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RESTORATION OF CUTTING PART OF USED DOWNHOLE MILLING TOOLS

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Abstract

Downhole cutting tools are used to repair oil and gas wells as well as to eliminate complicated accidents. However, their acute shortage at oilfield facilities is obvious. The conducted researches have shown that the restoration technology of downhole cutting tools are currently being introduced into production. Besides, there is no information about the layer applied to the damaged area of the cutting element, the optimal mode of operation, as well as the efficiency of the restored tool.

In the considered article, the problems which have found a scientifically grounded decision and possibility of direct introduction of the restored tool in manufacture are solved.

Keywords: *cutting tool, downhole milling machine, modeling, well, experimental unit*

Introduction

Acceleration of emergency and recovery operations in production and drilling wells at minimum costs is a significant reserve of oil and gas production growth (Müller, 2004).

The most complicated works in wells are performed with the use of downhole cutting tools. Experiments conducted during the operation of cutting tools show that, mainly, the cutting part of the tool is subjected to wear and destruction, the housing and other elements remain suitable for further operation. Restoration of working parts of, used downhole cutting tools, is a scientific and technical task in the oil and gas production industry.

At restoration of worn out or destroyed section of a working part of cutting tools are mainly applied in mine electric furnaces or HFC (high frequency current) in conditions of a manufacturing plant and by application of cutting and binding elements made in the form of special surfacing bars under the influence of a gas burner flame.

To solve the set task it is required to analyze modern methods of restoration of the worn cutting part of the used downhole cutting tools, study the efficiency of downhole cutting tools with the restored working part, to develop the technology of manufacturing of surbacing rods and technological methods of applying them to the worn parts areas of cutting tools, as well as conduct stand tests with restored cutting tools.

The conducted analyses on the issues of restoration technology of reinforced layer of used cutting tools showed that mainly "surfacing of restoration method" is applied in Azerbaijan and abroad.

The main brands of hard alloy surfacing rods are given in Table 1.

Table 1. *Brands of Hard-alloy rods*

Solid alloy			Matrix material	
Composition, %	**Grain size, mm**	**Hardness, HRS**	**Composition,%**	**Melting point,°C**
Carbides (Mo, Cg, V, Zn, Ti, Nb) + cobalt or a mixture of carbides and cobalt	0.5–5.5	85	1) Cu; 2) Cu + Zn; 3) Cu – Ni; 4) Cu – Zn – Ni; 5) Cu – Si	871–1343
Sintered tungsten carbide	0.355–0.255 0.255–0.180 0.180–0.120 0.120–0.065	85	Copper 46... 48 Zinc 39... 41 Nickel 10...12 Silicon 0.15 Phosphorus 0.02	873–1312
Sintered tungsten carbide + co-balt 4–12% + + nickel 5 + 35%	0.5–5.5	85	Copper-nickel-iron; Copper-nickel-tin; Copper-nickel-iron-tin; Copper-nickel-manganese	843–1317

Bars are mainly made of refractory carbides such as cobalt, tungsten, niobium, titanium, as well as matrix material based on alloys of copper with zinc, tin, nickel, iron, manganese.

For the manufacture of carbide bars, masses of crushed solid particles in the required sizes are first selected, then they are chemically treated to purify them from foreign material (Table 1). Solid particles together with pieces of solder along the specified length are placed in special molds and put into thermostatic furnaces. Under the influence of heat, the solder melts, coating the carbide particles. After cooling it forms a composite carbide rod of a given diameter and length.

Carbide surfacing rods used for restoration of working parts of downhole milling tools, are produced abroad. Mainly these rods are produced by the German company "Woka" (Müller, 2004). It produces industrial brand of surfacing rods "DURIT" (Table 2). The size of tungsten carbide particles ranges from 1 to 12 mm. Six fractions of tungsten carbide particles are used for manufacturing of rods: 1.0–2.0 mm; 1.5–3.5 mm; 3.5–5.0 mm; 5.0–6.5 mm; 6.5–8.5 mm; 8.0–12.0 mm. Rod dimensions – 9.5 × 450 mm.

These rods provide good adhesion of the surfacing with the base of the cutting tool, and also provides reliable protection of wear surfaces of drilling equipment parts.

Data on sintered fluxes of different granulometric composition produced by "Woka" for autogenous and electric surfacing are given in Table 3.

Table 2. *Surfacing with Woka rods*

No.	Type designation	Analysis results	Type of product property
DURITS 1	Carbide W_2C	Carbon:3.7–4.1% Other: 0.75% max. Residue: tungsten	Fine feather structure of maximum hardness

No.	Type designation	Analysis results	Type of product property
DURITS 1	Sintered carbide	Carbon: 6% Cobalt: 6% Titanium: 1% max. Other: 0.75% max. Residue: tungsten	For the manufacture of composite type rods and other welding filler materials
DURITS 4	Sintered carbide	Carbon: 6% Cobalt: 6% Titanium: 4% max. Other: 0.75% max. Residue: tungsten	For the manufacture of files and other types of tools, as well as for the manufacture of compozit type rods
DURITS 10	Sintered beads	Carbon: 5.75% Cobalt: 6% Residue: tungsten	For the manufacture of roller cone bits and tools for deep oil drilling technology

Table 3. *Autogenous and electric surfacing for different smooth-metal compositions*

No.	Established analysis	Rockwell hardness	Application area
DURITS 70	70% WC 10% C_2 Residue Fe	70	High-strength and wear-resistant metals against shockless surfacing loads
DURITS 70	80% WC 20% Fe	65	In parts subjected to abrasion and abrasive wear under low impact loads
DURITS 80 Ni	80% WC 10% Ni 10% Fe	60	In chip cutters, pressure rollers, impact bars

The American company "International Tool Co.", depending on the purpose of cutting tools, produces industrial brand of rods of various alloys 'Zitco', which is made of tungsten carbide, for hard-alloy coating on cutting areas of tools; cutting steel alloys "Zitco-1"; for working in soft and medium hardness rocks "Zitco-2", and in hard rocks "Zitco-3".

The American firm "Bowen" produces an industrial brand of "Itcoloy", which is used to cover the working surface of cutting tools, shoes, stabilizers, etc. (Bowen Tools Inc. 1972).

Itcoloy rod contains 80% of crushed tungsten carbides with hardness of 91–93 Rockwell units.

The binding material (matrix) is silver alloy with shear strength of 70 kg/mm^2 and hardness of 200 Brinell units.

In Azerbaijan and neighboring countries produce carbide materials consisting of tungsten carbides such as WC2, WC3. These materials have high wear resistance and chip formation. Composition and mechanical properties of hard alloy grades are given in Table 4.

Table 4. *Composition and mechanical properties of hard alloy grades*

Alloy grade	Approximate alloy composition, %		Hardness, HRS	Average bending strength, MPa
WC 2	98	2	90	1100
WC 6	94	6	88.5	1450
WC 8	92	8	87.5	1500
WC 10	90	10	87.0	1600
WC 15	85	15	86.0	1800

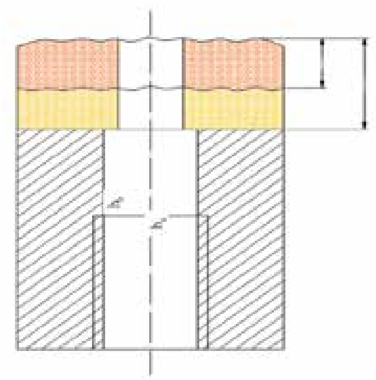
Model samples of downhole milling cutters, cutting edges consisting of composite materials containing crushed particles of tungsten-carbide alloys were manufactured for experimental studies and evaluation of wear resistance and metal chip formation. The conducted researches have shown that the best results are achieved in the case of application as cutting elements of grains of crushed tungsten-carbide alloy of WC8 grade and matrix bonding solder No. 4 or No. 7. These alloys have high wear resistance, the optimal ratio of carbide and solder is 60–65% carbide and 35–40% solder (Gasanov, 1978; Mustafaev et al., 2023; Mustafayev et al., 1997; Mustafaev et al., 2021).

Experimental studies have been carried out to investigate the effectiveness of the restored reinforcement layer of used downhole cutting tools. From the point of view of minimizing time and material costs, it was first decided to conduct experimental studies on model samples of cutting tools.

The method of physical modeling is the most acceptable method of research of the cutting process with the restored layer of the reinforced part is (Bondar, 1973).

The difference between the restored part of the reinforced layer of the cutter and the new one is specific.

Figure 1. *Model of restored milling cutter*



Taking into account the identical condition of the milling process of new and restored tools, we can use the known scaling factors.

Then we have the following relations to the restored borehole metal milling cutters:

$$C_Q = C_\Gamma^{\frac{-1}{2}};\ C_N = C_\Gamma^{\frac{-1}{2}};\ C_E = 1;\ C_\omega = C_\Gamma^{\frac{1}{3}}; C_\sigma = 1;$$

$$C_D = C_\Gamma^{\frac{-1}{3}}; C_\rho = C_\Gamma^{-1}; C_\lambda = C_\Gamma^{\frac{-1}{2}}; C_a = C_\Gamma^{-1}; C_\rho = C_\Gamma^{\frac{-1}{3}};$$

$$C_t = 1; C_{\Delta u} = C_\Gamma^{\frac{-1}{6}}; C_d = C_\Gamma^{\frac{-1}{6}}; C_c = C_\Gamma^{\frac{-1}{3}}; C_\rho = C_\Gamma^{\frac{-1}{3}};$$

$$C_a = 1; C_u = C_\Gamma^{\frac{-1}{6}};\ C_{y1,2} = C_\Gamma^{\frac{-1}{3}}; Ch_b / h_a = C_\Gamma^{\frac{-1}{6}} \quad (1)$$

These scaling factors make it possible to transfer the results of experiments on models to full-scale samples with sufficient reliability. On the basis of scaling factors the designs of model samples of cutter and milled object were developed.

The previously developed models of cutting milling cutters with a restored cutting edge height h_b and total reinforcement height h_a were used as models (Figure 1).

Tests of model samples were carried out on the experimental installation (Figure 2).

This installation makes it possible to regulate the supply of flushing coolant, air and to measure the temperature with sufficient accuracy. The installation is equipped with measuring instruments, mounting and dismounting of the investigated sample does not cause difficulties.

The model of the restored cutter is a metal cylinder made of steel 45 with an outer diameter of 31 mm and an inner diameter of 13 mm. The lower end of the cylinder consists of a worn layer of carbide composite material of different height h_a, on which a new layer of height h_b is clad (Figure 1).

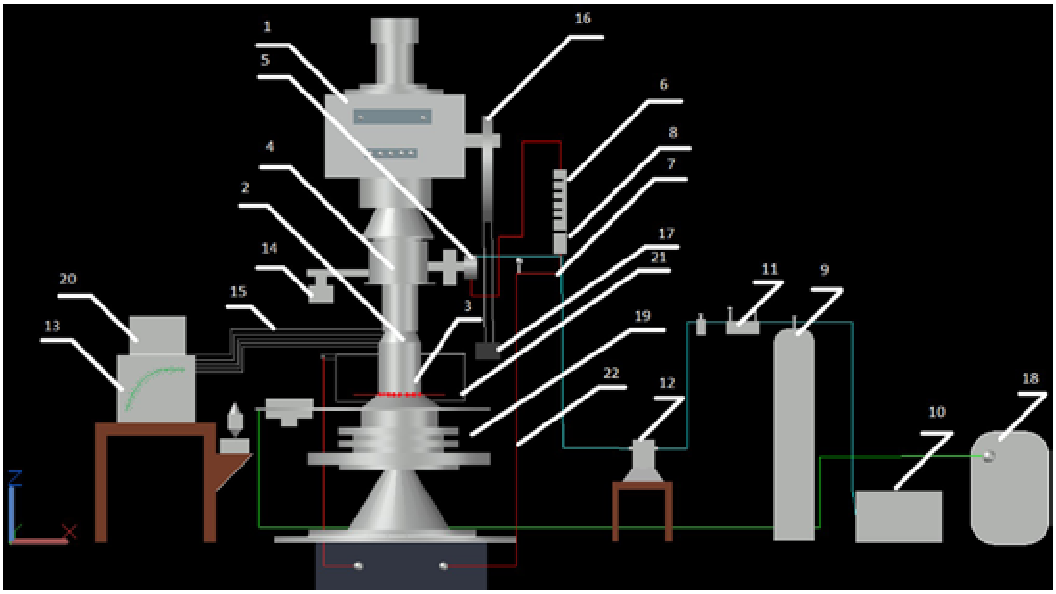
The experimental installation consists of the following units: a special machine 2H-135 (table size 450 × 500 M), a model sample of a milling machine (2), cooling devices (4), an object to be milled (3), a gas ejector (EG 750) (5).

The body of the model sample of the milling tool is made of 40X steel with an outer diameter of 34 mm and an inner diameter of 14 mm, its cutting part is made of carbide composite material BK8. Composite materials consisting of crushed carbide and binder, applied to the body of the model sample has the highest indicators of cutting ability and wear resistance. The process of milling of the emergency metal object by such milling cutters is self-sharpening, as new cutting elements come out of contact with the surface of the milled object as the cutting edge volumetrically wears out. The conditions of manufacturing of the model sample corresponded to the conditions of manufacturing of serial downhole milling cutters of WBM (wellbottom miller) type, reinforcement of the cutting part was made by HFC (high-frequency current) in AzINMAS H.

One of the requirements for cutting tools is to create the largest metal cut, which depends on the strength condition of the cutting element.

The cutting part is reinforced at a height of 10 mm. In the reinforced part there are horizontal stainless steel shutters with a diameter of 2 mm for chromel-alumel thermocouples (CAT), and vertically with a diameter of 3 mm for liquid supply. After reinforcement, the shutters were fully perforated. Then the thermocouples (semi-artificial thermocouples, calibrated to the accuracy of 10 °C) were installed on the body of the cutter and insulated with liquid resin. At high temperatures, this resin does not melt, but rather hardens and gives a good guarantee of heat transfer from the measuring point to the measuring instrument. Minor heat transfer to the medium is not considered.

Figure 2. *Experimental installation*

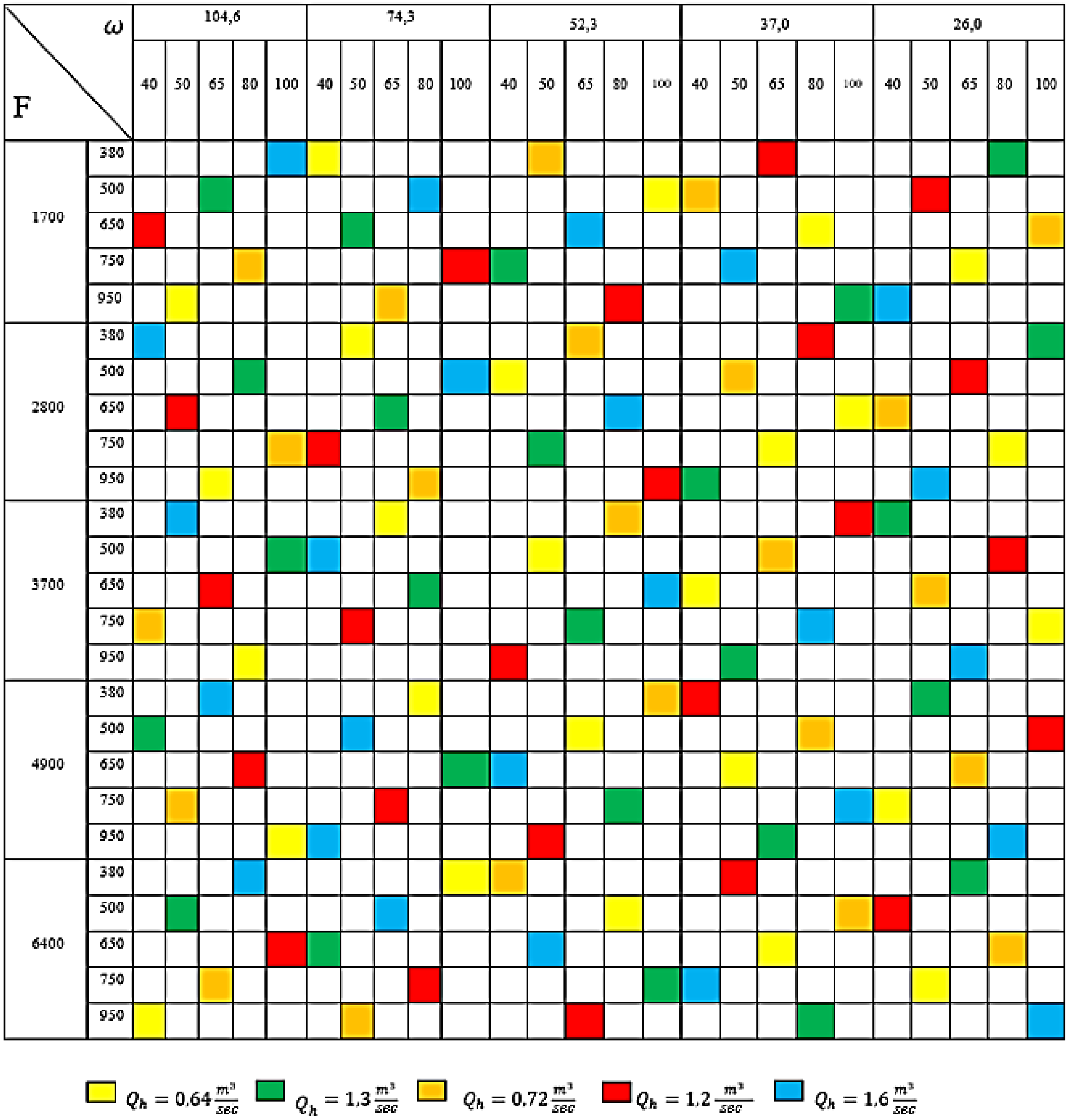


The experimental work spent on chip removal depends mainly on the physical and mechanical properties of the machined material. With the increase of mechanical properties of machined materials, the stress and deformation state of the chip formation zone increases, at the same time the force and energy indicators of the process increase. The stressed and deformed state in the zone of chip formation depends on the resistance of the machined material to plastic deformation. The higher the toughness and riveting ability, the greater the resistance of materials to cutting.

Increase of stressed and deformed state and temperature in the zone of chip formation, the manifestation of hardening in this zone, as well as the ability of materials to tilt leads to an increase in cutting forces, which in turn can contribute to blunted model tool specimen and tear out their cutting elements. Proceeding from this, milled samples are made of steels 20X, 40X, 30, 35, 45 – the mechanical properties of which are close to the mechanical properties of tubing. The samples have a cylindrical shape with an outer diameter of 34 mm and an inner diameter of 14 mm. Model samples are inserted into a special disk mandrel, changing the parameters of the milling mode, thus changing the samples in the mandrel.

The tool and the material to be processed are cooled by three components: 20 °C process water, air and their mixture. First, we regulate the amount of FC with the rotometer (6). Water is supplied to the cutting zone by the rotometer, which has a tee valve at the outlet. One end is connected to the manometer, and the other end is connected to the rotometer with a rubber tube. (For example: the valve is set to the manometer reading P = 0.15 atm corresponds to *Ql = 40 ml/sec*. The other indicators are given in Table 3).

Figure 3. *Combinaton cube of experiment planning*



In the first stage, the experiment was conducted without cooling. In the second stage of the experiment, the air supply is regulated. First, a gas cylinder (9) is filled bu a compressor (10), a reducer (11) is installed at the outlet of the cylinder, which regulates the air supply. Then the air is transferred by a rubber hose to the gas meter (CT-40) (12), where its readings are taken (Table 3), then to the gas ejector and the milling zones. When it is necessary to supply one or another component to the cutting zone, one side of the gas ejector (EG 750) is plugged. GE is designed for mixture of liquid with air.

High-pressure air and low-pressure water are fed into the EG (Fiqure 3), a mixture of air and water is formed in the displacement chamber and the air sharply increases the flow velocity. Having a significant speed, the air jet creates a zone of low pressure around itself, in which low-pressure water from the receiving chamber to the milling zone is tucked. The result is an aerated liquid. The EG is attached to the body of the cooling unit (CU).

The CU is a special designed device designed for tool cooling. The upper part of the device stem is prepared for Morse taper and seated on the spindle socket with a tension that prevents it from falling down when the

CU is rotated. In the middle of the CU 4 holes in the form of a blade are drilled to ensure the supply of aerated liquid at high speeds. Due to the movement of the flow through these holes there is a centrifugal force, creating a vortex motion, which moves the liquid and there is a diffusion effect. Aerated liquid enters the CU through the hole available on its body. Along the outer diameter of the stem below the body 6 grooves of 1 mm wide are cut (Figure 3). A copper ring insulated with epoxy resin is installed in each groove. The lower part of the stem is threaded and connected to the router model. Each ring is then connected by soldering the corresponding thermocouples of the cutting model. As the milled sample is processed, the milling plane approaches the junction of the thermocouple and the fixed temperature in the body of the cutter in the form of an electrical signal is transmitted through the current puller (14), to the self-recording device (SRD-9) (13), where the measurement results are recorded on chart paper. The current collector is connected to the self-recording device by compiling wires (15) and fixed on the body of the cooling device, where the body is stationary at the moment of rotation. The slip ringshabts are in sliding contact with copper rings mounted on the outer diameter of the rod when rotating the tool model.

Operation of the cutting model depends on the power of the power equipment combination with the axial load on the tool to realize sufficient metal removal. To ensure the required axial force delivery on the drilling machine, the handle is replaced by a pulley (16). A steel rope is wound on the pulley (pulley diameter Ø 400 mm) and a tripod is attached to its end. When changing the milling parameters, appropriate scales (17) are mounted on the tripod. The axial force is pre-torqued with a dynamometer for each 1000 N. The dynamometer is also calibrated with an accuracy of 5 kg.

When adjusting the axial force, the power of the experimental machine tool is taken into account. When measuring, the generated power (N_1) must not exceed the power of the machine tool ($N = PV$), i.e. $N_1 \leq N = 4200$ N m/sec. For example, at speed n = 31.5 rpm mechanical speed $V = \omega r_1 = 0.056$ m/sec; where $\omega = 3.3$ rad/sec is angular velocity; $r_1 = 0.017$m radius of router model) axial force will be 71430 N. So the axial force created in this revolution should not exceed 71430 N. The generated power is measured with a wattmeter (H350) (20).

In some cases, the stand does not allow the experiment to be performed by rotating the sample. During such rotation the cutter is stationary. The rotation of the borehole is performed by means of an electric motor (belt transmission) with 25000 N m/sec. Pulleys of different diameters allow to change the rotational speed of the borehole. The inner diameter of the rotating borehole is cone-shaped. Therefore, the lower part of the milled material is prepared in the form of a cone and is injected into the borehole to increase the strength, safety and manufacturability of the milling process. Supply of cooling agent to the cutting zone is provided from transparent pipes by a closed circular circuit (22). The beaker (21), in which the material to be processed is placed, is also made of transparent pipes, so that the processes taking place in the milling zone during the experiment can be seen.

Each sample of the restored cutter was first subjected to a test run to ensure that the existing solder layers and other irregularities on the cutting surface were fully worked in. Completion of running-in was determined by stabilizing the wear of the cutter, which was determined visually.

Depending on the quality of restoration of the cutting part of the cutter and the mode of operation, the burn-in was continued for 5–20 min. Experimental studies consisted of separate series, each of which included several experiments to ensure the accuracy of the obtained results.

The number of necessary experiments was determined by the general dispersion of observations and the acceptable dispersion of research results found out from preliminary studies. Experimental work was carried out to investigate the wear resistance of restored tools.

At different series of experiments the following main parameters of the investigated process were regulated: static axial load on the cutting mill – P; angular velocity – ω; flow rate of FC – Q; height of the restored layer – h_b.

Table 5. *Experimental parameters*

No.	Axial load of the milling cutter, N	Angular speed of the cutter, rad/s;	Consumption FC, м^3/s	Relative height of the restored layer, %	Milled metal
1	1.7	26	40	32	ST 40X
2	2.8	37	50	36	
3	3.7	52.3	65	50	
4	4.9	74.3	80	61	
5	6.4	104.6	100	68	

To evaluate the milling cutting performance, samples before and after the experiment were weighed on technical scales.

Based on the obtained data and visual observations, the results of the conducted experimental studies were summarized and processed.

The efficiency of work, restored cutting parts of milling cutters, depends on the correct choice of mode parameters and on the height of the restored layer of used milling cutters reinforcement.

The equation reflecting the physical essence of the process is related to the main parameters of the cutting process:

$$q_s = f\left(P, w, Q, h_a / h_b\right) \qquad (2)$$

where: $q_s = \frac{q_{c.m.}}{q_c}$ – specific productivity of milling cutting, gr/gr; $q_{c.m.}$ – wear rate of milled metal, g/min.; q_c – wear rate of model sample of cutting element, g/min.; P – axial load on the cutting element, *kN*; ω – angular velocity of the tool, *rad/s*; Q – pump capacity, m^3/s; h_b – height of the restored reinforcement layer, mm.

To determine the optimal parameters of the restored optimal height of the reinforcement layer, it is required to determine the qualitative and quantitative influence of various factors on the indicators of the milling process. As it isindicated above, when the elements of the cutting part of the tool are restored, their parameters change significantly. This fact requires to investigate the process of milling with restored samples, to study the relationship between the parameters and the degree of their influence on the process, to find a mathematical model.

Investigation of the efficiency of the restored elements of downhole milling tools on the basis of field data is difficult and requires considerable expenses. Methods based on dispersion, regression and correlation analysis can be used to solve this problem experimentally.

To solve the task at hand, it is advisable to use the method of rational planning of the experiment, because with a minimum number of experiments it is possible to obtain more accurate results. To achieve this goal, each experiment should differ from the others by a non-repeating combination of selected factors.

Combination squares, numerical matrices or orthogonal squares can be used in rational planning. Since four factors change in the process of milling with reclaimed tool cutting, the method of combinational square was applied in our study (Figure 3).

The combination cube was made in such a way that there were no repeated combinations in any row or column. Based on the combinational square, the need for 25 experiments was determined. The calculated variants and the obtained results of experiments are shown in Table 2.

By means of correlation and regression analysis the qualitative and quantitative influence of the selected factors on the process indicators was determined.

Variables (output parameter) and factors are random variables and there can be a correlation relationship between them, which is characterized by the correlation coefficient, and allows to assess the measure of statistical relationship between the indicators and process parameters, as well as between the regulated factors themselves.

The results of correlation analysis were the initial material for the construction of regression equations.

The experimental data were processed using correlation and regression analysis, and a statistical mathematical model of the process was obtained in the form of a regression equation. The results of the conducted experiment of the complete study were processed according to the optimal algorithm, in order to create a mathematical model of the process (Mustafaev et al., 2022; Dzhafarov, 2021).

This sequence was applied in the derivation of the regression equation of the active experiment to determine the effect on specific wear of the parameters included in the physical equation (Table 2) (2).

Using the results of active experiment, the following equations describing the metal milling process were obtained (Table 6):

– for specific productivity:

$$Y_{s.} = 142.41 - 0.93X_1 - 1.17X_2 + +2.2X_3 - 0.22X_4 \quad (3)$$

– for the wear rate of the milled material:

$$Y_{s.} = 7.51 - 0.025X_1 + 0.032X_2 - -0.0163X_3 - 0.003X_4 \quad (4)$$

– for the wear rate of the cutting tool:

$$Y_{c.t.} = 0.065 + 0.0001X_1 + 0.0006X_2 - -0.0010X_3 + 0.00006X_4 \quad (5)$$

where Y – random variables; $X_1, X_2 \ldots X_n$ – factors of varying small error.

The degree of correspondence between the experimental data and the values of specific productivity, wear of the processed material and cutting tool calculated by equations (3–5) determines the measure of identity determined by the formula:

$$\theta_y = \sum_{i=1}^{N} a_i r_y X_i \quad (6)$$

$$a_i = a_i \frac{\sigma_{xi}}{\sigma_y}$$

where a_i – the coefficient of the regression equation. For our case $\theta_s = 0.992$

The multiple correlation coefficient on the magnitude of the identity measure, which characterizes the degree of closeness of the experimental data to the linear model, was calculated from the relationship:

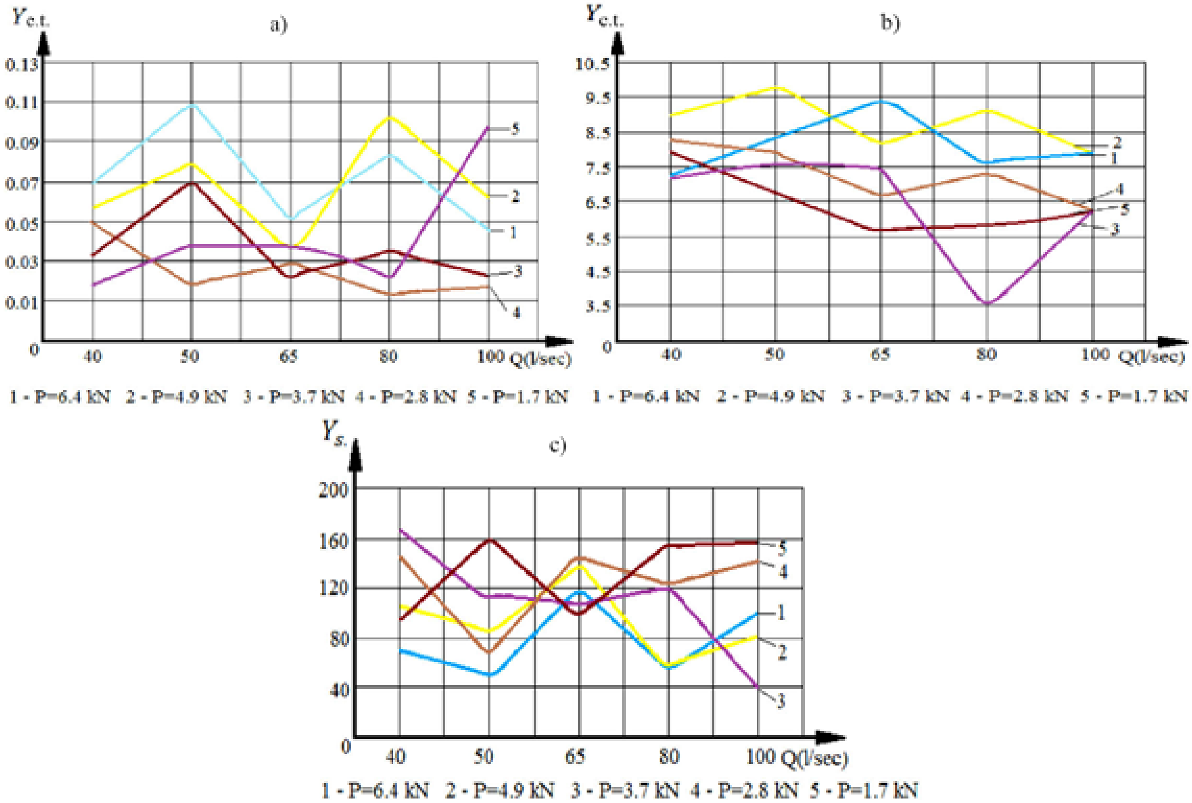
$$R_s = \sqrt{\theta_s} = 0.998 \quad (7)$$

Table 6. *Results of the conducted experiments*

Factors				Output factors		
ω, rad/s	**P, $10^2 N$**	**h_b/h_a %**	**Q, l/sec**	**Cutter wear rate Y_c, g/min**	**Wear rate of the cutter material $Y_{c.м.}$, g/min**	**specific productivity $Y_{s.}$, g/g**
26	6.4	65	65	0.05	8.57	141.28
37	6.4	20	50	0.11	7.67	58.03
52.3	6.4	77	100	0.04	7.58	125.58
74.3	6.4	45	40	0.07	6.68	82.01
104.6	6.4	55	80	0.08	6.71	73.06
26	4.9	20	80	0.02	8.48	77.68
37	4.9	77	65	0.04	7.63	155.23
52.3	4.9	45	50	0.05	9.13	101.01
74.3	4.9	55	100	0.06	7.58	99.32
104.6	4.9	65	40	0.05	8.32	123.01
26	3.7	77	40	0.02	6.53	205.03
37	3.7	45	80	0.03	7.01	137.22
52.3	3.7	55	65	0.04	6.75	126.45
74.3	3.7	65	50	0.02	3.12	147.61
104.6	3.7	20	100	0.01	5.32	48.02

Factors				Output factors		
ω, rad/s	P, $10^2 N$	h_b/h_a %	Q, l/sec	Cutter wear rate Y_c, g/min	Wear rate of the cutter material $Y_{с.м.}$, g/min	specific productivity $Y_{s.}$, g/g
26	2.8	45	100	0.033	6.57	148.34
37	2.8	55	40	0.034	7.63	168.13
52.3	2.8	65	80	0.018	6.01	165.43
74.3	2.8	20	65	0.068	7.14	87.68
104.6	2.8	77	50	0.028	5.58	168.32
26	1.7	55	50	0.026	6.28	196.77
37	1.7	65	100	0.023	5.47	194.23
52.3	1.7	20	40	0.051	7.26	115.67
74.3	1.7	77	80	0.016	5.28	188.24
104.6	1.7	45	65	0.03	5.15	126.11

Figure 4. *Dependencies of values: a)* $Y_{c.t.}$ *b)* $Y_{c.t.}$ *and c)* Y_s *pump capacity*



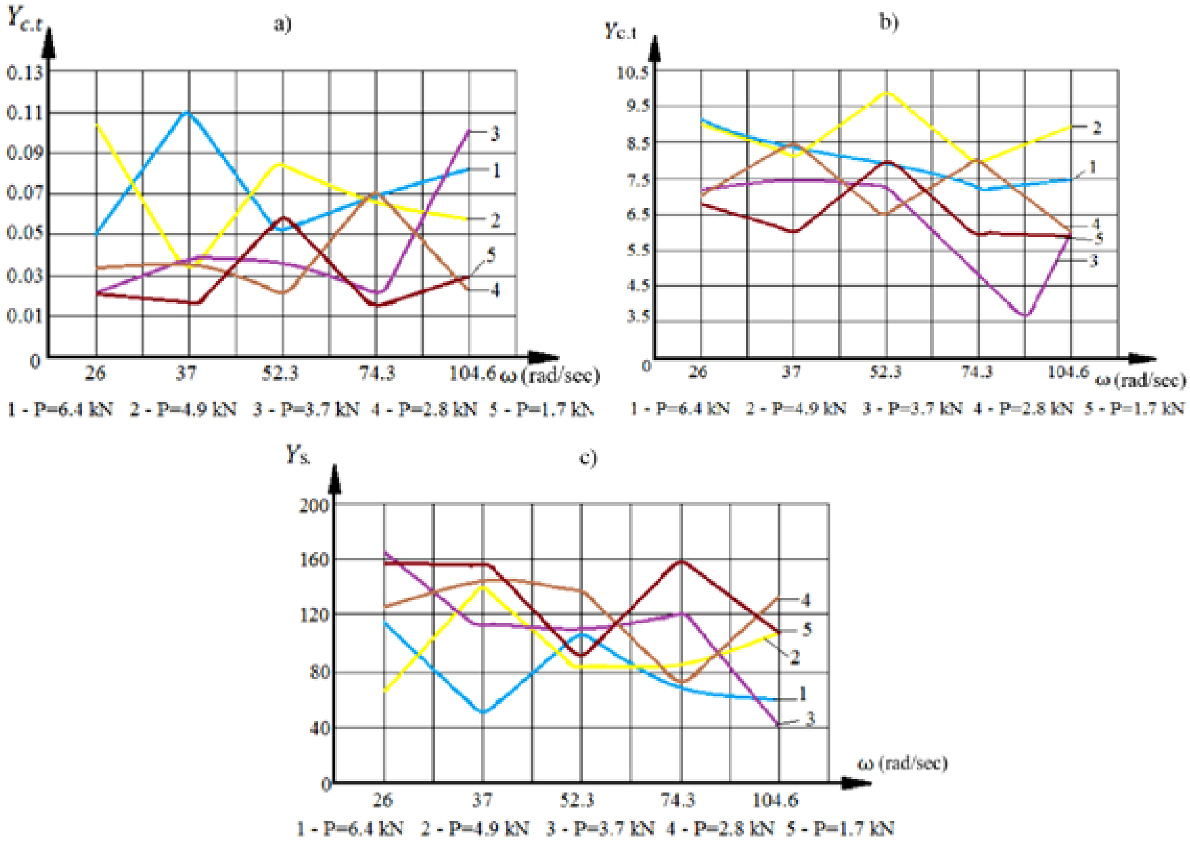
Determination of the adequacy of the obtained equation (the degree of its reproducibility) was checked using Fisher's criterion.

The obtained dependencies by Fisher's criterion showed that the selected mathematical models adequately describe the process of milling of emergency metals by the restored cutting edge.

In our case with respect to the equations: (4) – F_p = 6.15; (5) – F_p = 1.742; (6) – F_p = 5.33

For the degree of freedom $f_1=N-1=24$ and $f_1=N-(K+1)=20$ at the chosen level of significance q = 0.005–F_{table} (Mirzajanzadeh A. H., Stepanova G. F., 1977), since the condition $F_p \leq F_{table}$ equations (4–6) adequately describe the milling process.

Figure 5. *Dependencies of magnitudes: a) $Y_{c.t.;}$ b) $Y_{c.t.}$ and c) $Y_{s.}$ of the angular speed of the cutting tool*



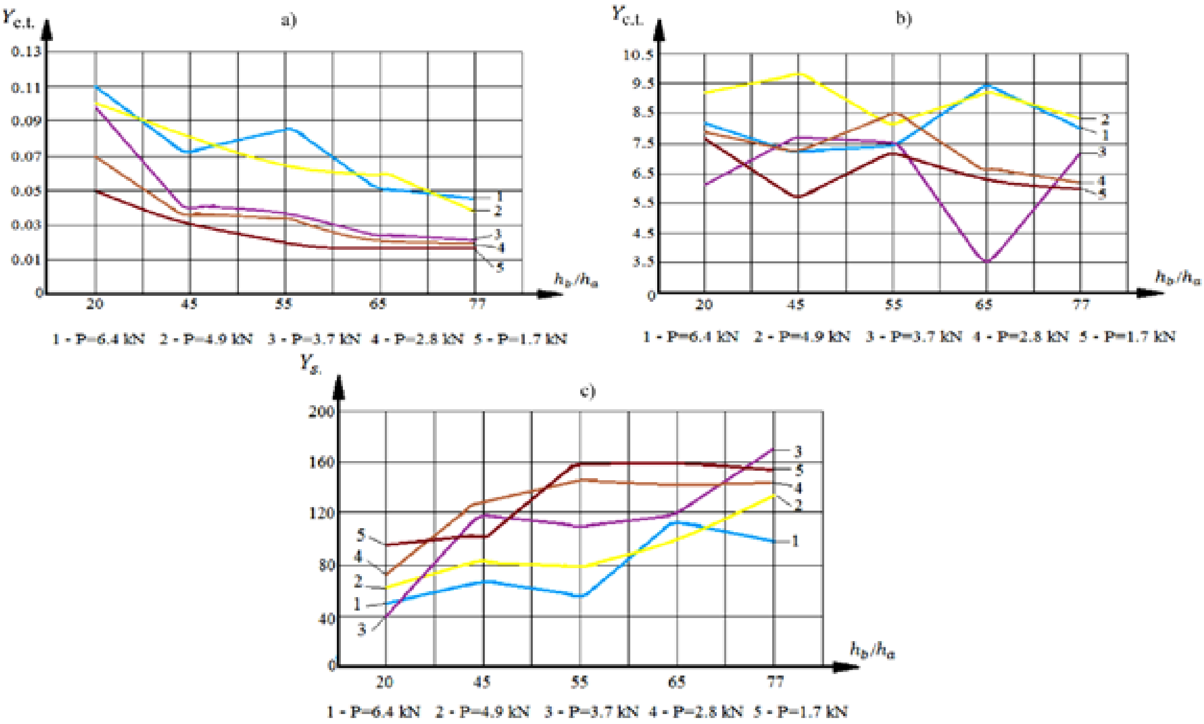
The obtained regression equations (4), (5) and (6) were used to select rational combinations of mode parameters and height of the restored reinforcement layer in order to obtain maximum process productivity within the tool life. According to the obtained data, the graphical dependences of $Y_{c.t.}$, $Y_{c.t.}$ and Y_s. values were plotted separately from each of the mode factors when averaging and neutralizing the influence of other factors (Figure 4). The graph shows that h_b/h_a change has a negative sign influence on Y_s. With the increase of the height of the reduced layer and its connection with the residue of the main layer thermal factors do not act. A proportional increase in the height of the reconstructed layer weakens the influence of these factors on the joint, thereby reducing the wear of the cutting edge.

One of the main requirements for cutting tools is the greatest penetration through the emergency facility with the least amount of cutting edge wear. The highest efficiency of metal cutting is achieved at the highest specific productivity. To establish this it is necessary to compare the dependencies $Y_{c.t.} = f\,(h_b/h_a)$ and $Y_{c.t.} = f\,(h_b/h_a)$.

At a sharp decrease of $Y_{c.t.}$ with the increase of the restored layer, $Y_{c.t.}$ slightly decreases (Figure 4 and Figure 5), and Y_s. increases (Figure 6). The obtained dependencies can predict that as the recovered layer increases, the productivity of the recovered tool increases. However, it is technologically impossible to increase the reduced layer indefinitely. Considering that after the ratio h_b/h_a=70...80%, q_s – specific productivity (q_s) increases insignificantly, so we consider it optimal.

The analysis of the curves shows that compared to new tools, the restored tools must be operated with a comparatively lower axial load, a higher angular velocity and the same applied FC (flushing coolant) flow rate.

Figure 6. *Dependencies of magnitudes: a) $Y_{c.t.;}$ b) $Y_{c.t}$ and c) $Y_{s.}$ on the ratio restored to the main reinforcement layer*



The process of milling of emergency objects during workover in the wellbore, as well as destruction of rocks during drilling occurs in identical conditions.

Based on the data of drilling operations, we make a ranking of the values of penetration – 6, 19, 20, 21 and check whether the minimum or maximum variants per defect.

To exclude defective data, we check the maximum and minimum values of each statistical combination by observing the inequality:

– to exclude the maximum variant:

$$\frac{C_n - C_{n-1}}{C_n - C_1} \geq K_n \tag{8}$$

– to eliminate the minimum variant:

$$\frac{C_2 - C_1}{C_n - C_1} \geq K_n \tag{9}$$

where, C is the value of penetration. Based on the number of variants in this set (Mirzajanzadeh et al., 1977), the value of *Kn* – we choose from the table at a given value of confidence probability (Typical methodology of industrial tests, 1975).

In our case:

— minimum variant:

$$\frac{C_n - C_{n-1}}{C_n - C_1} = \frac{-19-6}{21-6} = 0{,}86 \ \text{for} \ n = 6$$

$$K_n = 0{,}560 < 0{,}86$$

— maximum variant:

$$\frac{C_2 - C_1}{C_n - 1} = \frac{21-20}{21-6} = 0{,}06 \ \text{for} \ n = 6$$

$$K_n = 0{,}560 > 0{,}06$$

Since in inequality (8) the minimum variant is defective, therefore its value of penetration (6 m) is excluded.

At the same time, the maximum value of penetration in inequality (8) is observed and it is not defective. Therefore we make a new row – 19, 20, 21.

We check the defectiveness of the minimum and maximum variants by the new row:

— minimum variant:

$$\frac{C_n - C_{n-1}}{C_n - C_1} = \frac{20-19}{21-19} = 0{,}5 \ \text{for} \ n = 5$$

$$K_n = 0{,}642 > 0{,}5$$

— maximum variant:

$$\frac{C_2 - C_1}{C_n - C_1} = \frac{21-20}{21-10} = 0{,}5 \ \text{for} \ n = 5$$

$$K_n = 0{,}642 > 0{,}5$$

If inequalities (8) and (9) are not met in both cases, then the tested variants are not excluded (the aggregate is preserved).

Average penetration per cutting tool: 100/5 = 20 m

We determine the standard deviation of the value by formula (8):

$$S' = \frac{C'_n - C'_1}{dn'} = \frac{Vn'}{dn'} \quad (10)$$

where: Vn′ – different variation of the value in the newly obtained variation series; dn′ – a value determined according to (Typical methodology of industrial tests, 1975) depending on the number of members in the considered combination.

Then, with respect to our condition:

$$S' = \frac{C'_n - C'_1}{dn'} = \frac{21-19}{2{,}326} = 0{,}86$$

The sample coefficient of variation is determined by the formula:

$$Kb = \frac{S'}{n} = \frac{0{,}86}{20} = 0{,}043 \quad (11)$$

The maximum permissible relative error during testing is set (in fractions of one unit): $\delta' = 0{,}3$ and $\delta'' = 0{,}2$.

The value is calculated at a confidence level of 0.95:

$$\frac{ta'}{\sqrt{n}} = \frac{\delta}{K_b} \quad (12)$$

The value determines the minimum required number of prototypes of the compared designs for specific characteristic conditions, providing the necessary reliability and accuracy of the obtained experimental data (Typical methodology of industrial tests, 1975).

For reconstructed cutting parts of the tool:

$\frac{ta'}{\sqrt{n}} = 6{,}97$, $n_{\min} \prec\prec 5$ for cutting tools.

$\frac{ta'}{\sqrt{n}} = 4{,}65$, $n_{\min} \prec\prec 5$ for the new cutting tools.

Based on this calculation, the minimum required number of milling tools was determined, which is equal to 5 pieces. This number allows to obtain reliable results during testing.

For stand tests, 5 milling tools of DC-135 type were selected as milling tools. The cutting and abrasion areas of these milling tools were restored by means of a gas burner flame and carbide surfacing rods manufactured according to a special technology.

The following operating parameters were adopted during the tests: axial load on the cutter, 37 *kN*; angular speed of the cutter rotation, ω=52,3 r/sec; flow rate of the oil-water treatment fluid – 40–100 *l/sec*.

The analysis of the performed work on the restored downhole milling machines showed that the total wear of reinforcement made in the new and restored versions of milling machines at consecutive work on the tubing Ø73 mm and Ø89 mm for both versions of milling machines is approximately the same.

Evaluation of performance and reliability indicators of the restored downhole milling cutters according to the results of stand tests showed the following: specific penetration of the restored milling cutters on the tubing Ø73 mm and Ø89 mm will be 0.51 m/mm. The resource of the restored reinforcement layer at the maximum surfacing height of 10 mm will be: in terms of penetration 4.9 m; in terms of working time 12 hours.

Taking into account the result of the restoration of worn areas, the total height of the reinforced layer of milling cutters is about 11–19 mm. The resource of the reinforced layer of the restored cutter is about 65% of the resource of the total height of the new cutter.

Visual inspection of the restored milling cutters after tests showed that they can be reused for stand tests.

Thus, stand tests of the restored downhole milling cutters confirmed that restoration of the abrasion-cutting part of the used milling cutters is acceptable for the technological process, milling providing an increase in the service life of the milling tool without significant material costs.

Examination of the used milling cutter of DC-135 type restored showed that it can be reused in other wells. The wear of the reinforcement amounted to 2.5 mm.

The results of experimental tests of the restored DC-135 type milling machine showed its operability and reliability in milling various metal objects.

On the basis of positive results of stand and tests of restored downhole cutting tools the following instruction was developed.

According to the instruction the sequence of technological methods for restoration of abrasion-cutting section of used downhole milling tools, reinforced with crushed hard alloys, as well as the order of their quality control is determined. The essence of restoration of the abrasion-cutting section of milling tools reinforced with a hard alloy consists in surfacing the worn-out sections of the reinforcement with crushed hard alloy grains appluing carbide rods with the use of a gas burner operating on an oxygen-acetylene flame. Carbide bars are produced on sheets of carbide bars using a gas torch operating on an oxy-acetylene flame. Carbide bars are produced on slabs. They are used in molds made of graphite material in the presence of an electric furnace, providing the creation of a thermal field with a temperature of 1050 ºС.

The starting materials (charge) for the production of bars are:

— crushed hard alloy of grade BK8 and particle size 0.5–5 mm; solder of grade no. 4 or no. 7 TU 48–21–299–78; flux of grade PV 209X GOST 23170–78.

The material of the bar should contain in percent of the total mass (calculated amount): carbide 65–70; solder 30–35.

Crushing of carbide is performed by any method providing grain size (0.4–5 mm). Selection of carbide grains was performed by means of sieves.

Manufacturing of carbide bars consists in preparation of initial materials, their pouring into graphite molds, heating to melting and subsequent cooling in the molds in the air, removal of bars and checking the quality of their manufacture.

When preparing the crushed alloy, it is necessary to degrease the selected crushed carbide with gasoline or other solvent, and then mix with flux at the rate of 5 grams of flux per 250 grams of carbide.

To prepare the solder, cut the solder into pieces having a maximum side size of 5–1 mm in cross-section. Weigh the prepared crushed carbide and solder. Place them in the graphite mold along its entire length. The initial amount of carbide should be equal to its calculated amount, and solder 10–15% more than its calculated amount, depending on the degree of burnout.

The prepared charge should be covered with flux at the rate of 1–1.5 grams per 100 grams of charge. To produce bars, place the prepared mold with the charge in a thermal field and heat it to a temperature of 1050 ºС. After holding for 2–5 minutes at the specified temperature until the solder is completely melted and impregnated with hard alloy grains, stop heating, allow the mold to cool in the air and remove the bar from it.

Quality control of the bar is carried out by weighing it, and its weight should not be less than the weight of the initial materials by more than 10%. To check the mentioned technological methods, the bars were produced according to the following technological modes:

borax + carbide + borax + solder + borax; carbide + borax + solder + borax; carbide + borax + solder + borax; carbide + borax + solder + borax.

All samples were placed in a thermostatic furnace, heated to a temperature of +1100ºC and kept in the furnace for 20 min.

After the tests the following was found:

The first sample of bars turned out as separate pieces; 2,3,4,5 samples of bars turned out in one piece, the quality of bars is the same. It was found that removing the bars out of the molds is difficult, because the bars burned to the molds. To exclude this phenomenon, a part of graphite molds was painted with heat-resistant paint. 5 and 6 samples were made in graphite molds painted with heat-resistant paint.

Pictures of bars obtained by the above technology are shown in Figure 8. The quality of the bars is good, the surface of the bars is smooth, without cracks and abscesses.

When preparing the cutter for restoration it is necessary to clean it from dirt and wash with solvent the abrasion-cutting part to be restored. Visually inspect the area to be restored. If there are cracks and chips more than 5 mm deep, the abrasive-cutting part cannot be restored.

Restoration of the abrasion-cutting part of the milling tool with carbide rods is performed using acetylene-oxygen flame of a welding torch with tip № 4. The flame should be restorative and ensure uniform heating of the surface.

The maximum temperature should be in the reduction zone at a distance of 2–4 mm from the core. The flame torch should be located at an angle of $35^0–45^0$ to the surface to be hard-faced mounted horizontally. Reinforcing begins with heating the reinforcement area until the solder melts. Then, placing a carbide rod in the flame of the torch, carbide grains are applied to the heated area of the reinforcement. The process is repeated until the specified height of the hardfacing layer is obtained, but not more than 10 mm. Periodically, flux is poured into the molten area. The welded layer should be continuous, without cracks and chips. The solder should soak all the carbide grains. Lack of solder between the grains, overburning, chipping and cutting out of the reinforced layer are not allowed. It is allowed to restore a worn out abrasion-cutting section of the cutter (Mustafayev et al., 2021; Mustafayev et al., 2017).

The average life before writing off the restored cutter should be at least 60–70% of the average life regulated by the normative-technical documentation for a particular type of cutting tool.

Quality control of the restored abrasion-cutting layer of the milling tool is checked by external inspection using, if necessary, a magnifying glass with at least fivefold magnification. If cracks and chips with depth less than 5 mm are detected, they shall be repaired by re-facing. If overburn, cracks and chips deeper than 5 mm are detected, the milling machine is rejected.

Conclusion

1. The technology and tooling for manufacturing surfaced rods (bars) from composite materials containing crushed carbide of VKV 8 grade and solder № 4 or № 7 on the basis of zinc alloys have been developed.

2. Practically obtained and used in the restoration of the layer of spent borehole mills of hardfacing rods with the necessary technological parameters.

3. A number of fixtures for experimental tests, restored borehole cutting tools, including a fixture for measuring the wear of the cutter, have been developed and manufactured.

4. The minimum required number of tools to be tested was determined.

5. Experimental studies of the serviceability of reconditioned downhole milling tools have been carried out using methods of rational planning of experiments, in particular, combinatorial square methods.

6. Processing of the results of the planned experiment by methods of mathematical statistics allowed to obtain mathematical models describing the process of milling of emergency metals with the restored reinforcement layer depending on the relative height h_b/h_a of the reinforcement of the restored layer, axial load on the tool, circular speed of rotation, as well as the flow rate of flushing fluid.

7. Verification of the obtained results by regression analysis methods confirmed the correctness of the obtained dependences. It has been determined that restoration of the abrasion-cutting part of the used downhole milling tools increases their service life by 60–70%.

8. At the same time a considerable amount of metal is saved due to the reuse of bases of cutting parts of downhole tools.

References

Müller L. (2004). Composition of crushed hard metal bars // Patent DE 1068644, 2004. (Liza Muller. Welding hard metal composition //Patent DE 1068644,)

Waldrop R. (1962). Composite rod and method of making // U.S. Patent No. 3028644.

Bridwell H. C., Rowley D. S. (1965). Process for making hard metal carbide hardfacing material and composite casting // U.S. Patent No. 3175260.

Bowen Tools Inc. (1972–73). General catalog.

Gasanov A. P. (1978). Investigation of the efficiency of downhole cutter clad with composite material // Chemical and Petroleum Engineering. – No. 4. – P. 5–9.

Bondar A. G. (1973). Mathematical modeling in chemical technology. K.: Higher School.

Mirzajanzadeh A. H., Stepanova G. F. (1977). Mathematical theory of experiment in oil and gas production. – M.: Nedra.

Typical methodology of industrial tests, experimental and pilot batches of new design roller cone bits. – M.: VNIIBT, 1975.
Mustafaev A. Q., Nasirov Ch. R. (2023). Reduction of thermal tensions and temperatures formed in the tribonodes and surfaces of the equipment and tools used in well workover and restoration works. Nafta-Gaz 2023. – No. 10. – P. 661–669. DOI: 10.18668/NG.2023.10.04
Mustafayev A. G., Aliyev E. A., Huseynov Kh.A., Kerimova L. S. (1997). Thermal mode of operation of milling devices and increasing their efficiency during well repair. Sci., – Baku, 124 p. ISBN 5-8066-1483-7.
Mustafaev A. K., Nasirov Ch.R. (2021). Development of operational parameters of milling devices taking into account physical and mechanical characteristics of the cutting part of the tool reinforced with composite alloys. GSOTU, Proceedings of the X All-Russian Scientific and Practical Conference @Youth. Science. Innovations", – P. 391–398.
Mustafaev A. K., Nasirov Ch.R. (2022). Development of a method for increasing the productivity of drilling tools. Problems of geology. development and operation of fields, transportation and processing of hard-to-extract heavy oil. Proceedings of the All-Russian scientific and technical conference, Ukhta, – P. 1–208. ISBN 978-5-6045345-9-5.
Dzhafarov A. G. (2021). Method of designing cutting parts of downhole milling devices based on composite alloys. MODERN SCIENCE Founders: Scientific and Information Publishing Center "Institute for Strategic Studies", – Moscow, – P. 410–417. ISSN 2414-9918.
Mustafayev A. K., Nasirov Ch.R., Nagiyev A. E. (2021). Increase of cutting ability of downhole milling cutters reinforced with composite matrix materials. GSOTU, Materials of X All-Russian Scientific and Practical Conference "Youth. Science. Innovation", – P. 383–390.
Mustafaev A. K., Pashayeva V. B. (2017). Investigation of improving the efficiency of well-destructive tools. Actual problems of humanities and natural sciences, Russia, – 7: 50–53.

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