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Development of a drilling process control technique based on a comprehensive analysis of the criteria

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Compliance with drilling operations requirements is achieved by introducing advanced approaches to the management of the drilling process. Main requirement is to reduce the time and material costs for construction of the well. Increase in drilling speed is provided by rational selection of rock cutting tools and modes of its use. Development of a new generation of rock cutting tools is a complex process and requires systematic, integrated approach. In order for high costs of developing and manufacturing the tool to pay off without significantly increasing the cost of drilling, considerable attention should be paid to scientifically justified methods for its running. At well drilling using bottomhole telemetry systems with full computer support for the drilling process, there is a reasonable possibility of using a control technique based on objective results of the drilling process coming directly from the bottomhole of the well in real time. Use of a full factorial experiment is justified for processing data that affect drilling performance.

Aim of the research is to develop a drilling process management technique based on a comprehensive analysis of criteria online. Objects of research: rock destruction mechanism during drilling; parameters affecting the process of well drilling; optimization of well drilling processes. The research used the following: experimental drilling with a diamond tool at the bench, method of a full factorial experiment, analytical studies.

Article highlights the factors affecting the performance of a diamond rock cutting tool in the process of drilling a well, notes main criteria affecting the efficiency of the drilling process. It also describes mechanism of volumetric destruction, defines the conditions for the destruction of rock at various drilling modes and the dependence of the change in deepening per round on the parameters of the drilling modes. Technique of controlling the parameters of the drilling mode is considered, which allows determining indirectly the mode of rock destruction at the bottomhole of the well and choosing optimal values of the parameters for the drilling mode that correspond to the most favorable conditions.

***Key words*:** diamond drilling; full factorial experiment; diamond drilling tools; drilling process control; drilling tool run

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Introduction. Modern drilling is characterized by the use of expensive drilling tools designed to provide both high penetration rate and a significant, continuously growing resource as new superhard materials are created [9, 13, 18].

New technologies in the fields of materials science and designing of tools for processing and destructing solids, as well as many years of experience in using rock destruction tools at drilling, have revealed the most promising drilling instrument – diamond rock cutting tool, which at the present stage of development is characterized by the fact that for the manufacture of crowns and bits artificial diamonds are used both in the form of various sized crystals and cutters PDC (polycrystalline diamante cutters) [1, 5, 9, 10, 12, 13, 15, 17].

Following tendencies can be distinguished in the development of drilling tools: for the destruction of hard crystalline rocks mainly impregnated crowns and bits are created, the resource of which is determined by the quality of low grain sized rough diamonds and the degree of wear resistance (hardness) of the matrix, and for the destruction of soft rocks and rocks of medium hardness – PDC cutting tools [3].

Statement of the problem. Development of drilling rock cutting tools reinforced with diamond material requires simultaneous study of many factors affecting the efficiency of its work at the bottomhole zone [7, 11]. Such a factor is the analysis of aspects of the rock destruction mechanism, taking into account individual characteristics of equipment and the condition of drilling tools and the types of rocks being drilled, as well as the drilling process control mode. Control mode of the drilling process should be built using available computer technologies [4, 14, 16] and modern

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high-tech bottomhole telemetry systems that allows «conducting» the drilling process, adjusting key control parameters online, recording and processing incoming output data:

• bottomhole axial load, drilling tool rotation frequency, torque and bottomhole power;

• drilling tool vibration parameters;

• deepening per one round of tool rotation at the bottomhole $h_o = v_b/n$, where n is the rotation frequency of the rock cutting tool, min^{-1}; v_b – mechanical drilling speed, m/h.

• energy intensity of the rock destruction process N/v_b, where N is the power consumed to destruct the rock at the bottom of the well (bottomhole power), kW.

Aim of control is to achieve maximal tool life at high, but not extreme, values of the mechanical penetration speed.

Authors consider, that this result can be achieved based on a comprehensive analysis of the criteria for a well drilling process.

Comprehensive analysis of the criteria for a well drilling process. Set of criteria presented for analysis fully characterizes the process of rock destruction during drilling. So, the mechanical speed gives an indicator of drillability and the rate of penetration, and the criterion for deepening a drilling tool per one round at the bottomhole makes it possible to control the drilling process at a given optimal value of this parameter.

Energy intensity criterion N/v_b [8] reflects, first of all, possible resource of the drilling tool, since minimizing this criterion makes it possible to obtain maximum penetration per tool and optimize the cost of drilling, especially of long wells, during drilling of which amount of time for auxiliary and tripping operations increases significantly.

Therefore, considerable attention should be paid to scientifically justified methods for developing modern drilling tool so that high costs would pay off without significantly increasing the cost of drilling. During drilling of oil and gas wells using bottomhole telemetry systems with full computer support for the drilling process, there is a well-founded possibility of using a control technique based on objective results of the drilling process coming directly from the bottomhole of the well in real time.

For analysis, within the framework of the developed technique, current values of the parameters coming from the bottomhole of the well through bottomhole telemetry system sensors are used, these are the real values of the drilling tool rotation frequency n, the axial load P_{ax} and the torque on the drilling tool M_t. The bottomhole power N is calculated from a simple dependence $N = M_t n$ based on the obtained parameter values.

Methodology. Processing of the data obtained in the real time mode can be carried out in accordance with the methodology of a full factorial experiment using two (axial load of P_{ax}, kN and rotation frequency n, min^{-1}) or three (axial load, rotation frequency and amount of drilling mud Q), which influence drilling performance, factors k in accordance with the algorithm $N = 2^k$, where k is the number of factors [2, 6].

Full factorial experiment technique allows optimizing data analysis and obtaining empirical models of processes with statistically significant coefficients:

$$\begin{aligned} v_b &= A + BP_{ax} + Cn + DP_{ax}n; \\ h_o &= E + FP_{ax} + D\omega + HP_{ax}n; \\ \frac{N}{v_b} &= K + LP_{ax} + Mn + SP_{ax}n, \end{aligned} \qquad (1)$$

where along with the parameters of the drilling mode P_{ax} and n, numerical values of the coefficients are present, calculated in accordance with the methodology of the full factorial experiment.

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Combined analysis of models (1) allows solving the problem of finding the most acceptable parameter values, oriented to high penetration rates and a high resource of a drilling tool. For example, one of the mentioned above models can be used to determine the rational value of the axial force at selected value of the rotation frequency and a given value of deepening per one round

$$P_{ax} = \frac{h_o - E - Dn}{F + Hn}. \quad (2)$$

Thus, choosing the value of the rotation frequency n for a given value of deepening per one round h_o, one can determine the optimal value of the axial load corresponding to this rotation frequency and a given deepening.

If, as the third factor affecting the drilling process, quantity of supplied flushing fluid Q is considered, the model will be

$$h_o = A + BP_{ax} + Cn + FQ + DP_{ax}nQ. \quad (3)$$

The solution can be made as follows: first, the axial force P_{ax} is calculated by the formula (2) and the model for the deepening per round h_o by the formula (1), then the value of the flow rate of flushing fluid is calculated

$$Q = \frac{h_o - A - BP_{ax} - Cn}{DP_{ax}n + F}. \quad (4)$$

Construction of these models and the solution of the equations for determining P_{ax} and Q when implementing the methodology for controlling the drilling process of a well should be performed on a computer that controls the drilling process in real time with an instant assessment of the deepening per round, drilling speed and energy intensity of the rock destruction process, calculated sequentially as the drilling tool is running.

Clarity of the studied process analysis using full factorial experiment is solved by graphical interpretation of models (1).

Let us consider the possibilities of analyzing bottomhole situation at drilling tool running, through the example of drilling with gabbro diamond single-layer tool (crown 01A3-59) using water and water with a surfactant as drilling fluids. The results of drilling performed on the drilling bench are shown in the table.

Optimization criteria calculated on the basis of data at drilling with gabbro crown 01A3-59

Rotation frequency n, min^{-1}	Axial load P_{ax}, kN	Mechanical drilling speed with flushing v_b, m/h		Drilling power with flushing N_b, kW		Energy intensity of rock destruction during drilling with flushing $N_b/v_b \rightarrow$min, kW·h/m	
		water	water + surfactant	water	water + surfactant	water	water + surfactant
625	3	1.6	2.5	1.4	1.6	0.88	0.64
	6	3.2	4.4	2.8	2.7	0.88	0.61
	9	5.1	5.4	3.8	3.9	0.75	0.72
	12	6.2	6.3	4.7	5.4	0.76	0.86
	15	6.6	7.5	6.8	6.6	1.03	0.88
1020	3	2.1	3.2	2.1	2.06		0.63
	6	4.5	6.1	3.7	4.09	0.82	0.67
	9	6.1	7.8	5.7	6.9	0.93	0.88
	12	6.8	8.7	9.5	8.7	1.4	1
	15	6.1	9.9	11.5	9.4	1.88	0.95
1480	3	2.7	4.2	2.6	2.9	0.96	0.69
	6	5.8	8.4	5.0	5.96	0.86	0.71
	9	6.9	9.8	8.0	8.7	1.16	0.89
	12	8.6	10.6	12.2	12.5	1.42	1.18
	15	8.2	9.8	16.1	16.46	1.96	1.68

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After data processing, the models were obtained in accordance with the plan of the full factorial experiment, reflecting the process of drilling with gabbro with flushing by technical water at a constant flow rate:

$$v_b = 4.78 + 2.63\,P_{ax} + 0.675n + 0.125\,P_{ax}\,n; \quad (5)$$

$$p_o = 0.085 + 0.049\,P_{ax} - 0.024\,m - 0.0185P_{ax}\,n; \quad (6)$$

$$\frac{N_b}{v_b} = 1.21 + 0.29P_{ax} + 0.25n + 0.21\,P_{ax}\,n. \quad (7)$$

During flushing by water with the addition of surfactants, other models were obtained that reflect the process of rock destruction during drilling,

$$v_b = 6.0 + 2.65\,P_{ax} + n + 0.15\,P_{ax}\,n; \quad (8)$$

$$h_o = 0.083 + 0.026\,P_{ax} - 0.045\,n + 0.19\,P_{ax}\,n; \quad (9)$$

$$\frac{N_b}{v_b} = 0.97 + 0.31\,P_{ax} + 0.21\,n + 0.0094\,P_{ax}\,n. \quad (10)$$

As follows from the data of analytical models, use of drilling fluid with a surfactant led to an increase in the mechanical drilling speed by an average of 21 %, and a decrease in the energy intensity of drilling by 20 %. At the same time, the magnitude of deepening per one round of the crown at the bottomhole did not increase, but the level of influence of the rotation frequency and axial force on the deepening per one round of the crown at the bottomhole changed significantly: the effect of axial force decreased almost twofold, and the influence of the rotation frequency increased by 47 %.

Clearly presented conclusions follow from the graphical interpretation of the obtained analytical models. Fig.1 shows graphs constructed according to equations (5)-(10), depending on the values of the rotation frequency and axial load on the drilling tool. The analysis of the graphs presented allows identifying rational values of the deepening per round, corresponding to both high level of mechanical drilling speed and moderate energy intensity of rock destruction. The resulting models and graphs allow implementing rational control of drilling mode parameters. For example, dependence (2) may have a graphical solution showing the capabilities of the proposed methodology for managing drilling modes.

Figure 1, c shows an example of using the revealed functional dependence of the axial force on the drilling tool on the rotation frequency for a specific drilling case. So, if a certain value of the deepening per one round is set as the main parameter for controlling the drilling process (in this case, 0.097 mm/round), then at rotation frequency n_1 it will be necessary to maintain the axial load P_1, and if the rotation frequency is increased, for example, to increase the mechanical speed drilling to a value of n_2, the axial load will have to increase to P_2.

Moreover, analysis of points 1 and 2 (Fig.1, *e*) shows that the energy intensity of drilling, which determines the tool life, increased from 1.02 to 1.1 kW·h/m, which means a decrease in tool life by about 7 %. The drilling speed (Fig.1, *a*) may increase from 5 to 6.3 m/h, i.e. by 20 %. Thus, it is possible to search for the most favorable parameters of the drilling mode based on a comprehensive analysis of the most optimal combination of parameters of the three criteria for optimizing the drilling process.

In Fig.1, *e*, control area for the parameters of the drilling mode is selected by the deepening per one round and the circle of permissible values in the central part of the graph shows the most suitable boundaries of this control.

At drilling with gabbro using surfactants (Fig.1, *b*, *d*, *f*), a slightly higher mechanical speed and deepening per one round and more moderate values of energy intensity of drilling were obtained. For these drilling conditions, other rational parameters of the drilling mode can be applied if previous values of deepening per one round are taken (see Fig.1, *d*).

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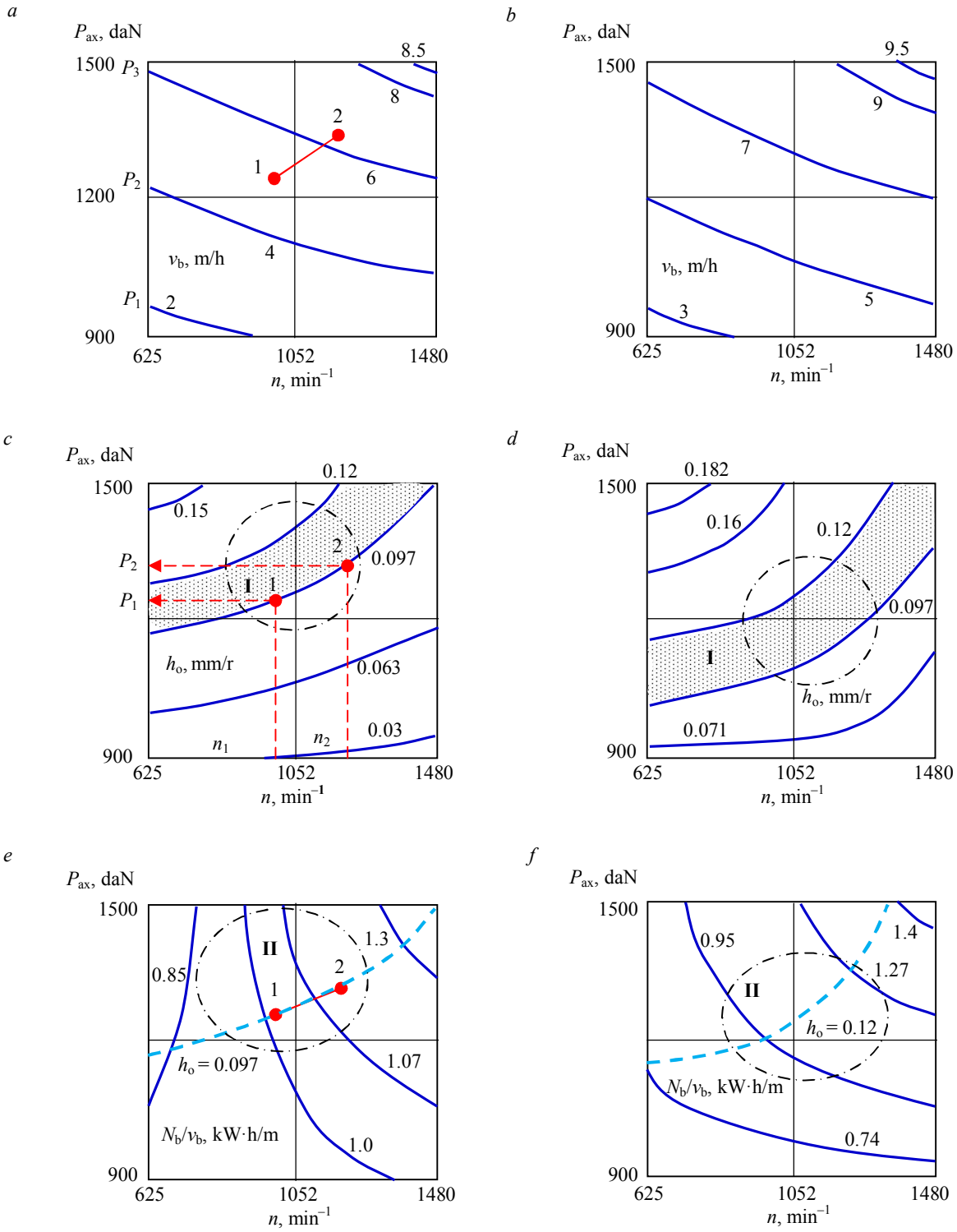


Fig.1. Graphical interpretation of the mechanical drilling speed equations (*a*, *b*), deepening per round (*c*, *d*) and criterion N_b/v_b (*e*, *f*) for single-layer diamond crown 01A3-59 at drilling with gabbro and flushing with water (*a*, *c*, *e*) and surfactant (*b*, *d*, *f*)
I and II – rational areas of rotation and axial load, respectively

Optimal deepening per round is understood as the value of cutting-chipping of the rock per rotation round of the drilling tool at the bottomhole, defined by the penetration of cutters into the rock, in which there is volumetric destruction of the rock, but there is no increased wear of the cutters, and the energy intensity of destruction has moderate values or downward trend.

In order to evaluate the process of rock destruction and identify the analytical relationship between the parameters of the drilling mode for a given crown deepening in the rock per one rotation round, it is necessary to make calculations using obtained analytical models and corresponding graphs (see Fig.1, *a*, *b*). To calculate the magnitude of the deepening at various values of the rota-

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tion frequency and axial load, calculations should be made using the intersections of the mechanical speed lines with the vertical lines that determine rotation frequency values. For example, for the minimum value of the rotation frequency of 625 min^{-1} (see Fig.1, *a*) there are three intersections with the speed lines of 2, 4 and 6 m/h, respectively, one can get three values of the deepening per one round:

$$h_{o1} = \frac{v_M}{n} = \frac{2}{625 \cdot 60} = 0.05 \text{ mm/r};$$

$$h_{o2} = \frac{v_M}{n} = \frac{4}{625 \cdot 60} = 0.1 \text{ mm/r};$$

$$h_{o3} = \frac{v_M}{n} = \frac{6}{625 \cdot 60} = 0.15 \text{ mm/r}.$$

Obtained values h_{o1}, h_{o2}, h_{o3} on the graph (see Fig.1, *a*) correspond to the values P_{ax}: $P_1 = 950$ daN, $P_2 = 1210$ daN and $P_3 = 1480$ daN.

Thus, dependence of the crown deepening per one rotation round at the bottomhole on the axial load at a minimum value of the rotation frequency is determined. To calculate such a dependence at rotation frequency of 1052 min^{-1}, intersections of mechanical drilling speeds lines of 4 and 6 m/h with the graph's axis are used, and for rotation frequency of 1480 min^{-1} intersections with lines of mechanical speeds of 4, 6 and 8 m/h.

As a result of the calculations, a graphical dependence of the deepening per one round of the crown at the bottomhole on the axial load is obtained for various values of the rotation frequency of the crown (Fig.2).

Figure 2, *a* shows the dependence of the deepening per one round on the rotation frequency and axial force. The graphs are constructed according to the drilling speed data (see Fig.1, *a*) and

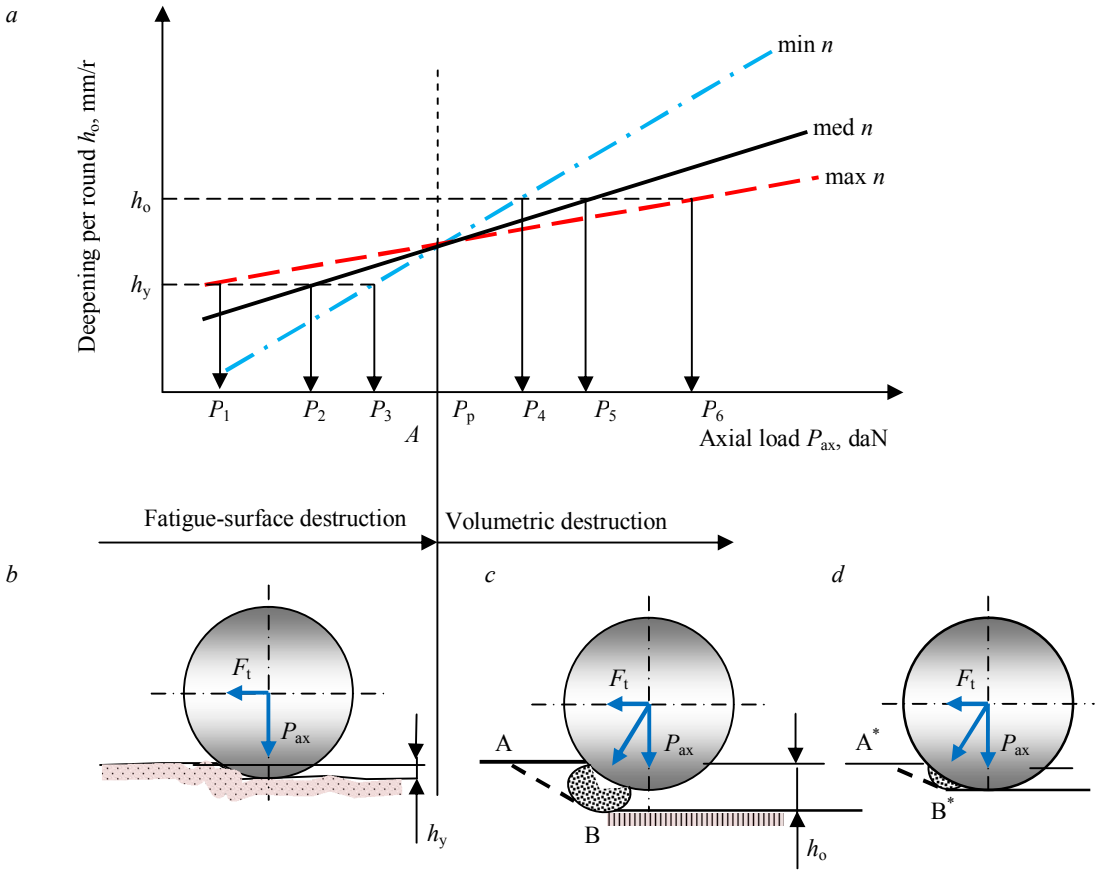


Fig.2. Dependence of the deepening per one round on the parameters of the drilling mode (*a*) and schemes, explaining fatigue-surface (*b*) and volumetric (*c*, *d*) rock destruction under the action of axial P_{ax} and tangential F_t forces

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objectively reflect the process of rock destruction. The magnitude of the deepening per one round increases with increasing axial force, regardless of the rotation frequency of the crown. This is due to the fact that as the axial load increases, penetration of the cutters into the rock increases.

Dependence of the deepening per one round on the rotation frequency has a complex character. In the case when the axial load is insufficient for volumetric destruction of the rock (interval of fatigue-surface destruction), larger values of the deepening per one round h_o are common for drilling at higher rotation frequency of the drilling tool, and the deepening per one round, which is equal to h_y, is reached at a higher axial load P_1, P_2, P_3 (see Fig.2, *a*) as the rotation frequency decreases. This is explained by the fact that due to cyclically repeated rock and formation loading, as well as the development of cracks in the rock, the fatigue destruction mode has an effect on reducing the hardness and durability of the rock. With insufficient axial load for penetration of the cutter into the rock, this destruction mode will be more intense in case of a higher crown rotation frequency. An increase in the rotation frequency will lead to a greater deepening of the cutters, and hence to a deepening per one round.

At a certain axial load P_p, destruction mode becomes volumetric, since the growing axial load is already sufficient for the penetration of the cutter into the rock. In this destruction mode, larger deepening per one round is achieved at a lower rotation frequency, and as the rotation frequency increases, deepening per one round decreases.

Action of this mechanism consists in the fact that when a fracture groove is formed, the rock is chipped before the cutter along the surface in the direction of the bottomhole (AB line in Fig.2, *c*). Conditions of the rock destruction will be optimal, when speed of cutter movement will be equal to the rate of formation of a crack fracturing the rock along AB line in the direction from the compression core to the surface of the bottomhole. With an increase in the rotation frequency, the rate of formation of a crack fracturing the rock in front of the cutter may lag behind the speed of cutter movement. Experiencing increased rock resistance to movement, the cutter «floats up» (see Fig.2, *d*). This is due to a decrease in the depth of its penetration into the rock and an increase in the buoyancy resistance of the rock that did not destruct in time. The «floating» of the cutter occurs until the length of the fracturing crack A^*B^* decreases, so that again the time of the translational movement of the cutter corresponds to the time of formation of the fracturing crack A^*B^*.

With volumetric destruction of the rock, an equal deepening per one round h_r can be obtained by increasing the axial force by a strictly specified value P_4, P_5, P_6 (see Fig.2, *a*) with increase in rotation frequency.

Volumetric rock destruction will be most effective at the most complete cleaning of the bottomhole from sludge and such a combination of rotation frequency and axial force at which the rate of formation of the fracturing crack AB (see Fig.2, *c*) equals the speed of rock cutting tool's cutter movement. In this case, the stresses in the compression core of the rock will be sufficient for effective chipping of the rock by the front edge of the cutter under the action of tangential and tensile stresses. These conditions of rock destruction that can correspond to the most effective destruction process. At the same time, minimum energy intensity of rock destruction and high resource of the drilling tool are achieved.

In the case of insufficient quantity of the flushing agent Q supplied to the bottomhole due to sludging, destruction conditions will worsen. When the axial load is sufficient for volumetric destruction of the rock, a regime similar to fatigue-surface is observed. Crown cutters, re-grinding sludge pad, cannot create stresses sufficient for the effective destruction of the rock. In this case, the dependence of the deepening per round on the rotation frequency will be similar to the fatigue-surface destruction mode, in which a larger deepening per round is achieved at a higher rotation frequency of the drilling tool (Fig.3, *a, b*).

With an excess of drilling fluid supply, the effect of hydraulic banking of the drilling tool will occur. A certain fraction of the axial force will be spent on overcoming hydraulic resistance, which will lead to a similar process of rock destruction.

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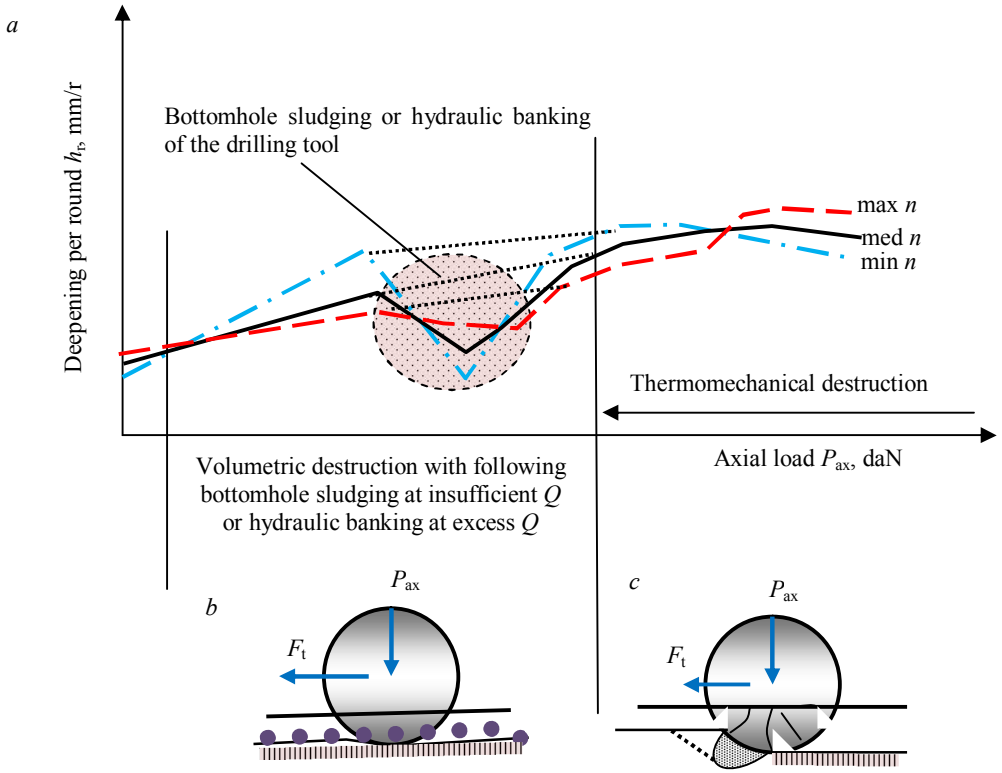


Fig.3. Dependence of the deepening per one round on the parameters of the drilling mode (*a*) and diagrams explaining the process of volumetric destruction during bottomhole sludging (*b*) and thermomechanical destruction (*c*)

With an excessive increase in axial load, a complex mode of thermomechanical destruction of the rock occurs (Fig.3, *c*). However, in this case, the destruction of the crown as a result of its thermal softening is observed. Too high rotation frequency leads to the destruction of the cutters, which is accompanied by a noticeable decrease in the deepening of the rock cutting tool into the bottomhole of the well [6].

Analysis of the graph section (see Fig.2, *a*) with the interval of the volumetric – the most effective – destruction mode allows obtaining in real time well drilling mode the most rational ratio of the main parameters: rotation frequency and axial load on the drilling tool for a given value of the deepening per one round.

If deepening per one round is set at the level h_o (see Fig.2, *a*), the values of the rotation frequency will correspond to the values of the axial force P_4, P_5 и P_6. As a result of such a solution, for a given deepening, a dependence will be obtained that strictly determines the relationship of the parameters (Fig.4). In this case, a solution is shown based on the analysis of three values of the rotation frequency and axial load, as well as a variant with five values of the rotation frequency and axial load, algorithm 2 is more accurate. Accuracy of the solution can be improved by analyzing more measurement points. Amount of drilling fluid supplied can also be taken into account when choosing values of axial forces at changing rotation frequency of the drilling tool.

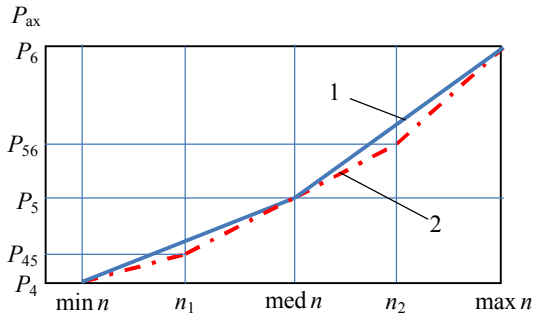


Fig.4. Algorithm for controlling the parameters of the drilling mode on the interval of volumetric rock destruction with drilling tool:
1 – by three values of the rotation frequency *n* and axial load P_4, P_5, P_6;
2 – by five values of the rotation frequency *n* and axial load P_4, P_{45}, P_5, P_{56}, P_6

Results of the research. Energy intensity parameter of rock destruction during drilling (see Fig.1, *e*, *f*) allows selecting the variation interval of the drilling mode values, taking into account predicted resource of drilling tool, since this parameter is strictly dependent on the resource capabilities of the drilling tool. For example, taking into account the moderate

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energy intensity, rational values of deepening per one round of 0.097 and 0.12 mm/r and the range of values for the rotation frequency and axial load II (Fig.1, *e, f*) can be determined, which will provide for a more significant resource of the drilling tool. For drilling with a higher speed, but with a smaller tool life, higher value of deepening per one round and a control area with increased energy intensity can be selected for control, which corresponds to higher values of the tool's rotation frequency and axial force.

Conclusion. Considered technique for controlling the parameters of the drilling mode, built as an algorithm for searching for optimal conditions according to three main criteria using real-time data on drilling, allows determining indirectly the mode of rock destruction at the bottomhole of the well and choosing optimal values of the drilling mode parameters, which, in turn, correspond to the most favorable conditions for the destruction of the rock. In this case, capabilities of modern drilling equipment, high-tech and expensive drilling tools, bottomhole telemetry systems and computer technologies are used most effectively, which allows building the technology focused on high productivity and high resource of the drilling tool.

As a result of research, following conclusions can be drawn.

1. Objective analysis of the rock destruction process during drilling and selection of optimal parameters for controlling the drilling process is possible based on a comprehensive analysis of criteria such as mechanical drilling speed, deepening per one round of the drilling tool rotation at the bottomhole of the well, and the energy intensity of rock destruction during drilling.

2. Technical capabilities of modern drilling make it possible to determine during drilling the parameters necessary for analysis in real time (online) using modern bottomhole telemetry systems, as well as the capabilities of computer technologies by which the analysis of parameters obtained from the bottomhole can be converted and analyzed in order to obtain a control algorithm for drilling process.

3. As a method of analytical research of parameters and analysis of the drilling process, the method of full factorial experiment can be used, which with high accuracy allows obtaining analytical models and conducting their geometric interpretation, determining indirectly both the mechanism of rock destruction and the region of the most effective values of drilling parameters with the purpose of identifying, with certain given parameters, a rational ratio of the tool rotation frequency, axial load and amount of drilling fluid supplied to the well.

4. As the main parameter for controlling the drilling process, set value of well deepening per one round of the drilling tool rotation at the bottomhole can be used at the specified values of the energy intensity of rock destruction during drilling in the region of volumetric rock destruction determined on the basis of the analyzed data.

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