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ESTIMATION OF THE DRILL PIPES RESIDUAL RESOURCE UNDER THE MULTIAXIAL STRESS STATE

Об'єктом дослідження д ної роботи є експлу т ція бурильних труб в умов х скл дного н пруженого ст ну. Одним із н йбільш проблемних місць в д ному вип дку є процеси втоми, тобто поступове н копичення пошкодження м тері лу бурильних труб під впливом змінних у ч сі н пружень. Це призводить до в рій, ліквід ція яких супроводжується зн чними м тері льними т ч совими втр т ми.

Н основі проведеного критичного н лізу н укових н пр цюв нь з д ною проблемою з зн чено, що використ ння кінетичних ді гр м втомного руйнув ння дозволяє експеримент льно вст новлюв ти емпіричні п р метри втоми м тері лу бурильних труб шляхом л бор торного дослідження невеликих зр зків. А т кож вр ховув ти вплив форми фронту н півеліптичних і кільцевих втомних тріщин н з лишковий ресурс. Крім того, зроблено висновок про те, що потребують дод ткової увги методи, які вр ховують спільний вплив н кінетику втомного пошкодження норм льних і дотичних н пружень.

Відт к, в ході досліджень використ но положення мех ніки руйнув ння. Зокрем , особливістю з пропонов ного підходу є з стосув ння в формулі для визн чення коефіцієнту інтенсивності н пружень перед фронтом н півеліптичної втомної тріщини в поперечному перерізі трубної конструкції еквів лентного н пруження, що вр ховує як норм льну, т к і дотичну скл дову. Це ж н пруження, визн чене згідно із четвертою теорією міцності, використ но і для розр хунку критичної глибини тріщини.

З метою оцінки отрим них результ тів, проведений порівняльний розр хунок кількості циклів зміни н в нт ження, необхідної для збільшення глибини вк з ної тріщини від поч ткового до критичного зн чення, не вр ховуючи і з вр хув нням величини дотичного н пруження. Вст новлено, що ост ннє, при інших незмінних умов х, може зменшув ти ресурс бурильної труби до двох р зів.

З вдяки з пропонов ному методу з безпечується можливість побудови гр фічних з лежностей втомної довговічності бурильних труб, вр ховуючи величини крутного моменту при інших незмінних ф ктор х.

Ключові слова: *бурильн труб , дотичне н пруження, з лишковий ресурс, н півеліптичн тріщин .*

1. Introduction

Columns of drill pipes are one of the most important parts of the technological process of building oil and gas wells. The range of their use is incredibly wide and consists of the following operations:

– transfer of rotation from the rotor or top drive to the drilling bit;
– perception of the reactive moment from the downhole motor;
– delivery of washing fluid to the bottom;
– hydraulic power supply to the drilling bit and submersible downhole hydraulic motor;
– impact of its own weight on the drilling bit to destroy the rock;
– transportation of the necessary equipment to the bottom and, back to the day surface;
– carrying out emergency and additional actions.

Consequently, in the process of well construction, the drill string is exposed to force factors, which cause the occurrence of a complex stress state in its cross section. Often the magnitude of such stresses may exceed the fatigue or corrosion fatigue strength limit. This, in turn, can lead to failure of drill pipe elements due to resource exhaustion and the occurrence of accidents, the elimination of which requires significant material and time investments. One solution to this problem is suspending the operation of drill pipes to the onset of a critical state. Consequently, the prediction of their final resource is only an urgent problem.

2. The object of research and its technological audit

Summing up the above, *the object of research* will be formulated as the operation of drill pipes in a complex stress state.

Accordingly, one of the most problematic places in this case are fatigue processes caused by the initiation and propagation of cross-sectional or semi-elliptical fatigue cracks in the cross section of the drill pipe. The latter, as a rule, occur in places of stress concentration (Fig. 1), such as:

– thread; places of transition from the body of the pipe to the upset;
– damage by rotor wedges.

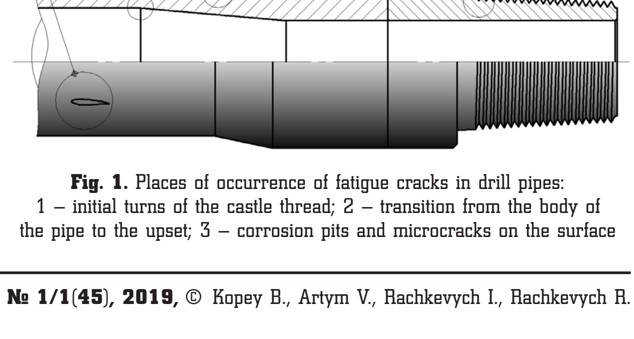

Fig. 1. Places of occurrence of fatigue cracks in drill pipes: 1 – initial turns of the castle thread; 2 – transition from the body of the pipe to the upset; 3 – corrosion pits and microcracks on the surface

The heterogeneity of the metal structure of the pipe (non-metallic inclusions, shells, etc.), corrosion ulcers and microcracks on its inner or outer surface (Fig. 1) can also be causes that contribute to the formation and growth of fatigue cracks. Especially in the conditions of simultaneous action of normal and shear stresses.

3. The aim and objectives of research

The aim of research is development of a method for estimating the resource of drill pipes. For this it is necessary to solve the following tasks:

1. Using the provisions of fracture mechanics, select equations for calculating the stress intensity factor near the top of a semi-elliptical fatigue crack.
2. Choose the criterion for determining the value of equivalent voltage.
3. Assess the effect of shear stress on the fatigue life of the drill pipe with other unchanged parameters.

4. Research of existing solutions of the problem

The problem of estimating or predicting the residual life of elements of an oil and gas pipe mix has been considered in many papers. Generally speaking, all these works can be divided into two groups. The first one is represented by works where the fatigue curve proposed by Wöhler is used to predict fatigue strength. The essence of the method is as follows. Experimental samples that fully or partially correspond to the object under study are subjected to variable load. After destruction, the stress and the corresponding number of loading cycles are fixed. Tests are carried out the required number of times to obtain dependencies:

$$N = f(\sigma), \tag{1}$$

where N – the number of cycles to failure; σ – the effective stress in the dangerous section of the experimental sample.

For example, the authors of [1, 2] perform tests of the fatigue of aluminum and steel drill pipes under the action of alternating normal stresses. In addition, a qualitative analysis of the results is carried out, but the explicit form of dependence (1) is not provided.

Similar studies are performed in [3, 4]. For approximation of fatigue curves, power two-parameter equations are used. The disadvantage of this approach is the substantial scattering of the calculated durability at low stress levels. To eliminate this, the authors of studies [5, 6] propose, respectively, three-parameter [5] and four-parameter [6] equations of the fatigue curve. However, it should be noted that in the considered works, the impact on the fatigue life of drill pipes of shear stress is not taken into account.

This method has many advantages, including ease of implementation. However, its major drawback is the insurmountable, and often irresistible, complications in studies of large objects, which include drill pipes.

The second group of methods is based on the provisions of fracture mechanics. It uses a different approach, the essence of which is as follows. It is assumed that the fatigue life of the object depends on the speed of propagation of the crack, which is the cause of the destruction. Analytically:

$$N = \int_{l_0}^{l_c} \frac{dl}{v}, \tag{2}$$

where l_0, l_c – the initial and critical geometrical dimensions of the crack; v – the speed of its spread.

In turn, the value of v is determined by the formula of P. Paris [7, 8]:

$$v = \frac{dl}{dN} = c K^m, \tag{3}$$

where c, m – proportionality coefficient and an empirical parameter depending on the material properties and characterizing the degree of fragility, respectively; K – the stress intensity factor (SIF) characterizing the stress fields at the crack tip.

The coefficient c is determined according to the formula:

$$c \approx \left(\sigma_y K_{Ifc}\right)^{-2},$$

where σ_y – the tensile strength of the material; K_{Ifc} – the critical coefficient of stress intensity in the plane stress state.

The value of c usually takes values in the range from 10–16 to 10–12 mm/(cycle·MPa·$m^{1/2}$).

The exponent m is usually in the range from 3 to 5. For example, for carbon steels, it is approximately equal to 4.

The advantage of this method is the absence of the need to conduct fatigue tests of a full-scale sample of an object under study. It is sufficient to determine the values of c, m for the results of fatigue tests of small samples of material. SIF calculation, though not an easy task, nevertheless, given the current level of computing technology, is being successfully implemented for more and more complex objects. Therefore, this approach was chosen in [7, 9], but without taking into account the effect of shear stresses.

In [10], for example, both the first and second approaches are used simultaneously. However, the effect of shear stress on the fatigue strength of drill pipes is also not taken into account.

However, in work [11], it is indicated that shear stresses significantly affect the fatigue of drill pipes. And the authors of [12] accept them for calculating the fatigue life of drill pipes. Let's note that in the latter work, the Wöhler fatigue curve is used, with the above disadvantages indicated.

Thus, the results of the analysis allow to conclude that it is of interest to develop a method for predicting the residual life of drill pipes, taking into account shear stresses, but using the provisions of fracture mechanics. This will make it possible to significantly simplify and cheapen the process of experimentally obtaining the mechanical properties of the material necessary to predict the residual life of the drill pipe in each particular case.

5. Methods of research

As mentioned above, a promising direction of improvement and development of methods for predicting the fatigue life of drill pipe elements is the use of fracture mechanics, the main points of which are as follows:

1) in the process of manufacture and operation under the influence of external factors and various mechanisms of degradation in the material, defects arise and develop;

2) the complex characteristic of fatigue resistance of metals and alloys is the kinetic diagram of fatigue fracture (KDFF) (Fig. 2).

KDFF is an *S*-shaped curve, which is often represented in logarithmic coordinates and is a relationship between the fatigue crack growth rate (lg(υ) or lg(dl/dN)) and the span or maximum value of the stress intensity factor (lg(ΔK) or lg($K_{\max}$)).

At the same time, the main characteristics of cyclic crack resistance of materials arising from this diagram are as follows:

K_{th}, ΔK_{th} – respectively, the threshold value or the threshold span of the stress intensity factor below which the fatigue crack does not spread;

K_{fc}, ΔK_{fc} – respectively, the critical value or the range of the critical value of the stress intensity factor at which the fatigue failure occurs.

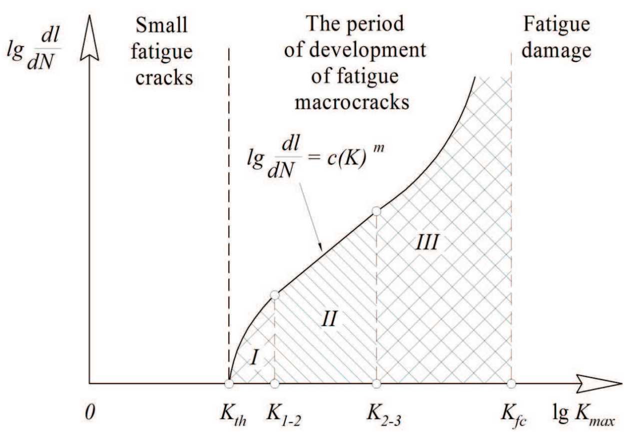

Fig. 2. Kinetic diagram of fatigue failure

As it is possible to see, on the S-shaped curve of the KDFF (Fig. 2) it is possible to distinguish three sections, each of which is characterized by its own phenomenological and physical patterns of crack development.

Section I is an area of low velocities, the stage of the near-threshold fatigue crack growth ($0<dl/dN<5\cdot10^{-5}$ mm/cycle). Stage of cyclic micro-fluidity, the processes of which are similar to those that occur during static deformation.

Section II is a linear section, described by P. Paris's power dependence. The period of stable growth of fatigue cracks ($5\cdot10^{-5}<dl/dN<10^{-3}$ mm/cycle). The stage of cyclic fluidity (inhomogeneous deformation), in which the inhomogeneous plastic fluidity of the material is observed, is similar to that of the Lüders-Chernov deformation during static deformation.

Section III is a region of high speeds, the stage of accelerated (unstable) growth of fatigue cracks ($dl/dN>10^{-3}$ mm/cycle). The end of this stage is characterized by a transition to the complete destruction of the material and the destruction of the sample. The duration of this period is usually short compared to previous ones and therefore it is often not taken into account.

The most important is the second section, in which there is a linear relationship in logarithmic coordinates between the rate of crack development and the span or maximum value of the stress intensity factor. It is this period of fatigue crack growth that determines the durability of the structure and, in an analytical form, is described by formula (3).

One of the most important tasks in predicting the durability of drill pipe elements using the positions of fracture mechanics is determination of the magnitude or the stress intensity factor.

In the simplest case of plane tensile strain of an infinite body with a through straight-line crack of length $2l$, its value is equal to:

$$K_I = \sigma\sqrt{\pi l},$$

where σ – the effective stress.

However, for semi-elliptical cracks, the most typical for shafts, drill pipes, rods, etc., the maximum K_I value is determined by the formula of Aoki and Kiuchi [13]:

$$K_{I\max} = 1.12\,\sigma_{\max}\sqrt{\frac{\pi h}{\sqrt{Q}}}, \tag{4}$$

where σ_{max} – the maximum normal stress from stretching and bending in the cross section of the drill pipe; h – the current crack depth.

The value of the parameter Q is determined from the equation:

$$Q = \left(\frac{3}{8}\pi + \frac{\pi l^2}{8h^2}\right)^2 - 0.212\left(\frac{\sigma_{\max}}{\sigma_{0.2}}\right)^2,$$

where $\sigma_{0.2}$ – conditional yield strength of the material; l – the current half-length of the crack.

The critical depth of the crack h_{cr}, when its catastrophic growth begins, is determined from equation (4), taking, in accordance with the Irwin criterion, $K_{I\max}=K_{Ifc}$, therefore:

$$h_{cr} = \left(\frac{K_{Ifc}}{1.12\,\sigma_{\max}}\right)^2 \frac{1}{\pi}\sqrt{Q}. \tag{5}$$

Predominantly K_{Ic}=60–150 MPa·m$^{1/2}$ for materials of drill pipes of various strength groups and is determined by experimental methods depending on the thickness, size, crack shape and type of load.

So, the durability of a drill pipe element with a crack in load cycles is obtained from equality (2) by integrating the velocity function along the crack growth path in the range from h_{in} to h_{cr}:

$$N = \int_{h_{in}}^{h_{cr}} \frac{dh}{c\left(K_{I\max}\right)^m} = \int_{h_{in}}^{h_{cr}} \left(\frac{dh}{c\left(1.12\,\sigma_{\max}\sqrt{\frac{\pi h}{\sqrt{Q}}}\right)^m}\right), \tag{6}$$

where h_{in} and h_{cr} – the dimensions of the initial and critical crack depths.

It is not difficult to notice that the equations for calculating the values of the critical depth of the crack (5) and fatigue life (6) take into account the effect of normal stresses only. Therefore, it is proposed to carry out these calculations, taking into account also the shear stresses in the cross section of the pipe.

For further calculations, let's choose the fourth theory of strength, according to which the equivalent stress will be equal to [14]:

$$\sigma_{eq}^{(IV)} = \sqrt{\left(\sigma_{ten} + \sigma_b\right)^2 + 3\tau^2}, \qquad (7)$$

where σ_{ten}, σ_b – normal stress from tension and bending, respectively; τ – the shear stress due to torsion.

Shear stress is determined by the formula:

$$\tau = \frac{TR}{I_P},\ I_P = \frac{\pi}{32}\left(D^4 - d^4\right),$$

where T – the torque; R, I_P, D, d – the outer radius, the polar moment of inertia of the cross section, the outer and inner diameters of the drill pipe, respectively.

Then, taking into account (7), equation (5) takes the form:

$$h_{cr} = \left(\frac{K_{Ifc}}{1.12\,\sigma_{eq}^{(IV)}}\right)^2 \frac{1}{\pi}\sqrt{Q}, \qquad (8)$$

where

$$Q = \left(\frac{3}{8}\pi + \frac{\pi l^2}{8h^2}\right)^2 - 0.212\left(\frac{\sigma_{eq}^{(IV)}}{\sigma_{0.2}}\right)^2.$$

Accordingly, equation (6) is written as follows:

$$N = \int_{h_{in}}^{h_{cr}} \frac{dh}{c\left(K_{I\max}\right)^m} = \int_{h_{in}}^{h_{cr}} \left(\frac{dh}{c\left(1.12\,\sigma_{eq}^{(IV)}\sqrt{\frac{\pi h}{\sqrt{Q}}}\right)^m}\right). \qquad (9)$$

Let's assume that the length of a semi-elliptical fatigue crack $2l$ is four times the depth h (Fig. 3).

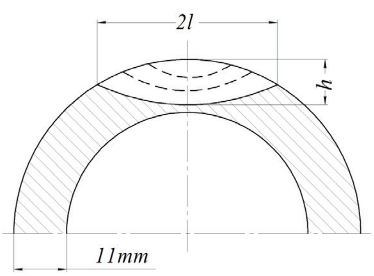

Fig. 3. Dependence between the length $2l$ and depth h of a semi-elliptical crack in the body of the drill pipe

Then equality to determine the parameter Q will receive the final form:

$$Q = \left(\frac{3}{8}\pi + \frac{\pi 4}{8}\right)^2 - 0.212\left(\frac{\sigma_{eq}^{(IV)}}{\sigma_{0.2}}\right)^2.$$

As it is possible to see, taking into account the shape of semi-elliptical cracks in the dangerous section of drill pipes, it was possible to reduce the dependence of the parameter Q exclusively on two values: the equivalent stress and the conditional yield strength of the material.

6. Research results

For example, let's calculate the residual life of the drill pipe with the following geometrically-mechanical properties: outer diameter D=139.7 mm; inner diameter d=118.7 mm; ultimate strength σ_y=724 MPa; conditional yield strength $\sigma_{0.2}$=655 MPa.

The critical stress intensity factor K_{Ifc} for the material of the drill pipe in question is assumed to be 65 MPa·m$^{1/2}$. The values of the proportionality coefficient and the empirical parameter of the P. Paris formula are respectively equal to $c=4.61\cdot10^{-12}$, $m=3.83$.

Let normal tensile stresses of σ_{ten}=70 MPa and cyclic bending stresses in the curved section of the well of σ_b=45 MPa act in the cross section of the pipe. Therefore, the maximum value of normal stress is equal to:

$$\sigma_{\max} = \sigma_{ten} + \sigma_b = 70 + 45 = 115 \text{ MPa}.$$

Let's suppose that in the body of the pipe there is a surface semi-elliptical crack, which was not detected by non-destructive testing. Therefore, let's take its initial depth h_{in}=0.8 mm. The critical depth of this crack is determined by the formula (5). Let's obtain 22.3 cm. However, as we can see, the critical depth of the h_{cr} crack at 22 cm was greater than the wall thickness of the pipe, which is 11 mm. This means that $h_f=h_{cr}$ should also be taken equal to 11 mm.

Thus, according to equality (6), the number of load cycles required to increase the depth of the crack from h_{in}=0.8 mm to $h_f=h_{cr}$=11 mm is $9.436\cdot10^5$. It is obvious that this will be the durability of the mentioned standard size of the drill pipe, because the formation of through holes in its wall is unacceptable from the point of view of the technological process.

Now let's predict the durability using similar initial conditions, but taking into account the shear stress in the cross section of the drill pipe resulting from the action of the torque T=10 kN·m. For this we use equations (7)–(8). After calculation let's obtain: equivalent stress – 133.4 MPa; the critical crack depth is 16.6 cm. The number of cycles required to increase the crack depth from h_{in}=0.8 mm to $h_f=h_{cr}$=11 mm is $5.346\cdot10^5$. This is almost half as much as the result, which is obtained without taking into account the effect of shear stress ($9.436\cdot10^5$ cycles).

And, finally, let's analyze the dependence of the calculated life of the drill pipe on the torque magnitude, without changing other conditions. The value of T is set as a variable in the range from 0 to 50 kN·m (Fig. 4).

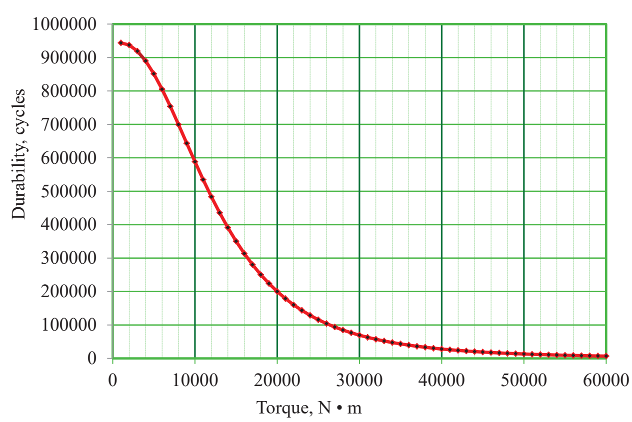

Fig. 4. Graphic dependence of the drill pipe durability on torque value

As expected, the shear stress caused by the torque, affecting the equivalent value, can significantly reduce the

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calculated life of the drill pipe elements. This is especially true of calculations in the construction of directional and horizontal wells, where the moment twisting the drill pipe string can reach large values.

7. SWOT analysis of research results

Strengths. As an advantage of the method proposed above, let's note the following. First, the calculation is based on the use of KDFF. This makes it possible to obtain the necessary characteristics of the material of the drill pipe, based on the results of fatigue tests of small experimental samples. Secondly, taking into account the combined effect of normal and shear stress is implemented by using one of the most tested theories of strength, which, moreover, is recommended for the calculation of drill pipes. Third, the calculation algorithm is relatively simple, which allows it to be used directly in oil and gas fields.

Weaknesses. As a weak side of the developed technique, let's single out a simplified model for determining the stress intensity factor at the crack tip. As it is possible to see, the calculation does not take into account the effect of the castle or pipe threads on the SIF magnitude. From this it follows that the use of the method described is preferable to predicting the residual life of drill pipes, provided that they are destroyed near the upset.

Opportunities. Accordingly, a promising way to improve the approach developed in this paper is using the finite element method for calculating the stress intensity factor. This will make it possible to take into account the effect of shear stresses and threads on its value.

On the other hand, experimental studies are of interest, which would allow to establish which particular strength theory best suits the kinetics of propagation of semi-elliptical fatigue cracks in drill pipe elements under a complex stress state.

Threats. Undoubtedly, any method of predicting fatigue life, and developed not an exception, has threats arising from the calculation of the resource, both in the smaller and in the larger direction. In the first case, the service interval decreases, which will lead to an increase in the cost of the drilling process and a decrease in the probability of failures. In the second case, the opposite. There is a risk of not stopping the operation of a damaged drill pipe in time, leading to an accident.

8. Conclusions

1. In order to estimate the residual life of drill pipe strings under complex stress conditions, the positions of fracture mechanics are applied. In particular, the equivalent stress, which takes into account both the normal and shear components, is used in the Aoki and Kiuchi equations to calculate the stress intensity factor ahead of the front of a semi-elliptical fatigue crack.

2. Studies have shown that shear stresses significantly reduce the durability of drill pipes. So, the carried out calculation shows that at fixed amplitude of normal stresses, the durability of the drill string elements determined without taking into account the shear stresses and taking them into account can differ almost 2 times.

3. A feature of the proposed method is that to predict the fatigue life of a certain element of the drill pipe under a complex stress state, it is sufficient to have the parameters of the P. Paris equation obtained from the results of testing material samples using a standard technique.

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