WELL DRILLING

Wear resistance of some elements of the drill string during drilling

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The article is concerned with questions of wearing capacity of some elements of the drill string, including the abrasive drilling of hard-alloy insert rolling cutter drilling bits. The given basic dependencies on probably wear property and damage determining characteristics of drilling tools are determined its wearing capacity during boring.

Consideration of drill string sustainability indicates that during rotary drilling even in vertical wells with minimum rotor rpm, drill pipes lose their straight shape and with a certain force contact with the wall of the well. Thus, in the process of drilling in the contact areas shear strength appears, and it consumes considerable work to break it, so the elements of the drill string wear.

During drilling in the bottom of the drill the pipes bent not only because of the centrifugal forces, but also from buckling, which leads to increase of the transverse force, to pressing half-waves of the drill string and its centering and expansion elements to the walls of the hole [1].

Friction forces also appear when armament bit interacts with rock face. Further we shall consider the definition of drilling bit kinematic pairs durability and especially its cutting structure.

Abrasive wear of destroying elements - bits occurs during its rock friction, which is a natural abrasive, resulting in scratching or microcutting action of abrasive grains during sliding of teeth, and as a result of direct penetration of abrasive grains on the contact surface at the moment of tooth impact on the face [2]. It is possible when the abrasive particles of rocks are harder than the material of teeth. Such wear mechanism can be applied to different centering and expansion structural elements of the drill string.

The attempts to calculate the depreciation of drilling bits were made taking into account information about the sliding cutters [3], but the slip was calculated for smooth face. But this phenomenon is connected with the heterogeneity of rocks face, drilling liquid pulse, random nature of dynamic loads. Thus, the wear of teeth has very probable nature.

In the work [4] it is offered to envisage the steel wear depending on the specific friction power. Evaluation of rocks abrasive properties depending on the wear of metal is necessary because the wear resistance of the metal determines drilling bits enduring quality.

Most rocks can wear metal, but the speed of wear will vary. The intensity of abrasive wear of the tool depends primarily on the ratio of the mechanical characteristics of the rocks and the hardness of its surface. Abrasion ability of rock is proportional to microhardness of minerals that form it.

Wear-out of the drill string elements depends on many factors, including the dynamic state. They all are probable.

The cutting structure of the drilling bits during drilling of wells may undergo the following types of destruction:

- physical wear-out under shear stresses that occur during rotation of cutters under the influence of axial load;

- abrasive wear of working surfaces under the influence of abrasive particles of rock and abrasive drilling liquid;
- chipping of work surfaces under high contact stresses in the presence of drilling liquid, which is a localized fatigue surface degradation;
- chipping of cracking (caused by chipping and wear of reinforced layer);
- teeth breakdown because of overstrain;
- tooth breakdown due to material fatigue with the appearance of cracks on the opposite side of cones movement.

Fig. 1 shows the wear of the drilling bit with combined cutting structure, there are visible abrasions of cutting teeth and fatigue fracture of hard-alloy button rolling cutter. Fatigue fracture and fracture of hard-alloy button rolling cutter drilling bit after considerable dynamic loads are presented in Fig. 2.

Limited levels of drilling bits cutting structure wear should be determined according to the economic and technical criteria of consequences. Thus, the maximum cutting structure wear can be defined according to the criterion of economic consequences - sharp falloff in drilling performance, especially mechanical speed of drilling in specific geological and technical conditions. Technical consequences are critical cutting structure wear that can lead to jamming of drilling bit legs, cutter body fracture, and in some cases - to catching of tool.

Separation of critical wear criteria on the technical and economic is arbitrary, since the change in technical parameters usually has economic consequences.

In some cases, the performance of the drill string depends on the wear degree of not only one piece, but the complex conjugation. A typical example is the rolling resistance cone (pin - sliding bearings, pin - ball bearing, rolling cutter and the state of its cutting structure). The state of the drilling bit during drilling is determined using the data from the previous calking in similar geological and technical conditions of drilling. Therefore, to determine the state of wear of the bit during rotary drilling method, you can use the inequation obtained by analyzing the data [5]:

$$U_{гр.max}\left(M_{р.max}\right) \leq U_{гр.г}\left(P_0, M_р\right); U_{гр.т}; U_{гр.е}, \qquad (1)$$

where $U_{гр.max}(M_{р.max})$ - deviations according to the safety criteria (leg jamming, cutting structure critical wear) $U_{гр.г}(P_0, M_р)$ - bounding deviations due to geological and engineering principles (the ability to deepen the well if the geological conditions of the drilling have changed) P_0 - axial strain on the bit; $M_р$ - torque on the rotor; $U_{гр.т}$ - bounding deviations caused by technical principles (the ability to satisfactorily perform job functions, the criteria of strength, vibration, etc.) $U_{гр.е}$ - the deviations from the criteria of efficiency.

It should be noted that the values on the right side of the equation (1) amount to the sum of bounding deviations interconnected by probable dependencies that vary depending on the specific conditions of drilling.

The methods for determining the critical wear limits have not found proper application in the calculation of the drill string for well drilling due to a variety of geological and technical conditions of drilling and failure of materials for analysis of drilling bits wear and other elements of the drill string during the drilling process in different regions.

In some cases, for an approximate calculation of wear durability there can be used the critical wear data of the details in similar mechanical systems. For example, the value of allowable level of wear of expansion and centering elements can be defined as

$$D_{гр} = k_т D, \qquad (2)$$

where k_T – is a factor that depends on the rock, which is in contact with the element, its limit size, the well design and drilling practices; *D* - initial diameter.

Critical wear according to the criteria of economic factors can be determined under the condition of minimum unit costs:

$$N_{с.о.п.}(t) \approx \frac{[C(t)+YR]}{Z(t)} \rightarrow \min, \qquad (3)$$

where $N_{с.о.п.}(t)$ - shows the corrected cost of one meter of drilling; $C(t)$ - operating costs; Y - specified efficiency ratio; R - book value of the drill string; $Z(t)$ - operational performance of the tool in given mode of drilling and geological conditions.

The above written wear limit determination approach is valid only when there is significant impact of the productivity factor on the conformity of function $N_{с.о.п.}(t)$.

Rolling bearing cone is a complex conjugation, which includes a number of kinematic pairs (bearings). In this case the limit gap enlargement will be equal to the sum of the working surfaces wear that form this coupling. Given that the surfaces wear is very probable, we can assume that the maximum wear of one piece at a regulated gap varies within the certain limits depending on the wear of other parts. A simplified model of the parts wear process till critical state is as follows (Fig. 3), obtained during the work [5], which can be used for further analysis. The following chart shows some wear curves of similar details. It is assumed that after the critical wear state is reached, the detail's resource is exhausted (state of failure). Due to the difference of curves the resource *R* is spread. The random variable of the resource *R* has distribution density $f_R(t)$.

This model can be used to describe all types of rough wear, except for chipping and bonding. Thus, the dependence of parts wear З(t) as a random function of operating time according to [5] we can write as follows:

$$З(t) = \alpha_з t^{\beta} + b_з, \qquad (4)$$

where a_3 - random variable that depends on the properties of surfaces that interact and for cutting structure of the bit - the properties of drilled rocks, reinforced teeth surface and is material; b - coefficient adopted as constant (wear of rolling bearings b = 0,8; abrasive wear of plain bearings b = 0,5-0,7; wear of cutter teeth b = 1,8-2). In case of variation coefficient $V_{a3} >$ 0.4 we can assume that the value of b_3 corresponds to Weibull distribution and characterizes wear during adjustment. Assuming that its value is small, it can be neglected . Then equation (4) can be written as follows:

$$З(t) = \alpha_з t^{\beta}. \qquad (5)$$

Based on Fig. 3 and formula (5), the dependence to determine the drilling bit cutting structure resource can be written as:

$$R = \left(\frac{З_{гр}}{\alpha_з}\right)^{\frac{1}{\beta}}, \qquad (6)$$

where $З_{гр}$ - limit drilling bit cutting structure wear while drilling (mechanical speed tends to zero).

Thus the probable argument is a $_3$, R = cf (a $_3$). To determine the resource R there may be used different forecasting methods.

The parameters which characterize the different working cycles of the drill string elements and their conjugation vary over a wide range. The particular importance has the number of cycles per unit which the drill string operated, taking into account the frequency of conjugation. At the same time the cycle can be considered as step filing tool bit turnover and its cones, dynamic state of the column and its elements per calk turn and etc.

One of the main tasks of solving the friction, lubrication and wear problem is to develop the criteria for determining the governing process in the friction zone. The results of these studies suggest that one of these criteria is the analysis of the vibration spectrum of the friction forces [6], which will be discussed further.

The probability of nonfailure of the rolling leg of hard-alloy button rolling cutter drilling bit may be represented as *P (A),* because during the drilling process none of the z -pins becomes damaged. The probability *P (A)* of nonfailure of the rolling legs is always greater than the probability P_3 of nonfailure of some selected hard-alloy pin which contacts with the shock rock bottom (maximum loaded) and at the same time is the least loaded on the cutter crown: P (A) > P3. This condition will become equation when the impact strength of all pins is the same and depends on their manufacturing. Credibility of nonfailure P_3 may be regarded as the probability of the condition, that tension $a_{B\,0}$ in root of press-in pin is less than the tension a_{r0} of the least strong teeth:

$$P_3 = P[(\sigma_{r0} - \sigma_{B0}) > 0]. \qquad (7)$$

In reliability theory, [7] the value of *P* is the probability of failure-free operation of the component or system. The probability of damage (failure) P_p of mechanical systems is associated with the reliability of the balance:

$$P = 1 - P_p. \qquad (8)$$

As the pin bit parts reliability measure a condition of strength can be taken, which is defined as the probability of exceeding the carrying capacity *R (t)* under axial load on drill bit *Q (t)*:

$$P = I_{\text{мов}}[R(t) > Q(t)]. \qquad (9)$$

These values in the progress of well deepening will vary over time.

If the distribution laws of R and Q are known, the formal comparison of two random variables in probability theory [7] leads to the following functional connection:

$$P = \int_{-\infty}^{\infty} f_R(x) F_Q(x)\, dx, \qquad (10)$$

where $f_Q(x)$ and $f_R(x)$ – density distribution of the axial load *Q* and carrying capacity *R*; $F_Q(x)$ and $F_R(x)$ – distribution function of *Q* and *R* (Fig. 4).

Fig . 1. Drilling bit 295 TK : abrasion wear of cutter tooth and fatigue destruction of plug pins

Fig.2 . Drilling bits 295 TK : fatigue destruction of collapsible hard-alloy teeth

Using (10) and (8), we define :

$$P(A) \geq P_з = 1 - \int_0^\infty f_{B0}(\sigma) F_{r0}(\sigma) d\sigma, \qquad (11)$$

where f_{B0} (s) - density of tension distribution s_{B0}; F_{r0}(s)- cumulative function of tension distribution s_{r0}.

$$u_p = \frac{n_0 - 1}{\sqrt{v_{r0}^2 n_0^2 + v_{B0}^2}}, \qquad (12)$$

If the tension points s_{b0} and s_{r0} are normally distributed, then the probability of P3 can be found in the tables of normal distribution depending on equivalent deviate u_P:

where v_{r0} and v_{b0} - coefficients of stress variation s_{r0} and s_{b0}; n_0 – conditional safety factor :

$$n_0 = \frac{\bar{\sigma}_{r0}}{\bar{\sigma}_{Bo}},$$

where s_{r0} and s_{b0} - the average value of the stress s_{r0} and s_{b0}.

During calculation of fatigue strength (of collapsible hard-alloy teeth) the destructive tension means the endurance limits with normal distribution.

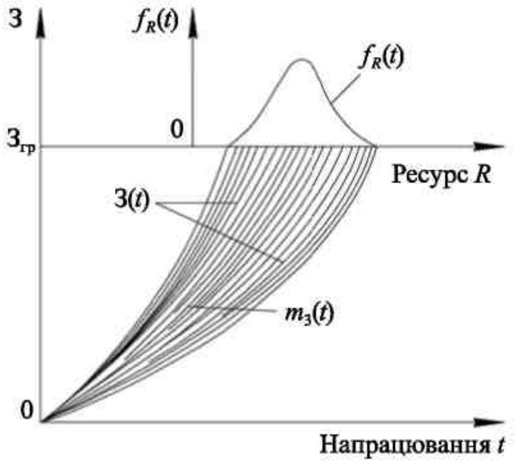

Fig.3. A simplified model of the part's wear process to critical state.

Tension distribution parameters sr0 as the minimum breakdown member of normal population is recommended to be determined [8] with the formulas:

$$\overline{\sigma}_{r0} = \overline{\sigma}_r - \mu S_r, \quad (13)$$

$$v_{r0} = v_r \frac{\varepsilon}{1 - \mu v_r}, \quad (14)$$

where S_r - root mean square tension deviation s_r; m and e - statistical coefficients (selected on the basis of experimental data , depending on the sample size, equal to the number of teeth on peripheral crown cones); v_r - coefficient of variation of breaking stress s_r.

Calculation Analysis shows that one of the most effective images to improve reliability without increasing the average endurance limits is to reduce the coefficient of variation v_{r0} and v_r. Reduction of V_r is associated with the use of materials with homogeneous structure and increase of the stability of cutting structure reinforcement, forms of teeth, heat treatment etc.

Interaction of drilling bit cutting structure with bottom-hole is associated with the transfer of loads on its elements, and on the rock face. This interaction has pulsed character. The magnitude of the energy transferred by pulses to the bottom is connected with oscillating processes that occur in the drill string, as well as geological and technical conditions of drilling.

Numerous studies [9] have demonstrated the existing influence of the drill string dynamic state on the drilling performance, and hence the reliability of the bit as a whole and its components.

Analysis of the vibrations records on the bit and on the square rod [9] shows that the peak load is unevenly distributed across the teeth cutting structures. And this is primarily due to the heterogeneity of the surface of the face (such as cracks, anisotropy of rock that is drilled, etc.). Also, the duration of the dynamic load is significantly less than the time in which the cone makes one revolution. As a result the load distribution differs from the distribution of dynamic loads on the drill string.

Proportionality between stress and vibration velocity made it possible to perform recording of bit vibrations and top of the drill string, and the spectrogram was formed (Fig. 5).

Fig. 5 shows that the peak values of bit vibration velocity and top of the drill string (during synchronous recording) do not coincide in frequency.

There is a need to apply statistical dynamics methods and the theory of process probability for evaluating the bit parts load, including cutting structures in different similar geotechnical conditions, with different bit bottom assembly and in different modes of drilling.

To establish the probability characteristics of the process that determines the mode of bit parts load, including cutting structures, you need to get the frequency response of the drill string, which includes this bit type. It is necessary to develop a design scheme that would characterize shaft parameters and consider drilling mode, as well as mechanical compliance of elements and damping coefficients.

Forced oscillations of drilling bit during drilling are the results of force impact caused by interaction of cutting structure with the rock face, uneven treatment of drill string, engine and its replaceable resistance movement, as well as kinetic disturbance of cutting structure in contact with the rock, due to manufacturing error of bits.

Destruction cutting structure of hard-alloy bit teeth occurs mainly due to prolonged cyclic stress changes. At random stationary vibration of the drilling tool there are no specific order of high and low stresses, at the same time, destructive effect and strengthening during small tensions cancel each other out. Fatigue damage accumulation hypothesis was suggested by some researchers, in particular by Palmgren [10]. This hypothesis is called the linear law. It determines the damage index in the following manner:

$$D = \sum \frac{n_i}{N_i}, \qquad (15)$$

where n_i - number of stress cycles with amplitude s_i; N_i – number of cycles till fatigue failure at constant tension amplitude s_i.

Damage Indicator can vary from zero to one, the decomposition occurs when D approaches to one. During calculations it is necessary to put in coefficient that take into account the physical and mechanical properties of the rock face , the frequency of interaction of teeth with rocks connected with the drilling mode and bit bottom assembly.

For further explanation of hard-alloy cutting structure button destruction and evaluation its reliability Shanley [11] hypothesis can be used , because it is more appropriate in case of direct physical interpretations, as well as for the reliability calculation of the button cutting structure.

In this theory it is provided that the fatigue destruction is due to cracks in the material which are distributed according to the law :

$$h = Ae^{\beta n}, \qquad (16)$$

where h - the depth of the crack ; A - constant ; β - coefficient which depends on the tension amplitude; n - number of stress cycles.

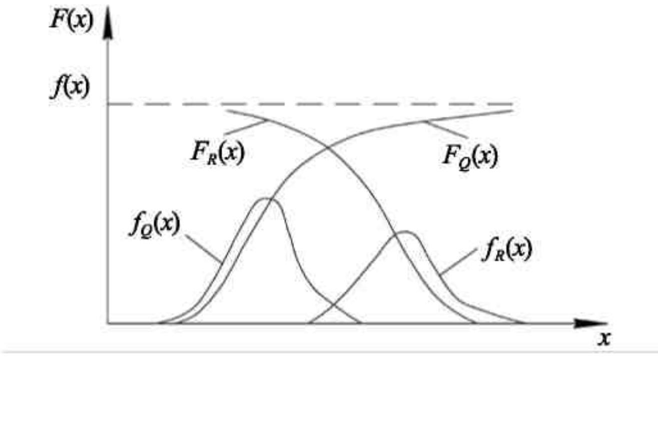

Fig. 4. Load and bearing capacity distribution curves [7]

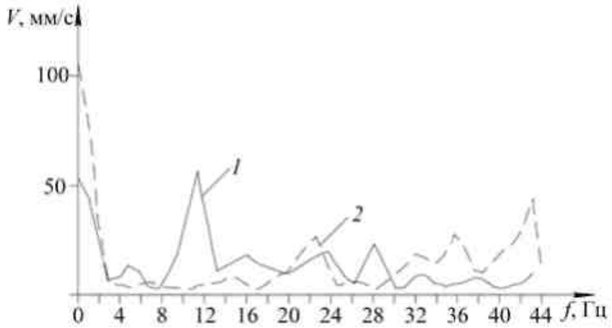

Fig. 5. Oscillation spectrogram of button drilling bit (1) and the top of the drill string (2) at simultaneous recording of the data points H = 800 m ; POC = 200 kN ; n = 70 rpm; light ray, drilling bit SZE -295.

Formula (16) may be used to calculate tooth lifetime in the form of button during laboratory testing at the following conditions:

1. Suppose $h = h_0$ - crack depth at which the fracture occurs..

Suppose n = N - the number of cycles till the moment of destruction.

Suppose the parameter b, which characterizes the crack growth rate, is given by:

$$\beta = C\sigma^{\alpha}, \quad (17)$$

where C - constant ; s - nominal tension ; α- a figure that is determined by the experimental data. Using (17) in (16), we get the following:

$$h_0 = Ae^{C\sigma^{\alpha}N}. \quad (18)$$

So, at the first approximation we can experimentally determine the reliability of the single tooth of the hard-alloy button rolling cutter drilling bit, using the listed linear connections and vibrations records of the drilling tool to calculate the number of load cycles.

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