ABSTRACT

Purpose  is to determine regularities of the development of corrosive fatigue cracks in terms of high-strength drill pipes.

Methods. Basing upon the approaches of the material failure mechanics, the crack has been characterized by the area that is the integral characteristic. Having applied the equivalent area methods, semicircle fatigue crack has been considered instead of the plane fatigue crack of the arbitrary shape; the semicircle fatigue crack is equivalent to the plane fatigue crack of the arbitrary shape in terms of the area. Kinetics of its growth has been analyzed basing on the solution of the first order differential equation which determines dependence of the equivalent semicircle radius upon the number of loading cycles in terms of the specified initial condition. Critical radius dimension has been defined provided that the condition of transition to unstable failure is met within at least one contour point.

Findings. Remaining lifetime of drill pipe TBPV 127×9.19 S-135 with the detected cross crack of the fixed area has been evaluated; in terms of the specified operating modes, the lifetime was 653000 cycles, i.e. 181 hours. According to the production data, that pipe operated 3215 hours in the well including 200 hours after the last defectoscopy; that correlates with the obtained results.

Originality. The proposed mathematical model of the fatigue crack development makes it possible to calculate the remaining lifetime of drill pipes approximately but sufficiently enough for practical needs.

Practical implications. The obtained regularities may be used to sort out the defected pipes as well as to substantiate periodical non-destruction control in the process of drilling and tripping operations. Studies of the fatigue crack growth may be the basis to develop measures aimed at reducing stresses effecting the drill string and minimizing washout formations; that will help prolong the drill pipe life.

Keywords: drill pipe, crack, stress intensity coefficient, kinetics, loading cycle, remaining lifetime

1. INTRODUCTION

1.1. Statement of the problem

Practice of drilling oil and gas wells shows that fatigue and corrosive-fatigue damages are the most often reasons for the failures of drill string elements (MacDonald, 1994; Dzheyson, Reynold’s, Ellis, & Stuyart, 2004; Artym, Yatsynyak, Hrytsiv, Yurych, & Rachkevych, 2012; Zamani, Hassanzadeh-Tabrizi, & Sharifi, 2016).

Table 1 represents the data concerning failures of drill pipes in terms of well drilling within the area of Ukrburgas drilling division (DD) in 2015 – 2017. The mentioned period demonstrates 75 failure cases in terms of pipe body and 2 failures in terms of threaded joints. Main reasons of the first failure type are as follows: formation of micro-cracks with their further erosion and fatigue-related complete breaking (44 cases); fatigue breaking due to the effect of considerable sign-reversing loads (19 cases). Other accidents occurred due to the non-observance of technological processes during trips and as a result of bit overloading or jamming.

Pipes were most often damaged within the range of 0.5 – 0.6 m from the face of coupling or nipple (27 cases); in general, the failures were recorded at the distance of 1 m from a coupling (38 cases) or nipple (37 cases).

The damaged pipes operated in the holes during different periods of time: 17.2% of pipes operated up to 4000 hours; 26.7% – from 4000 to 8000 hours; 18.7% – from 8000 up to 12000 hours; 26.7% – from 12000 up to 14000 hours; and 10.7% – more than 14000 hours. After defectoscopy, the pipes operated from 30 to 380 hours more. That indicates the fact that the pipes operating in the well had certain mechanical damages being the stress concentrators and reducing operating period of drill pipes. Bottom of those failures contains a layer of plastically deformed (during the failure formation) metal.
Fatigue failure which are usually described by equation: 

\[ V = \frac{dN}{dP}, \]  

(1)

where:

- \( V \) – the rate of fatigue crack propagation.
- \( N \) – the number of cycles up to the failure of a drill string element.

To predict endurance of drill string elements basing upon the results of studying their current state, authors of papers (Ivasiv, Artym, Hrytsiv, & Rachkevych, 2010; Kryzhanivs’kyi & Kopey, 2010) propose to apply \( G \) criterion. Ratio of fatigue area to nominal area of weak pipe section is used as the failure degree while bending. Failure degree \( G \) is the growing linear function depending upon the number of loadings; it varies within the range from 0 to 1. It has following form:

\[ G = G_0 - \left( G_0 - G_k \right) \frac{N_T}{N}, \]  

(2)

where:

- \( G \) – the current value of the criterion;
- \( G_0 \) – the value of the criterion at the initial registration moment;
- \( G_k \) – the value of the criterion at the moment of failure;
- \( N_T \) – the current number of loading cycles;
- \( N \) – the number of loading cycles before failure.

Another approach to the problem solution is based on the failure mechanics (Migal', Kopey, Karpash, & Kirindas, 1980; Hnyp, Babyuk, & Chernov, 1990; Kryzhanivs’kyi, Shats’kyi, & Petryna, 1997). Following idea is taken as the basis: endurance of a specific drill string element in stipulated by the number of loadings; it varies within the range from 0 to 1. It has following form:

\[ N = \int_{l_0}^{l_C} \frac{dl}{V}, \]  

(3)

where:

- \( V \) – the rate of fatigue crack propagation.

Thus, endurance of the damaged drill string elements is calculated with the help of the crack propagation rate determined by the state of pre-failure zone being described by a stress intensity coefficient (SEC) \( K \) (or by the range of a stress intensity coefficient \( \Delta K \)). Practically, graphic dependences \( V \) upon \( K \) or \( \Delta K \) are used which are usually called kinetic diagrams of fatigue failure (KDIFF) or diagrams of the material crack-resistance. The mentioned papers contain formulas to calculate a stress intensity coefficient (or range of stress intensity coefficient) which have different variants of representation depending upon the shape of the fatigue crack front and the selected mathematical model.

Paper (Kryzhanivs’kyi, Shats’kyi, & Petryna, 1997) represents the data on studies dealing with fatigue endurance of drill pipes; the data are based on the model of semielliptic fatigue crack within a hollow cylinder. The equation describing kinetics of its development is based on the idea on the crack opening in terms of local plane elastoplastic deformation.

Paper (Vaisberg, Vincke, Perrin, Sarda, & Fay, 2002) describes in detail a cycle of formation and deformation of a fatigue micro-crack. It may be divided hypothetically into three stages (Fig. 1).
Stage 1. During the drill pipe rotation, micro-cracks are being formed on the drill pipe surface near the stress concentrators under the effect of cyclic sign-reversing loading.

Stage 2. Micro-cracks propagate within the pipe body perpendicular to the direction of the effective stress; rate of the micro-crack propagation correlates with its magnitude. Rate of the micro-crack development grows within the areas of stress concentration: threaded joints, points of transfers from a tool joint to a drill pipe body, sections of drill pipe gripping by slips and wrenches, internal surfaces of a drill pipe affected by the pit corrosion (MacDonald, 1994; Macdonald & Bjune, 2007; Fangpo, Yonggang, Xinhu, & Caihong, 2011).

Moreover, rate of the micro-crack development is affected by the operating environment (Pokhmurskii, Kryzhanovskii, Ivasiv, Poddubnyi, & Yanyshvskii, 1984; Zamani, Hassanzadeh-Tabrizi, & Sharifi, 2016), i.e. drill mud. During the rotation within the curved well shaft, a micro-crack in a drill pipe opens and closes in turn while passing along short and long radius. When it opens, vacuum is formed in a micro-crack acting as the pump to suck in the fluid from the operating environment. After the semi-rotation, a micro-crack closes and the fluid stays inside under pressure resulting in additional breaking effect, so-called wedging effect.

Stage 3. Micro-cracks propagate inward the pipe body resulting in its failure. When the crack depth reaches the pipe side thickness, the opening is formed; flow of drill mud goes through that opening; after that, determine stress-strain state (SSS) close to it. After that, determine stress-strain state (SSS) within the considered cross section.

Knowing SSS, it is necessary to study failure kinetics, i.e. regularities of the defect development which can be the basis to determine remaining lifetime of the pipe. To analyze kinetics of the crack growth in a pipe, assume the following:
- conditions of automodeling is implemented around the crack top, and stress-strain state within the pre-failure zone is determined only by KDFF;
- crack propagates towards the normal to its surface at any contour point.

Thus, our task is to define dependence of crack area $S$ upon the number of loading cycles $N$ in terms of the initial condition $S(0) = S_0$.

Select origin of coordinates in the crack center (Fig. 2). In general case (in terms of complex SSS), a crack will propagate along the curvilinear trajectory which equations in polar coordinate system are as follows $\rho = \rho(N, \phi)$, $\phi = \phi(N)$.

1.3. Statement of the problem

Problem to control corrosive-fatigue failure of the drill string elements is rather topical. Pipes in the well operate in terms of huge amount of loading cycles resulting in origin and growth of cracks either in the pipe body or at the points of stress concentration (thread, fillet, grooves etc.). At the same time, some cracks are not dangerous from the viewpoint of possible sudden breakdown and pipe can operate with such defects for some time. Consequently, there is a necessity to evaluate the pipe lifetime (both new and the ones with operating defects like fatigue cracks) before the critical situation taking into consideration possible dispersion of fatigue characteristics of the pipe material.

Thus, objective of the study is to determine regularities of the development of corrosive fatigue cracks in terms of high-strength drill pipes.

2. RESEARCH METHODOLOGY

To solve the specified problem, use the approaches of failure mechanics. Basing upon analysis of the drill string loading conditions and possible reasons of drill string elements failure by non-destructive methods, find the crack-type defect. It is characterized by area $S_0$ being the integral characteristic. A crack is within the plane perpendicular to the effective load (well axis), i.e. stress-strain state is symmetric relative to the crack plane. The area is of semieliptic shape with semi-axes $2a$ (length along the circle) and $l$ (depth along the pipe body) or close to it. After that, determine stress-strain state (SSS) within the considered cross section.

Use equations (Panasyuk, 1988; Andreykiv & Darchuk, 1992) for a fatigue crack developing within one plane:

$$
\frac{\partial \rho}{\partial N} \left[ 1 + \frac{1}{\rho^2} \left( \frac{\partial \rho}{\partial \phi} \right)^2 \right]^{-\frac{1}{2}} = \nu(K_f),
$$

(4)
where:

- $\nu(K_i)$ – the dependence of the fatigue crack rate (FCR) upon maximum KDFF value per cycle being determined by kinetic diagram of fatigue crack (KDFC) of the drill pipe material in terms of the specifies loading conditions;
- $\rho(N, \phi)$ – the required radius-vector of the moving crack contour in the polar coordinate system;
- $\rho_0(\phi)$ – the radius-vector of the initial crack.

Taking into account that:

$$
\int_0^{2\pi} \int_0^{\rho_0(\phi)} \rho d\rho d\phi = \pi \rho_0^2(\phi),
$$

(5)

differentiate expression (5) in terms of $dN$ and get:

$$
\frac{dS}{dN} = \int_0^{\rho(N, \phi)} \rho(\phi) \frac{d\rho}{dN} d\phi.
$$

(6)

Taking into consideration (4), we will have:

$$
\frac{dS}{dN} = \int_0^{\rho(N, \phi)} \sqrt{1 + \left(\frac{d\rho}{d\phi}\right)^2} \nu(K_i) d\phi.
$$

(7)

Having defined that $dt = \sqrt{\rho^2 + \left(\frac{d\rho}{d\phi}\right)^2} d\phi$ is the element of the crack contour arc, rewrite (7) as follows:

$$
\frac{dS}{dN} = [\nu(K_i)] dt.
$$

(8)

It is difficult to integrate the expression in the right part (8) since the formulas to find $\nu(K_i)$ are of complex form and depend upon geometric parameters of the crack contour. In practice, cracks usually have complex configurations; in general, fatigue propagation of such a crack is described by non-linear differential equation with partial derivatives. Nowadays, methods to solve such nonlinear equations have not been developed yet. However, approximate method – equivalent area method proposed in monographs (Panasyuk, 1988; Andreykiv & Darchuk, 1992) – helps simplify the situation considerably (as a rule, with minor errors).

The essence of the method is based on the assumption that to describe kinetics of the growth of a plane fatigue crack of arbitrary configuration, it is enough to study kinetics of the growth of a circular fatigue crack being equivalent to it in terms of the area.

Introduce parameter $a_{eq}(N)$ – radius of the “equivalent” semi-circle which area is equal to the crack area (Fig. 3) – near value $S(N)$, i.e.:

$$
\frac{\pi a_{eq}^2(N)}{2} = S(N),
$$

(9)

Then, differential equation (8) will be rewritten as follows:

$$
\frac{da_{eq}}{dN} = \frac{1}{\pi a_{eq}} \int v(K_i) dt.
$$

(10)

Consider that function $v(K_i)$ is continuous and limited within all the points of crack contour; then the latter expression will be of following form:

$$
\frac{da_{eq}}{dN} = v\left(K_{eq}\right).
$$

(11)

Applying Paris formula $v = C K_i^n$, value $K_{eq}$ may be represented as:

$$
K_{eq} = \left[ \frac{1}{\pi a_{eq}} \int v(K_i) dt \right]^{\frac{1}{n}}.
$$

(12)

Thus, $K_{eq}$ is the generalized SSS characteristic in the neighbourhood of the developing crack top; it has the specified area $S$ and takes into consideration KDFF changes along its contour.

Move on to the next problem:

$$
\frac{da_{eq}}{dN} = v\left(K_{eq}\right), \quad a_{eq}(0) = \sqrt{\frac{S_0}{\pi}}.
$$

(13)

Ratio (13) describes approximately kinetics of the growth of the fatigue crack developing within one plane in the invariant form not depending on the defect shape. Value $K_{eq}$ depends insignificantly on the crack configuration and is determined mostly by its area.

According to the studies of pipes disruption, the crack is mostly of semielliptic (or close to it) shape. KDFF for the edge semielliptic crack is determined using following dependence:
\[ K_{\text{eq}} = \frac{2}{\sqrt{\pi}} \sigma \cdot \sqrt{a_{\text{eq}} \cdot f\left(\frac{b}{a}\right)}, \quad (14) \]

where:
\[ f\left(\frac{b}{a}\right) \] - the complex function of the parameters of ellipses and angle \( \beta \). It is close to the constant being taken as 1.1 (Andreykiv & Darchuk, 1992).

In terms of the edge effect, value \( K_{\text{eq}} \) depends slightly on the ellipses semi-axes ratio; thus, we take:
\[ K_{\text{eq}} = 1.24 \cdot \sigma \cdot \sqrt{a_{\text{eq}}} \cdot (15) \]

Taking into account (15), rewrite problem (13) as follows:
\[ \frac{da_{\text{eq}}}{dN} = C \cdot \left(1.24 \cdot \sigma \cdot \sqrt{a_{\text{eq}}} \right)^n, \quad (16) \]

\[ a_{\text{eq}}(0) = \frac{S_0}{\pi}, \]

where:
\( \sigma \) - the tensile stresses within the crack plane.

Ratio (16) describes approximately growth kinetics of the fatigue cracks which shape is close to a semielliptic crack developing within one plane of a drill pipe.

Having integrated (16), we obtain:
\[ \frac{da_{\text{eq}}}{dN} = C \cdot \left(1.24 \cdot \sigma \cdot \sqrt{a_{\text{eq}}} \right)^n \cdot a_{\text{eq}}(N) = \]
\[ \left[ (a_{\text{eq}})^{\frac{n-2}{2}} - \left(\frac{n}{2} - 1\right)C \cdot (1.24 \cdot \sigma)^n \cdot N \right]^{\frac{2}{n-2}}. \quad (17) \]

Dependence (17) helps determine radius of the equivalent semi-circle in \( N \) cycles which area will be:
\[ S(N) = \frac{\pi \cdot a_{\text{eq}}^2(N)}{2}. \quad (18) \]

Critical dimension \( a_{\text{eq}} \) is determined basing upon the fact that condition of transition to unstable failure is met within at least one point of the contour:
\[ K_{\text{eq}} = K_{fc}, \quad (19) \]

i.e. a crack loses its stability, and its spontaneous growth begins (stage 3 of the fatigue crack development).

Period of the development of initial area crack \( S(a_{\text{eq}}^*) \) up to the critical dimension with corresponding value \( S'(a_{\text{eq}}^*) \) is determined according to formula:
\[ N^* = \frac{\sigma_{\text{eq}}^*}{a_{\text{eq}}^*} \cdot \frac{da_{\text{eq}}}{dK_{\text{eq}}}, \quad (20) \]

3. PRACTICAL CALCULATIONS

To perform the calculations, drill string of Perekopivska #63 well was analyzed. In October 2014, there was an accident in this well. There was a parting of drill pipe TBPV 127×9.19 S-135 at the depth of 2775 m. Cross section was represented by the even pipe failure with minor washout traces of 3 – 4 cm length around the circle. The failure was caused by the crack formation with further washing out and parting of the drill pipe. Using the proposed model, we have studied the growth kinetics of that fatigue crack.

We analyzed the drill string consisting of two sections: drill pipes TBPV 127×9.19 S-135 with the length of 4727 m and heavy-weight drill pipes OBT 165×70 with the length of 146 m. Operating parameters were as follows: bit loading varied within the range of \( G = 6 – 8 \mathrm{t}, \) washing liquid loss was \( Q = 24 \mathrm{l/s}, \) pressure was \( P = 10 \mathrm{MPa}, \) and drill string rotation frequency was \( N = 50 – 70 \mathrm{rot/min}. \) Drill mud was of \( \rho = 1.18 \mathrm{g/cm^3} \) density and \( T = 60 \mathrm{s} \) viscosity.

There was a cross section at the depth of 2775 m; the cross section contained a cross crack within the drill pipe body. The crack shape was close to semielliptic and characterized by cross section area \( S_0. \) Calculations were performed for different values \( a_{\text{eq}}(0) \) of the “equivalent” semicircle radius which area was equal to the crack area.

In terms of the cross section, there were tensile and bending stresses; oscillation processes occurring within the drill string while hole drilling were taken into account as well. In terms of the specified operating modes of the drill string, stresses varied within the range from \( \sigma_{\text{min}} = 90 \mathrm{MPa} \) up to \( \sigma_{\text{max}} = 250 \mathrm{MPa}. \)

Calculations were performed for drill pipes 127×9.19 S-135 with following crack-stability characteristics:
\[ – n = 3.45; \]
\[ – K_{fc} = 142.8 \mathrm{MPa} \cdot \sqrt{\mathrm{m}}; \]
\[ – C = 4.45 \cdot 10^{-12} \mathrm{m/(MPa} \cdot \sqrt{\mathrm{m}})^3. \]

Figure 4 demonstrates the calculation results.

![Figure 4. Kinetics of the fatigue crack growth in a drill pipe depending on the effective load: (a) \( a_{\text{eq}} = 2 \mathrm{mm}; \) (b) \( a_{\text{eq}} = 3 \mathrm{mm}; \) 1 – 90 \mathrm{MPa}; 2 – 120 \mathrm{MPa}; 3 – 180 \mathrm{MPa}; 4 – 250 \mathrm{MPa}](image)
Analysis of the results shows that in terms of the specified operating modes, the crack does not reach critical dimensions, and the pipe may operate within the well for some time more. As soon as the “equivalent” semicircle radius reaches its critical value \( d_{eq} = 5.6 \text{ mm} \) for the conditions under consideration, critical crack growth begins resulting in the pipe failure. According to the calculations, pipe with the crack should operate 653000 cycles more, i.e. 181 hours. According to the production data, that pipe operated 3215 hours in the well including 200 hours after the last defectoscopy; it correlates with the obtained results.

4. CONCLUSIONS

The proposed mathematical model of the fatigue surface crack development helps calculate the drill pipe lifetime to the extent being rather sufficient for practical implementation. The obtained results may be used to sort out the damaged pipes as well as to substantiate periodic non-destruction control while drilling and tripping.

Analysis of the process of the fatigue crack growth makes it possible to develop measures for reducing stresses effecting the drill string and to minimize formation of openings which help prolong the drill pipe life.

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REFERENCES


PROГНОЗУВАННЯ ЗАЛИШКОВОГО РЕСУРСУ БУРИЛЬНИХ ТРУБ ЗА КІНЕТИКОЮ ВТОМНОЇ ТРІЩИНІ В ДОКРИТИЧНИЙ ПЕРИОД

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Мета. Визначення закономірностей розвитку тріщин корозійної втоми у високоміцних бурильних трубах.

Методика. На основі підходів механіки руйнування матеріалів тріщину охарактеризовано площею, яка є інтегральною характеристикою. Скориставшись методом еквівалентних площ, замість площі втомної тріщини довільної конфігурації розглянуто еквівалентну їй за площу напівкуругову втомну тріщину. Досліджено кінетику її росту на основі розв’язку диференціального рівняння першого порядку, який визначає залежність радіусу ви- росту на основі розв’язку диференціального рівняння першого порядку, який визначає залежність радіусу ви- росту на основі розв’язку диференціального рівняння першого порядку, який визначає залежність радіусу ви-
RESULTS. The estimated residual resource of the drilling pipe ТБПВ 127×9.19 S-135 with a revealed transverse crack of fixed area, which at given modes of operation contained 653000 cycles, i.e. 181 hours. According to the industrial data, this pipe worked in the well 3215 hours, including 200 hours after the last inspection, which correlates with the obtained result.

SCIENTIFIC NOVELTY. The proposed mathematical model for the development of the fatigue crack allows for approximate, with sufficient accuracy for practical purposes, to calculate the residual life of drilling pipes.

PRACTICAL SIGNIFICANCE. The obtained regularities can be used for the rejection of damaged pipes, as well as for the establishment of the periodic non-destructive control in the process of drilling and the implementation of spooling operations. Based on the study of the process of fatigue crack growth, measures can be developed to reduce the stresses acting on the drilling column, minimize the formation of grooves, which will allow to increase the durability of drilling pipes.

KEY WORDS: drilling pipe, crack, coefficient of intensity of stresses, kinetics, cycle loading, residual life

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