SOCAR Proceedings

Production & Operations

journal home page: http://proceedings.socar.az

BOREHOLE MILLING TOOL AND WAYS TO IMPROVE ITS CUTTING PART

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A B S T R A C T

The article proposes the design of the cutting part and its reinforced material, which allows to prevent intensive work of the cutter in its central part and maximise the destructive potential of the tool. In this regard, a rational geometric parameter of the milling cutter's cutting part is determined by creating and studying a mechanical-mathematical model of the interaction process between the milling tool and the object to be destroyed, based on the theory of wear of mating surfaces. Since in the process of destruction there is a detachment of fine chips from the emergency facilities, contributing to intensive and uneven wear of the reinforcing structure, a milling tool whose cutting part is equipped with a cavitation-exciting element is developed. Possible dynamic loads on the rock-cutting tool due to the creation of cavitation loads have been experimentally determined and the possibility and necessity of drilling operations with the use of cavitator in the drilling tool arrangement have been confirmed. To address the uneven wear of the cutting part of the milling tool and to strengthen the radial hardening contours from the periphery to the centre when using a composite alloy with a non-uniform composition of granular solid filler, the analogy of the process of actualisation of composite surfacing with the Markov process was used. For this purpose, on a special bench, studies were carried out with a measurement step of 30 min. to synthesise the areas of compatibility of operational parameters with physical and mechanical pro¬perties of the destroyed emergency facilities, reinforcing parameters and design of downhole cutting tools.

Keywords: milling machine; reinforcing parameters; theory of contacting sphere's wear; cavitation element; Markov process; operational parameters; granulometric alloy.

Date submitted: 08.09.2024 **Date accepted:** 28.02.2025

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1. Introduction

It is known that the number of wells in operation in the Commonwealth countries is 247014, including 13000 new wells. At the same time, the volume of overhaul is 47592 units, and the demand for drilling tools – such as catching, cutting, and auxiliary tools – amounts to 11100 units. At the same time, each overhaul crew has about 22 wells per year, and with round-the-clock operation, it takes 700 days to repair and restore emergency wells. This in turn leads to an increase in the number of idle wells waiting to be repaired [1-3].

Despite the development and implementation in practice in the commonwealth countries and abroad of an extensive fleet of main, auxiliary tools and relevant normative and technical documents, the volume of produced equipment meets only a little more than half of the need for it, and the insufficient number of modifications does not allow the choice of a reasonable technology of repair and rehabilitation of abandoned wells with high operational efficiency.

It is necessary to take into account that the modern stock of oil and gas wells, which are characterised by significant depths, narrowing the borehole in the lower sections, increased complexity and other features, is the source of complex emergencies. Besides, the growing number of drilling and producing wells leads to an annual increase in the volume of repair and recovery works. The production of works related to the repair and rehabilitation of wells, aimed at reducing their accident rate, consumes large amounts of money and thus contributes to high material costs in the national economy.

It should be noted that theoretical, experimental and field studies of scientists and industrialists of the former USSR have achieved a certain level of perfection of repair and recovery equipment and developed many methods to ensure operational efficiency, as well as technological regulations for the operation of the existing range of equipment.

However, there are opportunities to enhance operational efficiency of repair and recovery operations and they consist in the necessity to take into account the mechanisms of more reliable theoretical and experimental modelling of the process of interaction of downhole tools with an emergency facilities considering the parameters of emergency situation; synthesis, as part of reinforcing of wear-resistant materials with specified properties compatible with the design and technological parameters of cutting tools functioning; devel-

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http://dx.doi.org/10.5510/OGP20250101046

opment of the operational principles of cutting tools. These tasks are highly relevant and require an urgent solution in the interests of oil and gas industries and the national economy as a whole.

The novelty of the work is that the study of the mechanism of mutual influence of the component composition of the reinforcing, design parameters and operational factors on the performance of cutting tools and the definition of ways to classify their compatible combinations, and as a result, the development of algorithms for the synthesis of the component composition, prediction of properties and structural state of the composite alloy clad on the reinforcing tools, as well as the definition of the optimal configuration and design parameters of their working tools.

The main part of these tools should be innovative and developed at the level of inventions and protected by patents A.R. Some of the developed designs, such as milling tool with modernised cutting actuating elements are recognised by specialists and companies of different oil regions of the world as competitive with existing foreign analogues, in this connection they are recommended for serial introduction at the enterprises of industrial formations of the fuel and energy complex of the country and have been repeatedly introduced.

The Baku Machine Building Plant of Oilfield Equipment has also adopted the relevant recommendations on the modernisation of the cutting part and reinforcing of downhole milling tools for the purpose of their practical development and production. More than 100 samples of tools have been realised by the plant after acceptance of the corresponding proposals of the authors to the operators [4]. The technology of computer-aided [3] design for production processes [1, 2] of repair and restoration works, including the authors' developments, is also introduced into the system of the «Azneft» PU of SOCAR. The work carried out on the development and implementation of downhole milling tools allowed to modernise the design characteristics of the developed milling tools on the basis of contract work carried out on the basis of national and international financial support under joint contractual obligations. Such developments of downhole milling tools are tool designs protected by copyright certificates in the period 1980-1990 [5-8].

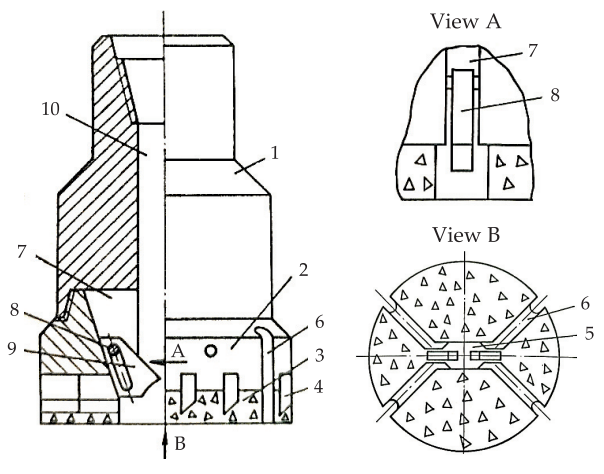


Fig. 1. Bottom-hole milling tool-catcher with upgraded cutting section [7]

2. Objects and methods of research

The main task of the study is to improve the cutting part of downhole milling tools, research of their classification and prevention of complications arising in the process of wear of its structure, as well as synthesis of compatibility of design parameters and operational factors of the milling process with the component composition of the cutting structure, and physical and mechanical properties of the processed facilities.

Task 1. The operation experience of downhole milling tools has shown that, regardless of the applied force component (namely axial force), the distribution of contact pressure under its working surface is known to be non-uniform and obeys the hyperbolic law [9] and increases from the periphery to the centre, i.e. the maximum value of contact pressure will be observed in the centre of the tool's working part, and the distribution of load intensity and working out of its reinforcing along the radius will also have the shape of a hyperbola, determined by the shape of a hyperbola:

$$q_i = 0.5Q\frac{1}{2R_i - 1} \quad (1)$$

where Q – the tool load; R_i – the current radial coordinate.

This type is also characteristic, as the practice of development shows, of downhole milling devices reinforced with composite alloy.

This type of cutting wearing does not allow the full destructive potential of the composite alloy plated on their working parts to be used, as the central part wears along the axis much faster than the peripheral part. As a result, the destructive potential of the reinforcing of the peripheral part remains unused and the milling machine, due to the complete wear of the reinforcing in its central part, loses its serviceability without reaching the operational indicators laid down in the normative documents, in particular, the resource of work on the emergency facilities. If we consider that the volume of composite alloy plated on the working tools is limited by a number of other reasons (mechanical, vibratory, thermal, chemical effects, etc.), it becomes clear that the non-uniform wear pattern of the cutting part of downhole milling tools is unacceptable from the point of view of tool operating resources. This performance of reinforced part of wearing is one of the main reasons that reduce the efficiency of downhole cutting tools. Prevention of this type of wear on the cutting part of downhole milling tools is possible by implementing measures aimed at modernising the design of their cutting part. The design of the cutter, the principle of operation of which is shown in figure 1, is one of these realisations. The practical acceptability of such a design of a downhole milling device is confirmed by the results of the authors' work and research. The device differs from its analogues in the perfection of both the design of the cutting element and the design of the reinforcing mounted on it. It comprises a body (1) with a working part (6) of the abrasive cutting type, reinforced layer by layer with a hard alloy with a bonding material and carbide plates (4, 9) pressed into the body (1).

The device differs from its analogues in the perfection of both the design of the cutting part and the reinforcing mounted on it. It consists of a body 1 and a working part 2 connected by threads. The working part 2 consists of a body and a reinforcement, and it is made in layers, consisting of a crushed hard alloy with a bonding material 3 and carbide plates 4 pressed into the body of the working part 2. The

working part of the cutter is provided with flushing channels – axial 5 and diverging radial channels 6 for supplying flushing fluid to the peripheral part of the cutter. On the walls of the axial channel, there are longitudinal grooves 7 in which the cutters 9 are placed, which are fixed to the body of the working part 2 by means of pins 8. The longitudinal grooves 7 allow the cutters 9 to move on the supporting inclined surface. As the cutter rotates, part of the emergency facilities which enters the central channel 10, extends the cutter 9 by means of the grooves. In this case, the flushing liquid, which passes through the space not occupied by the emergency facilities (EF) in the rectangular section, has the possibility of entering the interaction zone. The EF is destroyed in the interaction zone by abrasion (coating 3) and cutting (inserts 4).

The cutter works as follows. The cutter is lowered into the borehole on the drill string. Then the drill string with the cutter is rotated and the axial load is gradually increased. This causes the emergency facilities to be broken by the end part of the cutter. The part of the emergency facilities in the area of the rectangular hole is milled and enters the central channel by moving the cutters 2 inside the working part 9. As long as the tool is under a certain axial load, the cutters 9 do not prevent the emergency facilities from rising through the central channel.

When the milling machine works on the emergency facilities, the first layer of reinforcement, consisting of crushed hard slab with binder material, interacts with the emergency facilities. The period of interaction of this layer with the emergency facilities corresponds to the milling mode, in which its destruction occurs by abrasion and hourly cutting. After the first layer of reinforcement is worn out, the second layer, consisting of carbide alloy plates (4), which are pressed into the body of the cutting part (9) and integrated into the volumetric reinforcement, becomes exposed. After that, the process of destruction of the emergency facilities by cutting and partial abrasion takes place. This contributes to a significant increase in the operating efficiency of the cutter.

When the cutter has reached the end of its life, it is detached from the emergency facilities by lifting the drill string. At the same time, cutters 9, descending around their axis along the groove, penetrate the undamaged part of the emergency facilities. The rotating cutter then cuts off this part and transports it to the surface together with the tool.

Such a design of the cutting mechanism and its reinforcing allows to avoid intensive wear of the cutter in its central part and to maximise the destructive potential of the tool.

It should be noted that the beneficial effect described can be ensured by determining the rational geometric parameters of the cutting part. For this purpose, the authors studied the mechanics-mathematical model of the process of interaction between the milling tool and the object to be destroyed based on the theory of contacting sphere's wear [10, 11]. The results of the study made it possible to identify the area of the contact zone most susceptible to wear, equal to $(1/4+1.5)R$ (where R is the radius of the tip of the cutter).

In order to determine the optimum cross-sectional area of the central groove of the developed milling machine, the problem is solved, the statement of which is formulated as follows: to find the values of factors of the vector $P=x(x_1, x_2, ..., x_n)$ providing the minimum probability of complications in the milling process by one of the quality indicators in the presence of restrictions of the probability of successful result by all other quality criteria. In this case, the milling quality indicator K_1 – the probability of reducing the wear of the tool reinforcing to ensure K_2 – a certain level of probability of exceeding the industrial norms of penetration into the emergency facilities is taken as the determining one.

At such formulation of the problem its mathematical model is presented in the form: to find the values of the factors of the vector of features $P=x(x_1, x_2, ..., x_n)$, providing the minimum sum of diagnostic coefficients according to table 1 for recognition of the quality feature, i.e.

$$\sum_{J=1}^{3} DK_1(x_j) \to \min \quad (2)$$

with the restriction of the sum of the diagnostic coefficients according to table 1 for the recognition of the quality attribute, i.e.

$$\sum_{J=1}^{3} DK_1(x_j) < B \quad (3)$$

Table 1

Value of diagnostic coefficients

Factors / DC	Notation of factor	Change interval	Specific performance diagnostic coefficients	Diagnostic coefficients for sinking AO
Cross sectional area of the groove in the cutter mm^2	x_1	126-125	0.58	2.5
		175-224	-0.67	-2.14
		224-273	-1.76	-4.96
		273-322	-1.29	-3.81
		322-371	0	0
		371-420	1.55	0
Tool load, N	x_2	90-100	-0.77	0.6
		100-110	-0.21	-0.16
		110-120	0.26	-0.76
		120-130	0.58	-0.74
		130-140	0.58	-0.25
		140-150	0.58	0.46
Tool rotation speed, rpm	x_3	125-137.5	-4.09	9.03
		137.5-150	-3.10	17.74
		150-162.5	-1.81	2.08
		162.5-175	2.04	4.87
		175-187.5	4.33	12.66
		187.5-200	6.6	29.39

At the same time, it should be noted that when evaluating the results of milling operations on the emergency facilities, the state of ϖ_1, was considered as the unsuccessful class, and the successful result was marked as ϖ_2. In addition, if we set the value of the threshold B=–13, which corresponds to the ratio of probabilities of achieving the industrial norms of penetration on the emergency facilities, i.e. 95% probability of successful outcome, taking into account that the problem is presented in the following form $P_2(\varpi_1/\prod)/P_2(\varpi_2/\prod)$=0.05. Find the value of the factors of the vector of features $\prod=x(x_1, x_2, ..., x_n)$ that give

$$\sum_{J=1}^{3} DK_1(x_j) = \sum_m DK_1(x_m) + \sum_l DK_1(x_l) \to \min; \quad (4)$$

$$\sum_{J=1}^{3} DK_2(x_j) = \sum_m DK_2(x_m) + \sum_l DK_2(x_l) \angle -13, \quad (5)$$
$$n = m + 1$$

where DK_1 and DK_2 – diagnostic coefficients of quality characteristics K_1 and K_2; m and l – index of uncontrollable and controllable factors, corresponding to the ratio of probabilities for the first quality indicator K_1, which corresponds to the ratio of probabilities for the first quality indicator K_1

$$\frac{P_1(\varpi_1/\prod)}{P_1(\varpi_2/\prod)} = 1.1 \cdot 10^{-1} \ (10\%) \quad (6)$$

and the second quality indicator

$$\frac{P_2(\varpi_1/\prod)}{P_2(\varpi_2/\prod)} = 1 \cdot 10^{-2} \ (1\%) \quad (7)$$

It is obvious that the choice of design solutions is carried out in the first approximation with a sufficient degree of probability of ensuring both quality indicators of milling of the emergency facilities. At the second and subsequent stages, by selecting the desired cross-section of the central groove of the cutter part at the design stage, it is possible to achieve more stringent probabilities of quality indicators of the milling process.

So, for example, if we assume x_1=400 mm^2, then

$$\sum_m DK_1(x_m) = 1.55; \quad -\sum_m DK_2(x_m) = 0 \quad (8)$$

Consequently, the total sums of the diagnostic coefficients according to the accepted values of the operational factors will be equal to

$$\sum_{J=1}^{n} DK_1(x_j) = 1.55 + 7.18 = 8.73;$$
$$\sum_{J=1}^{n} DK_2(x_j) = 0. - 4.24 = -4.24 \quad (9)$$

which corresponds to the ratio of probabilities

$$\frac{P_1(\varpi_1/\prod)}{P_1(\varpi_2/\prod)} = 8 \cdot 10^{-2} \ (8\%);$$
$$\frac{P_2(\varpi_1/\prod)}{P_2(\varpi_2/\prod)} = 1.2 \cdot 10^{-1} \ (12\%) \quad (10)$$

On the contrary, if the cross section is reduced to x_1=150 mm^2, we have

$$\sum_m DK_1(x_m) = 0.58;$$
$$\sum_m DK_2(x_m) = 2.5 \quad (11)$$

which corresponds to the sum of the diagnostic coefficients,

$$\sum_{J=1}^{n} DK_1(x_j) = 0.58 + 7.18 = 7.76;$$
$$\sum_{J=1}^{n} DK_2(x_j) = 2.5 - 4.24 = 1.74 \quad (12)$$

indicates an increase in the error in determining the second indicator of milling. The analysis of the total volume of experimental studies showed that the most acceptable cross-sectional area of the central groove in the milling cutter is the interval of

$$x_1 = (220 + 270) \text{ mm}^2$$

This interval was included in the design of 136 mm diameter downhole milling machines, of which a pilot batch (7 pieces) was manufactured by the Zabratsky Machine-Building Plant. Bench and field tests were conducted in accordance with the developed and approved programme and methodology. According to the test results, this design of milling machine was recommended for mastering by serial production.

This interval was included in the design of 136 mm diameter downhole milling machines, of which a pilot batch (7 pieces) was manufactured by the Zabratsky Machine-Building Plant. Bench and field tests were conducted in accordance with the developed and approved programme and methodology. According to the test results, this design of milling machine was recommended for mastering by serial production.

Let's prove the method of solving the formulated problem on the example of a series of experimental studies. As uncontrollable we take the factor x_1 (the cross-sectional area of the central groove), and to the controllable – factors (x_2, x_3) mode-technological.

The example of problem solving is based on one of the implementation variants: experiments with the following values of controlled and uncontrolled factors:

x_1=250 mm^2	(DK_1=–1.8)	(DK_2=–5.0)
x_2=120 N	(DK_1=–0.3)	(DK_2=–0.8)
x_3=160 rpm	(DK_1=–1.8)	(DK_2=1.3)

(13)

For the given values of uncontrollable factors, we have

$$\sum_m DK_1(x_m) = -1.8$$
$$\sum_m DK_2(x_m) = -5$$

In order to fulfil the conditions for the controlled factors, the following value ranges and corresponding values of the diagnostic coefficients are determined:

x_1=130 N	(DK_1=0.58)	(DK_2=–0.74)
x_2=120 rpm	(DK_1=6.6)	(DK_2=–3.5)

For the selected intervals of controllable factors, we have

$$\sum_l DK_1(x_l) = 0.58 + 6.6 = 7.18$$
$$\sum_l DK_2(x_l) = -0.74 - 3.5 = -4.24$$

The total sums of diagnostic coefficients according to the condition are as follows

$$\sum_{J=1}^{n} DK_1(x_j) = -1.8 + 7.18 = 5.38$$
$$\sum_{J=1}^{n} DK_2(x_j) = -5 - 4.24 = -9.24$$

Task 2: The process of EF destruction is accompanied by the removal of small chips from the emergency facilities, some of which adhere to the destructive element, contributing to its intensive wear and reducing the operational efficiency of the tool. Furthermore, as observations indicate that chips tend to accumulate mainly in the central part of the tool due to poor removal conditions.

Therefore, as a further measure to address the uneven wear of the tool, a milling cutter is developed whose cutting part is equipped with a cavitation exciting element [12]. This element is in the form of a cup with a perforated bottom (fig. 2) and is installed in the central flushing channel of the tool.

When the fluid passes through the perforated bottom of the beaker, made in the form of a set of Venturi tubes, the cavitation process is initiated, saturating the liquid with air bubbles. As these bubbles develop, they collapse and generate shock waves, the pressure at the front of which relaxes over a short distance. Spreading along the coaxial flushing channels, it reaches the end of the cutting element as micro-dynamic shocks. Excitation of the micro-dynamic shocks under the lower part of the cutting unit prevents the milling products from sticking to it. The conditions of their removal from the zone of interaction of the tool with the object to be destroyed are improved, and thus its operational parameters are increased (approx. by 40÷60%). The author's proposal was accepted by the Zabrat machine-building plant for practical use in the production of downhole milling tools [13].

To determine the values of the «span», i.e. the value of $\Delta P=P_{2max}-P_{2min}$ and the frequencies of the auto-oscillations, as well as the vibration loads generated by the hydrodynamic generator on the installation set up on the territory of the Logistics Department of the KBR, SOCAR , experimental studies were carried out on the installation presented below (fig. 3).

Here the installation of a pump (1) with a capacity of 26 l/min is a source of high pressure and generates a maximum working pressure of 50 MPa. The pump is driven by a 30 kW electric motor and the actuation fluid is water, which is pumped to the cavitator (3) through a high pressure pipe and a turbine flow meter (9). Then the fluid is transferred to the central channel of the nozzle (2) and passing through the throttle (5) entered the storage reservoir.

The amplitudes of the cavitation oscillations of the fluid (output pressure P_2), the frequencies of the auto-oscillations (f) as well as the vibrational loads (nz_3) acting on the walls of the working section of the borehole were determined by the conducted experiments (table 2). The dependencies of the above parameters on the ratio of the average values

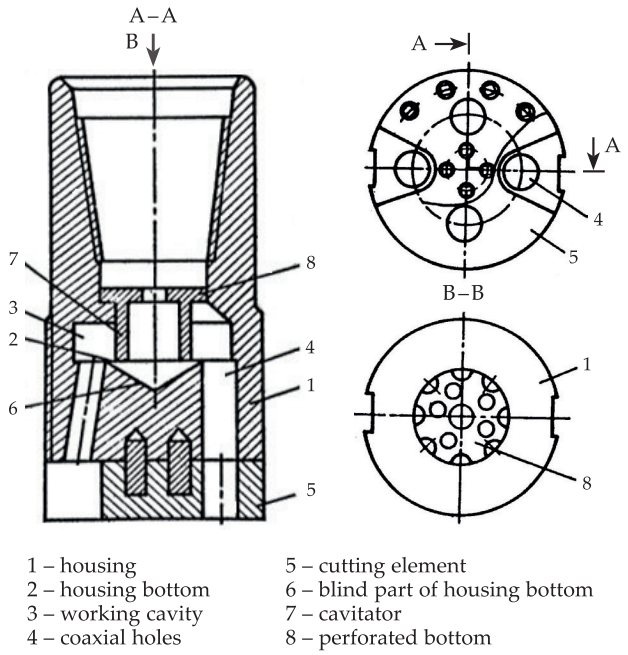


Fig. 2. Cutter with cavitation forming element

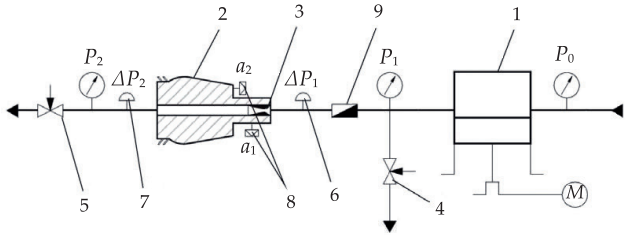


Fig. 3. Scheme of hydraulic installation for testing of hydrodynamic vibrator [6]

Table 2

Data from experiments

Inlet pressure P_1, MPa	Output pressure P_2, MPa	Ratio of average differential of output pressure and input pressure , $\Delta P/P_1$	Automatic oscillation frequency $f\cdot10^2$, Hz	Vibration loads nz_3
5	14.0	0.2	1400	16.0
	9.5	0.4	900	10.0
	4.0	0.6	400	5.0
	1.0	0.7	200	3.0
10	25.0	0.2	2400	27.0
	17.0	0.4	1800	18.0
	6.0	0.6	600	9.0
	2.0	0.7	150	6.0

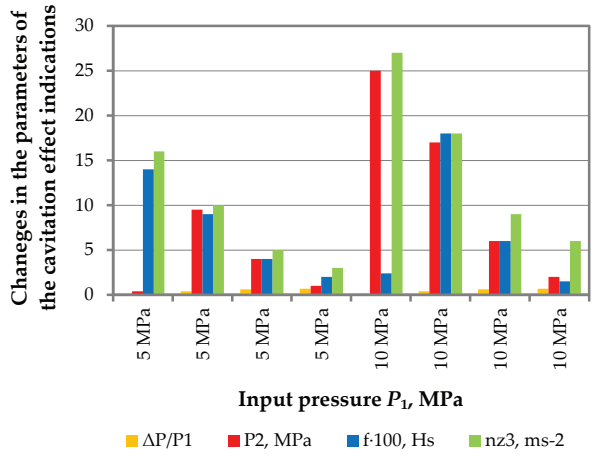
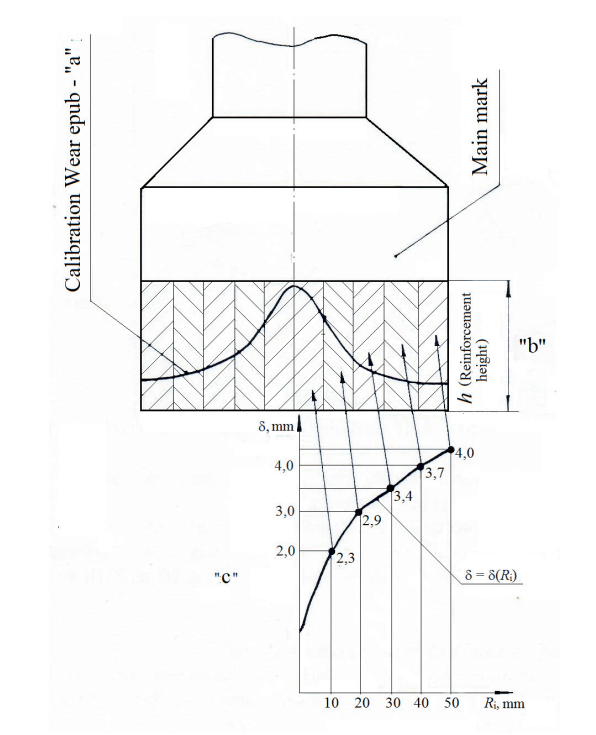


Fig. 4. Histogram of cavitation vibration distribution based on the results of experimental studies



a – wear diagram of the cutting edge of the milling tool
b – view of the end face of the tool
c – structure of the variation in the granulometric composition of the filler of the milling tool

Fig. 5. Milling tool with variable granulation of the filler in the working part of the composite overlay

of the difference between the output and input pressures ($\Delta P/P_1$) were then determined. The experiments were carried out at input pressures of 5 and 10 MPa (fig. 4).

The experiments revealed the possibility of creating different levels of vibration effects on the near-wellbore space using hydrodynamic vibration stimulators was confirmed. It proves the potential of the proposed device for application in various technological processes aimed at restoring the reservoir rock properties. Further it is necessary to carry out research aimed at specifying the design features of the units, controlling the stimulation of vibration effects.

The results obtained in experimental studies confirmed the possibility of obtaining different vibration loads on the rocks of the near-wellbore when using stimulators of hydrodynamic oscillations by applying the developed device in various technological schemes, which can be used to restore its reservoir rock properties, which requires research and specification of design features of the cavitator unit for stimulating of vibration effects on the tool.

Task 3. Another, not less promising direction of addressing uneven wear of cutting part of milling tools is strengthening of radial contours of reinforcement from the periphery to the centre by using composite alloy with uneven granulometric composition of granular solid filler. To confirm this assumption, an analogy can be used between the process of wearability of composite cladding and the biological processes of birth, reproduction and death, the significance of which has been proved [10, 14]. The process of birth in a composite alloy with a hard grain filler corresponds to the process of growth of a single grain, the process of reproduction to the process of destruction of a carbide grain, and the process of death to the process of detachment of a grain from the matrix.

To realise this analogy, research is carried out on a specially equipped stand, research is carried out, the results of which are provisionally divided into three groups according to the value of specific productivity:

$$q_1 = 50 \text{ units};\ 50 < q_2 \le 150 \text{ units};\ q_3 > 150 \text{ units}$$

Specific productivity measurements were taken at equal intervals of 30 minutes. The tools were tested with a composite alloy with both homogeneous and heterogeneous granulometric filler compositions. In the latter case, grains size of which is increased from the centre to the periphery over the entire height of the tool were used as filler for the composite coating according to the law (fig. 5)

$$\delta_i = \delta_0 + \sum_{i=10}^{n} \frac{R}{2(2R_i - 1)};\quad n = 10, 20, 30.....$$

here δ_0 – the grain size of the filler in the central part of the tool, equal to D of its diameter, δ_0=0.001; R – radius of the tool; R_i – current radial coordinate.

The validity of the division of the instruments by specific productivities according to the above structure was checked by the linearity of the dependence $F_1=F_1(F_2)$, where $F_1=N/M$, $F_2=L/M$ (N, M, L – determinants composed of functions $P_i(t)$ and their moments).

To make a preliminary assessment of the effect of the inhomogeneity of the particle size distribution of the granular filler on the operating performance, graphs were made showing the change in the relative number of tools for each group over the entire test period. These plots are shown in figure 6a, b and c. From the nature of the changes in the curves obtained, it can be concluded that the relative number of tools with constant filler granulation in the first group increases sharply at the end of the test, whereas in the second and third groups a decrease in the relative number of tools is observed.

On this basis, the effective reinforcement of the cutting tools of wellbore milling equipment can be considered as a composite alloy with a heterogeneous granulometric composition of gra-nular solid filler. After this preliminary analysis, the transition probability matrices are calculated from the test results. For the first six levels, the experiments with

tools reinforced with alloys with constant filler granulation gave a matrix.

$$P_{1-6}=\begin{vmatrix}64 & 0.36 & 0.00\\ 0.14 & 0.68 & 0.18\\ 0.05 & 0.66 & 0.29\end{vmatrix} \quad (14)$$

For the second stage of experiments with constant filler granulation

$$P_{7-12}=\begin{vmatrix}0.99 & 0.00 & 0.00\\ 0.10 & 0.82 & 0.08\\ 0.00 & 0.86 & 0.14\end{vmatrix} \quad (15)$$

For tools reinforced with alloys with variable filler granulation for the corresponding stages, matrices have been obtained accordingly

$$P_{1-6}=\begin{vmatrix}0.68 & 0.24 & 0.08\\ 0.11 & 0.65 & 0.24\\ 0.22 & 0.77 & 0.00\end{vmatrix} \quad (16)$$

$$P_{7-12}=\begin{vmatrix}0.10 & 0.74 & 0.16\\ 0.52 & 0.24 & 0.24\\ 0.00 & 0.99 & 0.00\end{vmatrix} \quad (17)$$

Using the matrices obtained, we formulate systems of equations to find the stationary vectors ∏ [15]. Thus, to find the vector ∏-6 for the first stage of the experiment with tools reinforced with alloys with constant filler granulation, we obtain a system of equations

$$\begin{cases} n_1 = 0.64n_1 + 0.14n_2 + 0.05n_3 \\ n_2 = 0.36n_1 + 0.68n_2 + 0.66n_3 \\ n_3 = 0.18n_2 + 0.29n_3 \\ n_1 + n_2 + n_3 = 1 \end{cases}$$

and for the second stage

$$\begin{cases} n_1 = 0.99n_1 + 0.01n_2 \\ n_2 = 0.82n_2 + 0.86n_3 \\ n_3 = 0.08n_2 + 0.14n_3 \\ n_1 + n_2 + n_3 = 1 \end{cases} \quad (18)$$

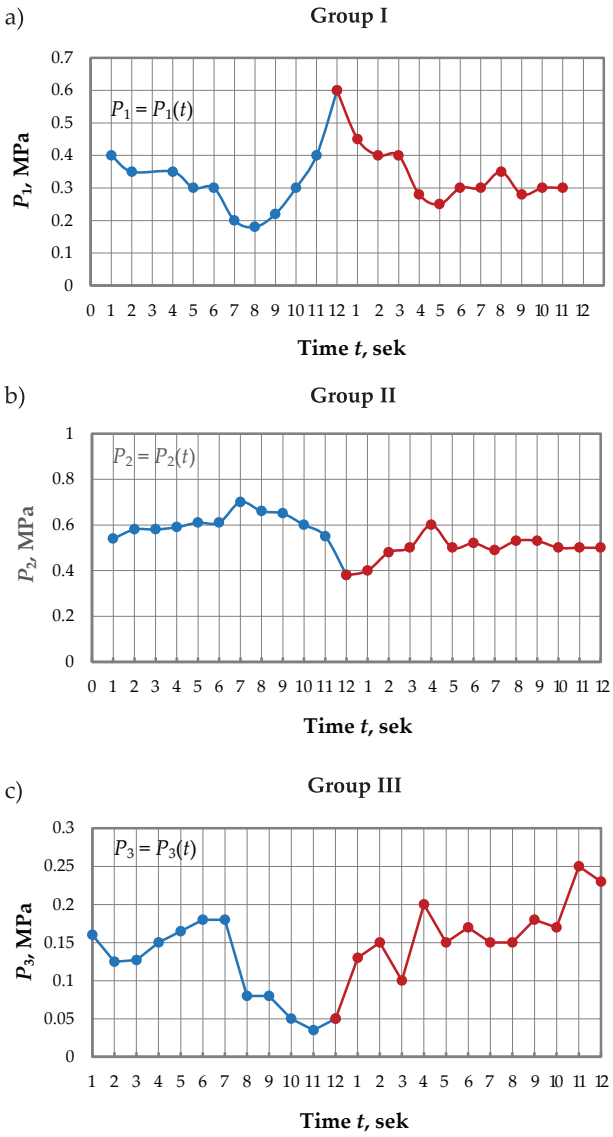
With variable filler granulation, these systems are represented as

$$\begin{cases} n_1 = 0.68n_1 + 0.11n_2 + 0.22n_3 \\ n_2 = 0.24n_1 + 0.65n_2 + 0.77n_3 \\ n_3 = 0.08n_1 + 0.24n_2 \\ n_1 + n_2 + n_3 = 1 \end{cases}$$

$$\begin{cases} n_1 = 0.1n_1 + 0.52n_2 \\ n_2 = 0.74n_1 + 0.24n_2 + 0.99n_3 \\ n_3 = 0.16n_1 + 0.24n_2 \\ n_1 + n_2 + n_3 = 1 \end{cases} \quad (19)$$

The stationary probability distribution vectors for each of the periods are found by solving the given systems of equations. They are as follows

$$\begin{aligned} \prod\nolimits_{1-5}^{dis} &= (0.25; 0.60; 0.15) \\ \prod\nolimits_{7-12}^{dis} &= (0.9; 0.09; 0.01) \\ \prod\nolimits_{1-5}^{dis} &= (0.26; 0.67; 0.17) \\ \prod\nolimits_{7-12}^{dis} &= (0.30; 0.52; 0.18) \end{aligned} \quad (20)$$



a) for the first group (q_1=50 units)
b) for the second group (50<q_2<150 units);
c) for the third group (q_3>150 units)

Fig. 6. Probability of changing the number of trials with results

If the obtained stationary vectors are interpreted as long-term predictions of the distribution of the relative number of trials (by specific productivity) between groups, the following conclusions can be drawn. In the case of constant filler granulation in the composite material, the number of trials with specific productivity from 50 to 150 units and more than 150 units in the second grinding stage would decrease sharply to 0,09% and 0,01%, respectively. That is, the predicted value of the distribution of the relative number of trials with specific productivity for the third group at the end of the milling process would be 1% of the total number of trials. The number of trials where the specific productivity was less than 50 units rises sharply from 0.25 to 0.9. This means that with constant filler granulation, the number of trials with «low specific productivity» increases. Therefore, there is a certain time limit [11] after which there is a sharp decrease in the efficiency of tools based on composite materials with constant granulation of the filler.

This is explained by the onset of a period of «avalanche» like wear of the cutting part of the tool due to the weakening of the matrix under the influence of thermomechanical disturbances. As a result of using composite materials with variable filler granulation for the first stage of the experiment, a large percentage of experiments with average specific productivity and a relatively small percentage of experiments with low specific productivity (26%) are planned. In addition, the relative distribution between the groups does not change significantly at this stage compared to the constant filler granulation composite. In this respect, the second stage of the milling process is characteristic, where, with variable filler granulation, the number of trials with medium and high specific productivity remains at the same level as in the first stage, with 0.52 and 0.18 respectively. Only in the first two groups - there is a minor distribution. A comparison of the results of the second stage trials shows that throughout the process, with variable filler granulation of the composite material, the majority of the tools will have a specific productivity of more than 50 units. In the case of constant granulation, this is only observed in the early stages of milling. Subsequently, the tools will have a specific productivity mainly below 50 units.

This proposal was also adopted by the Zabrat Machine-Building Plant, where the production of downhole -milling tools with variable filler granulation is currently organised [4].

Conclusions

1. Research has been carried out to determine the structure of the filler in the composite material applied to the working part of the cutting tool to diagnose its operational efficiency.
2. A new structural design of the cutting tool equipped with composite material has been developed, which eliminates uneven wear in the volume of its working part during the destruction of the emergency facilities in well conditions.
3. The actuating element of the milling tool was optimised based on the experimental studies carried out and the optimisation procedure of the diagnostic coefficients of the parameters defining the kinematic chain of the cutting structure parameters, including the structural and design indicators of the composite cladding.
4. The effect of the cavitation process on the wear resistance of the cutting part has been developed and experimentally studied, which helps to improve the fracture process of the emergency facilities in the well.
5. A Markov model of composite processing, analogous to the biological processes of birth, reproduction and death, was developed and validated by computer studies, allowing the identification and correlation of the parameters of the component composition of composite cutting structure and the operational efficiency of milling tools;
6. As a result, the scientific basis for the synthesis of compatibility ranges of operational-technical parameters with the physical-mechanical properties of the damaged emergency facilities, cutting structure parameters and the design of well milling machines has been created.

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