock destruction and reduces the techno-economic indicators of drilling in general.

2. Literature review and problem statement

Papers [8, 9] provide a wide overview of studies on the distribution of temperature, forces, and stresses arising at cutting. Their authors also considered the effectiveness of the cutting elements, the mechanism of rock destruction, the theory of cutting, the wear and the causes of failure of rock-destroying tools. They compared the metal cutting theory and the rock cutting theory the focus being the similarity of these processes. To a large extent, the cited papers give a theoretical overview whereby it is possible to assess the state of and prospects for resolving the issue of ensuring effective rock destruction. In particular, they emphasize the need for various studies involving the analysis of industrial material, conducting analytical and experimental modeling of processes, the development of cutting elements of new types and designs based on the newest materials.

The above-specified study directions were reflected in other scientific works. The estimation of PDC bits operation based on the results of their application, as well as the proposals for improving efficiency, are given in [10]. The criteria of evaluation were the average values of drilling run, mechanical speed, and drilling time. The authors proposed for the examined bits to increase the fitting reserve, the number of inserts, and to decrease the diameter of the cutting elements. It is noted that a series of analytical, as well as experimental, studies are necessary to confirm the feasibility of the proposed design solutions. In such works, the aim is to adapt the bits to use them under certain geological and technical drilling conditions. Therefore, no patterns in the strength interaction between the rock-destroying tool and a borehole were considered in detail.

Since the indicators of bit operation are strongly dependent on the arrangement scheme and geometric parameters of tools, many papers have tackled these issues. Thus, work [11], based on analytical studies, the authors derived dependences for determining the depth and resistance of cutting-chipping. They proposed, for the examined cutting elements, a procedure for choosing their parameters and arrangement schemes. Further studies [12] established the cause of worsening in a cutting-chipping process when turning, at a slight angle, the cutting elements in a bit. The authors prepared recommendations for the application of the front angle module depending on the arrangement of a cutting element relative to the bit axis. They derived empirical dependences of the rock reaction force on the axial and tangential components at a constant front cutting angle. They noted the influence of the high frequencies of drill column rotation on vibration intensity that leads to the chipping of DCI. In the course of their analytical studies, the authors considered the standard cylindrical PDC cutters without signs of wear. That was likely due to the substantial complexity of the estimated scheme of a cutting process and analytical determination of its strength parameters.

Certain parameters that characterize the process of destruction cannot be established analytically. Given this, laboratory experimental studies into rock destruction by cutters of various shapes and types are widespread. Thus, a study of the operational indicators for a PDC cylindrical cutter, specifically the angle of friction, cutting power, the energy used for destruction, is reported in [13]. The main feature of this work is performing the research both in the air and in the environment of drilling mud. In this case, despite the technical possibility to determine the influence of toolset condition on the cutting parameters, the specified direction was not addressed.

The development of digital and computer technologies has led to numerous studies involving simulations. Thus, paper [14] examined the interaction between rock and a diamond cutting element of the new type (3-RDE). The authors built a three-dimensional (3D) model of the dynamic rupture of rocks by a cutting element of the 3-RDE type. They explored differences in the mechanism of rock destruction by the 3-RDE and cylindrical cutting elements. In addition, they analyzed the effect of cutting depth, angle of rotation, and rock properties on the destruction of rock.

The above-cited studies and the results reported are only a small part of the body of research related to issues on improving the efficiency of cutters and PDC bits. Much effort has been made to understand the interaction «cutter-rock» and related phenomena, to design new structures of cutting elements and bits. As the performance of PDC bits in the process of drilling is the aggregate result of the operation of individual cutters, the research that is aimed at improving their efficiency under laboratory conditions typically begins with studying the behavior of a single cutter. The focus is on the friction and heat exchange during the interaction between a cutter and rock, on the optimization and estimation of geometric parameters of PDC cutters, including their spatial distribution, on monitoring and controlling the rock cutting process.

In this case, they do not take into consideration a change in the characteristics of cutters related to the degree of their wear. Given this, it is a promising task to undertake a study aimed at identifying the effect of the condition of cutting elements in rock-destroying tools on the strength parameters of cutting and the ways to keep them within allowable limits. The results to be obtained could serve to reduce the cost of wells construction through the optimum operation of bits.

3. The aim and objectives of the study

The aim of this study is to determine the influence of the degree of wear of a DCI cutter on a change in the strength and energy parameters of the rock cutting process. This would give an additional opportunity to assess the condition of a bit toolset, as well as to ensure normal operating conditions for drilling equipment in general, by adjusting the operational modes of drilling.

To accomplish the aim, the following tasks have been set:

– to plan and perform an experimental study under parameters that are characteristic of the drilling process;

– to process experimental data and build dependences for cutting parameters at different wear degrees of the cutting element;

– to consider the possibility of assessing the condition of the rock-destroying tool in the process of drilling.

4. Experimental study into the influence of the degree of DCI wear on the rock cutting parameters

4. 1. Materials and equipment

Our experimental study was carried out involving the blocks made of abrasive sandstone from the Terebovlya field;

their average compressive strength is 86.8 MPa, and the elasticity module E=14,300 MPa.

The study was conducted at an experimental bench based on the turning-carousel machine 1M552. The bench is equipped with a three-dimensional dynamometer whose design is protected by a Ukrainian patent [15]. The dynamometer makes it possible to simultaneously measure, with a band frequency of 0–500 Hz, three components of the cutting effort: P_z (circular) to 100 kN, P_y (normal), and P_x (radial) to 50 kN. The component of effort P_y is perceived by a force sensor, mounted at the internal end surface of the case. The coefficient of friction, taking into consideration the losses in a bearing suspension, is 0.0015–0.0020. Thus, the losses do not exceed 0.2 % of the value of the P_y component. The components of cutting efforts P_z and P_x are registered by four sensors, mounted in two mutually perpendicular directions. In the contact area between the sensors' adapters and the shaft, the losses are possible due to the friction forces amounting to 0.03–0.07 of the effort magnitudes. In this regard, the necessary corrections are implied, based on the results of calibration. The losses and the interaction between the components of the cutting force did not exceed 1–2 % of the absolute cutting effort values.

To measure the components of the cutting effort, we applied the U3 sensors (up to 100 kN) and C9V (up to 50 kN), produced by Hottinger Baldwin Messtechnik (Germany). To measure and register the cutting force components, we used the system made by Werktoff Prufmashinen Service (Germany), certified in accordance with the international standard ISO 9000. The system, in addition to strength sensors, includes a device to acquire and convert information (Spider) and software to register and process the results of measurements.

The design of DCI [16] represents the two-layered plates with a diameter of 13.5 mm and 3.5 mm in height, one layer of which, a height of 0.5–0.8 mm, is a diamond polycrystal, and the other one is the base made of a solid alloy (Fig. 1, *a*, *b*). The main operational characteristic of DCI is the durability of the diamond-containing layer of the plate. Drilling of wells in the complicated and abrasive rocks leads to the intense wear of DCI and requires an increase in the overall force applied to the cutting element.

In order to simulate the operation of the cutting elements at different stages of wear, we made flats on DCI, the size of 5.0 and 8.0 mm (Fig. 1, *c*, *d*).

a *b* *c* *d*

Fig. 1. General view of a diamond-carbide insert (DCI): *a, b* — new; *c* — with a length of the flat (chord) of 5.0; *d* — with a length of the flat (chord) of 8.0 mm

In the course of our study, we used the DCIs that are the components of the cutter RSH-140.

4. 2. Procedure for conducting a study into the process of destruction of hard rocks

Before the tests, the surface of the sandstone block was rubbed by a cutter until a homogeneous smooth plane.

The main technical and economic indicators of bit application are the mechanical drilling rate (m/h), run per bit (m), and the cost of drilling 1 meter of a well (UAH/m). Therefore, when simulating drilling by the cutter RSH-140, we accepted the study parameters, characteristic of the process of well (hole) drilling when they are applied:

a) cutting depth (per revolution of the machine faceplate) – 0.5; 1.0; 1.5; and 2.0 mm;

b) the speed of movement of the cutting element along the block – 0.523–0.561 m/s.

The cutting depth is chosen based on the results from our review of the mechanism of destruction of hard rocks and the design of an effective drilling tool. It was established that at rock destruction the feed per tool rotation should be at least 0.3 mm. At a smaller feed, the process of destruction is carried out in a low-efficiency surface abrasion mode.

The speed of movement was determined by estimation taking into consideration the specifications of the experimental installation.

In the course of our research, we recorded the components of the cutting force in a digital form. Based on them, the minimum, maximum, and average values for the force components, as well as the length of cutting time, were determined. In addition, we determined the work used in the cutting process and the specific energy of rock destruction process.

Comparative analysis of the geometric parameters of destruction products was performed based on studying the fragments of sludge obtained during cutting.

5. Processing of experimental data and construction of graphical dependences

The results obtained in the course of our study are visualized in the chart shown in Fig. 2, which illustrates the effect of wear simulated by flats with a width of 5.0; 8.0; and 0 mm, at cutting depth 0.5; 1.0; 1.5; and 2.0 mm, on a change in the cutting force components (P_z and P_y).

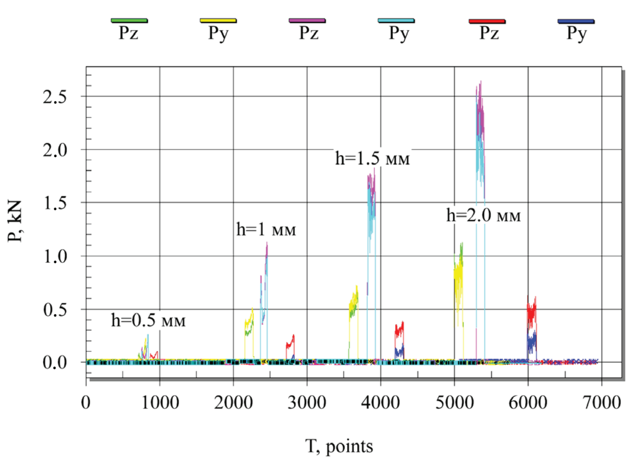
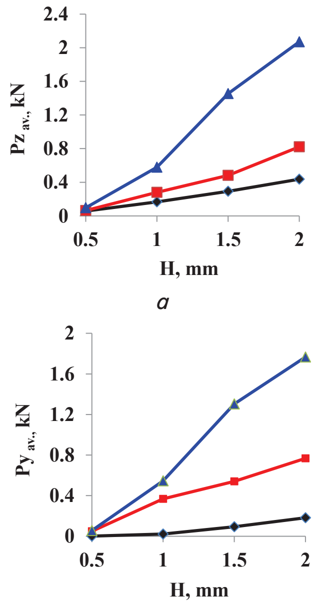


Fig. 2. Results of studying the influence of wear flat width of 5.0; 8.0; and 0 mm on a change in the cutting force components (P_z and P_y) at cutting depth 0.5; 1.0; 1.5; and 2.0 mm

Fig. 3 shows the general view of cutting traces at the surface of the block at different cutting depths 0.5; 1.0; 1.5; and 2.0 mm.

Fig. 3. General view of traces at the surface of the block at different cutting depths 0.5; 1.0; 1.5; and 2.0 mm



a

b

Fig. 4. Dependence of change in the average values of the cutting force components on the cutting depth and the wear degree of DCI: *a* – P_z component; *b* – P_y component; — sharp DCI; — flat 5 mm; — flat 8 mm

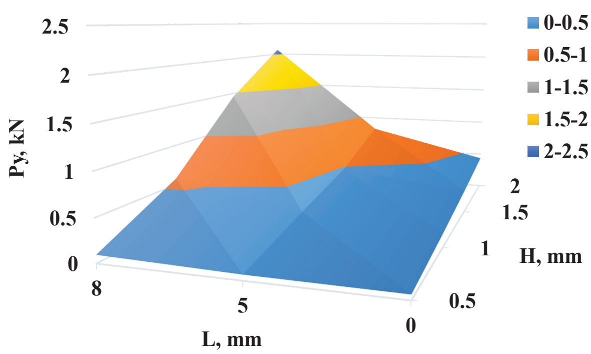


Fig. 5. Dependence of change in the P_y component on the cutting depth (H) and the wear degree of DCI (L)

Separate fragments were cut out from the chart in Fig. 2 that correspond to the cutting depth from 0.5 to 2.0 mm. Based on them, we established the main cutting parameters (Table 1).

Based on the results of processing, we have built the graphic dependences of change in the average values of the cutting force components (P_z and P_y) (Fig. 4), the dependence of change in P_y on the cutting depth and the wear degree of DCI (Fig. 5).

By separating and matching the values corresponding to the characteristic plots of the generalized chart (Fig. 2), we have built the dependences of change in the instantaneous values of the cutting force components at different degrees of wear of the cutting element (Fig. 6).

Fig. 6 shows that the component of force P_y for sharp DCI at the cutting depth of 0.5–1 mm has substantially smaller values than P_z. When increasing the cutting depth, the component of force P_y accepts values commensurate to the component of P_z. For the cutting element with signs of wear, the magnitudes of the cutting force components are commensurate at all depths.

Table 1

Results of experimental study

DCI ∅ 13.5 mm	Cutting depth, mm							
	0.5		1.0		1.5		2.0	
	$P_{z\,av.}$, kN	$P_{y\,av.}$, kN	$P_{z\,av.}$, kN	$P_{y\,av.}$, kN	$P_{z\,av.}$, kN	$P_{y\,ar.}$, kN	$P_{z\,av.}$, kN	$P_{y\,av.}$, kN
Flat 0, mm	0.05703	0.0012	0.16564	0.02164	0.29159	0.093629	0.43593	0.181489
Resultant force, kN	0.0583		0.167		0.306		0.472	
Chip width, mm/ cutting path length, m	7.5/1.094		10/1.129		15/1.187		20.2/1.324	
Work used for cutting, Nm	0.06376		0.188		0.363		0.624	
Specific energy of rock destruction process, kJ/m^2	3.88		8.32		10.19		11.66	
Flat 5, mm	0.06251	0.04896	0.280268	0.367524	0.481051	0.540773	0.822301	0.767591
Cutting force, kN	0.0794		0.46219		0.7237		1.1249	
Work used for cutting, kNm	0.0896		0.5218		0.9034		1.27	
Flat 8 mm	0.09563	0.05643	0.5778	0.546	1.45398	1.30347	2.06978	1.7664
Cutting force, kN	0.111		0.7949		1.953		2.721	
Work used for cutting, kNm	0.121		0.897		2.31		3.603	

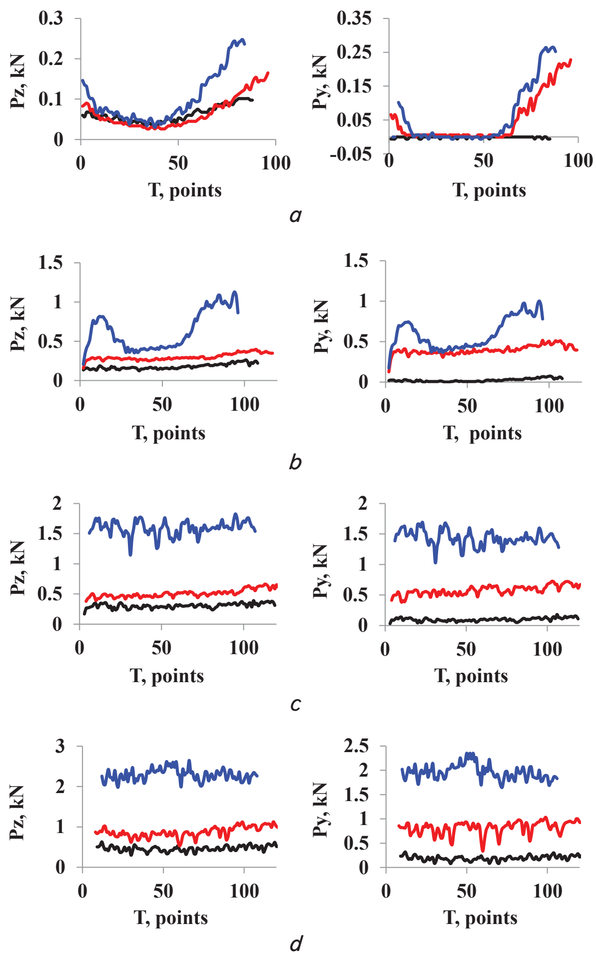


Fig. 6. Change in the instantaneous values of the cutting force components (P_z and P_y) when working with a tool with a varying degree of wear: *a* – cutting depth 0.5 mm; *b* – cutting depth 1 mm; *c* – cutting depth 1.5 mm; *d* – cutting depth 2 mm; — – sharp DCI; — – flat 5 mm; — – flat 8 mm

6. Discussion of results of studying the impact of the cutting element wear on cutting parameters

The results obtained (Table 1) indicate that with an increase in the cutting depth by a round-shaped DCI (that is, sharp) from 0.5 to 2.0 mm, the resulting force grows by 8 times. An increase in the wear degree of DCI (the size of a flat is from 0 to 8 mm) leads to a growth of the resultant force. Thus, at cutting depth 0.5 mm, the resultant force grows by 1.9 times. At the same time, a simultaneous change in the degree of DCI wear (the size of a flat from 0 to 8 mm) and in the cutting depth, up to 2.0 mm, leads to an increase in the resultant force by 46.7 times.

Based on the results of our analysis of sludge fragments, it was determined that as DCI penetrates deeper, a rock fragment is discretely chipped (jump-like – Fig. 3). In this case, the volume of a chipped-away fragment, in contrast to the ratio of volumes of the zone of chipping and crushing under the impact of a carbide insert penetrating deeper, is larger than the crushing area. With a cutting depth of 2 mm, the maximum value of the ratio for a DCI cutter reaches 5.2 times (Fig. 3).

For a sharp DCI (without accumulated wear), energy intensity of the rock destruction process, at increasing the cutting depth from 0.5 to 2.0 mm, increases by 3.08 times (Table 1). This is due to a significant increase in the rock destruction work by DCI (by 9.8 times) and the surface area of the chips (by 3.7 times). It should be noted that when cutting to a depth of 2.0 mm using a cutter with a flat size of 8 mm, the resultant force on a single cutting element reaches 2.721 kN. Thus, the overall effort on the cutter in RSH-140 with four cutting DCIs should be up to 10.88 kN, and this exceeds the permissible value for it.

Given that an increase in the axial and twisting loads on a drill string causes the growth of stress levels, and, consequently, predetermines the probability of destruction of its elements, the results obtained make it possible to regulate the degree of wear of the cutting elements in rock-destroying tools.

Applying the obtained results for the process of operation of the rock-destroying tools, there is an obvious reduction, within the resultant force, in the component directly directed to the cutting of rock. This increases the component responsible for the indentation of the cutting element (Table 1). Thus, at cutting depth 0.5 mm, for a sharp DCI, the resultant force is 0.0583 kN, and the component $P_{y.\,av.}$=0.0012 kN. At the same time, for a worn-out DCI (flat is 8 mm), at the resultant force 0.111 kN, the component $P_{y.\,av.}$=0.05643 kN.

On the other hand, at an increase in the cutting depth by a round DCI (that is, sharp) from 0.5 to 2.0 mm, the component of force P_y increases by larger than 150 times. Increasing the degree of DCI wear (the size of a flat is from 0 to 8 mm) at a constant cutting depth of 0.5 mm predetermines a growth of the force component by 56 times.

When carrying out drilling operations the axial load on a bit is regulated over a certain range of values. Creating the loads close to maximum values of load range when using a new rock-destroying tool would predetermine the emergence of its intense vibrations under a «stick slip» mode. Given this, it is necessary, when defining the operational parameters for drilling, to plan a flexible program for loading the bit, depending on the condition of its toolset. To adopt the minimum load for a new bit required for the implementation of the technical and technological task. As the toolset wears the load should be increased. Such a program would reduce the likelihood of bit vibrations under a «stick slip» mode. That could reduce the circular and longitudinal loads on a drill string and would improve the durability of its elements.

It should be noted that the change in the wear degree of the cutting element alters the amplitude and fluctuation frequency of the instantaneous values of the cutting forces components (Fig. 6). This gives a reason to suppose the possibility of assessing the condition of a rock-destroying tool based on the characteristics of the oscillatory process of drilling tools and to predict the probability of its destruction.

In order to confirm and advance a hypothesis about control over the condition of rock-destroying tools based on the monitoring of the drilling string and the strength parameters of cutting, experimental studies should be carried out involving industrial specimen of the rock-destroying tools.

7. Conclusions

1. We have experimentally tested the cutters, equipped with diamond carbide inserts with flats of different sizes, which made it possible to simulate the impact of DCI wear on a change in the strength parameters of rock cutting process. The study was based on the parameters, characteristic of the

process of drilling wells (holes) with the use of the cutters RSH-140: cutting depth – 0.5; 1.0; 1.5; and 2.0 mm; linear cutting velocity – 0.523–0.561 m/s. By applying the results, we have recorded the cutting force components in a digital form.

2. The average values of force components have been established, as well as the amount of work used in the process of cutting and the magnitude of specific energy in rock destruction. In particular, at cutting depth 0.5 mm, with an increase in the degree of DCI wear (the size of a flat is from 0 to 8 mm), the values of the specified parameters changed in the following range: $P_{z\,av.}$=0.05703–0.09563 kN, $P_{y\,av.}$= =0.0012–0.05643 kN, A=0.06376–0.121 Nm. The energy intensity of the rock destruction process, at an increase in cutting depth from 0.5 to 2.0 mm, for a sharp DCI (without signs of wear), increases from 3.88 kJ/m^2 to 11.66 kJ/m^2.

We have derived the graphic dependences of change in the average values of components of the cutting force and the component P_y on the cutting depth and the degree of DCI wear.

3. A considerable effect of the degree of wear of the cutting elements on the growth of strength parameters of the process has been established. The increase in the degree of wear decreases, within the resultant force, the component directed directly to the cutting of rock. In this case, there is an increase in the component responsible for the indentation of the cutting element. With a cutting depth of 0.5 mm, for a sharp DCI, the resultant force is 0.0583 kN, and the component $P_{y.\,av.}$=0.0012 kN. At the same time, for a worn-out DCI (a flat of 8 mm), at resultant force 0.111 kN, the component $P_{y.\,av.}$=0.05643 kN.

We have determined a tendency towards an increase in the resultant strength and specific work of rock cutting with an increase in the degree of wear. This makes it possible, based on the indicators of fluctuations in the instantaneous force values on a string at well drilling, or based on a change in power (indicated by a wattmeter), to determine the degree of wear of the cutter and to predict the probability of its destruction.

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