SOCAR Proceedings

Well Driling

journal home page: http://proceedings.socar.az

EVALUATION OF THE CONDITIONS OF DRILL PIPES FAILURE DURING TRIPPING OPERATIONS

Ye.I.Kryzhanivskyi, O.Yu.Vytyaz*, V.V.Tyrlych, R.S.Hrabovskyy, V.I.Artym

Ivano-Frankivsk National Technical University of Oil and Gas, Ukraine

Abstract

The experimental evaluation of the power criterion for the metal fracture of the reserve and the long operated drill pipes was carried out. The conditions under which, during tripping operations, the failure of explored drill pipes, containing external or internal transverse annular cracks are possible. An interrelation between the depth of critical external or internal transverse annular cracks in drill pipes with the weight of the drilling string is considered, taking into account the influence of dynamic loads during tripping operations. It is shown that internal transverse annular cracks in lowering operating drilling strings at depths of more than 1400 m are more dangerous than external ones, while at depths up to 1400 m, external cross-sectional circular cracks are more dangerous.

Keywords:
Critical intensity of stresses;
Critical size of external or internal transverse annular crack;
Characteristic depth of external or internal transverse annular crack.

Introduction

Today in the world one of the promising directions for solving the problem of increasing the production of energy resources is deep drilling. In particular, in Ukraine huge reserves of oil and gas are explored on the territory of the Dnipro-Donets depression and the Carpathian oil and gas province at a depth of approximately 6.5-7 thousand meters. However, drilling at such depths leads to a significant increase in the number of accidents due to the failure of the elements of the drilling strings, since operational stresses contribute to the formation and development of fatigue cracks in their cross-sections. It is known that in the range of drilling 2500-4500 m, the number of failures increases 4.8-5 times, and in the range of 4500-5000 m - 9.8 times [1].

Emergency destruction of the elements of drilling strings (DS) in rotary drilling, which are caused by the action of dynamic loads acting on the drill pipe (DP) and by the influence of the drilling fluid [2-7], can be divided into three main groups: the failure of pipes in the upset part, the destruction of threaded tool joints and breakage along the smooth part of the pipes. The most common is transverse destruction of the body of the pipe in the joint on the thickened end, which amount to 60-70% of the total number of accidents [1,3,8,9]. Moreover, the range of generally accepted mechanisms of primary damage (fig.1) includes plastic fracture, brittle fracture and corrosion-fatigue fracture [7].

A characteristic feature of the failures of this type is that they have local character, occur suddenly, most often during the tripping operations, which, in drilling deep wells, make up 80% of the total production time and exceed the mechanized drilling time 3 – 3.5 times, and for the entire drilling time 70-80 thousand stands are lowered and lifted [1].

In the joint venture «Ukrburgaz» conducted analysis of accidents with DP leads to the conclusion that their cause is corrosion-fatigue fracture. In 2007, the share of accidents involving such destruction of the elements of the string amounted to 40% of their total number, in 2008 - 50%, in 2009 - 50%, in 2010 - 42.8%. The distribution of failures indicates that about 41% of accidents caused by corrosion-fatigue fracture of DS occur on the body of DP, 42% - due to the fracture of threaded joints, 17% - other parts of the string. Moreover, the destruction of pipes on the body occurs according to the following division: 80% - DS, 20% - drill collars (DC), and in threaded joint: 80% - DC, 20% - DP. For 2015-2016, respectively, 29 and 18 fractures of the drill tool were recorded, mainly on the body of the pipe.

The main reason for such breakdowns is the formation of microcracks, their rapid erosion and the subsequent breakdown of the pipe, respectively, 24 and 12, which is about 80% of the total number. In addition, there were 13 ruptures at a distance of 1 meter from the end of the clutch or nipple, and most often within 0.5 to 0.6 meters. The approximate number of worked hours before pipe ruptures was in the range from 6000 to 15000, including 30 - 380 hours after the defectoscopy. This indicates that the

**E-mail:* o.vytyaz@gmail.com
http://dx.doi.org/10.5510/OGP20210100478

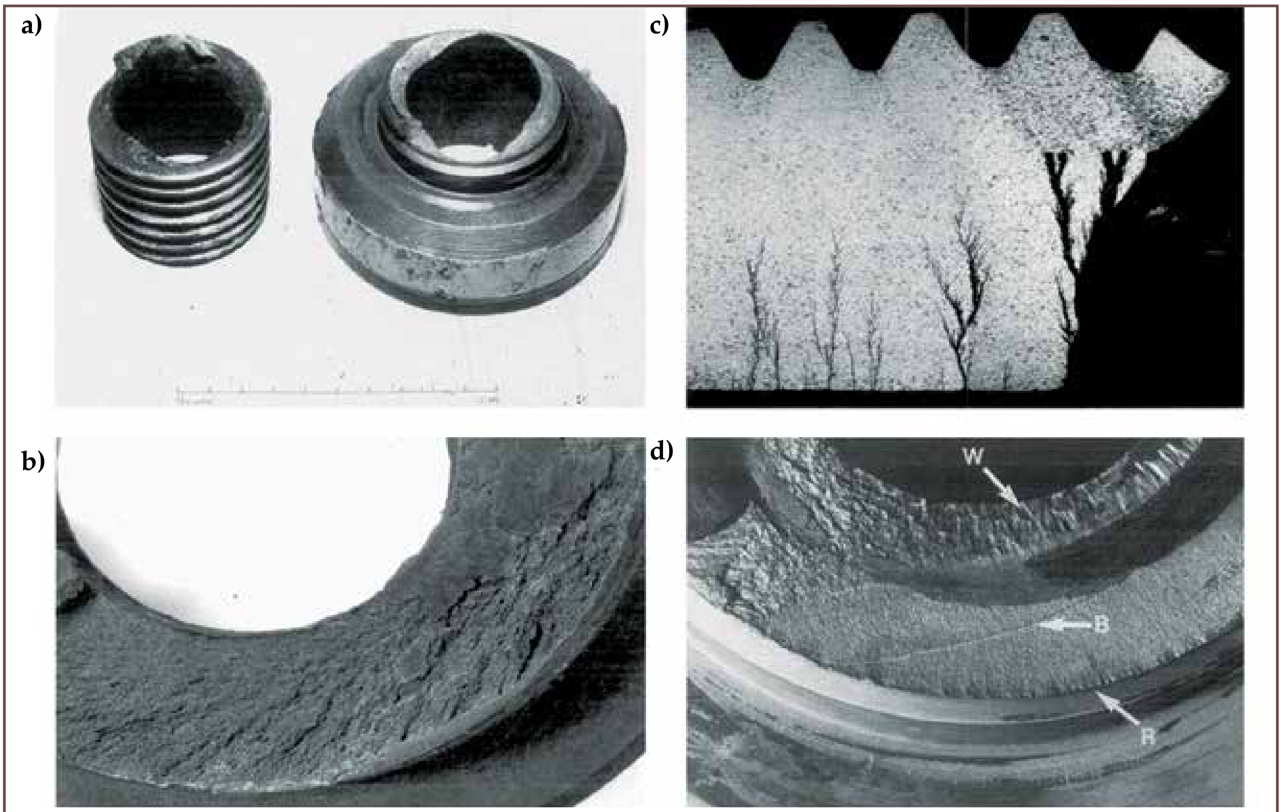

Fig.1. Failure modes of DP: a) plastic; b) brittle; c) corrosion-fatigue and d) [7]

pipes worked in the well with mechanical damages, which became stress concentrators, and accordingly reduced the life of the drill pipes [3,10,11].

Thus, in the vast majority of cases, uncontrolled transverse destruction of the body of the pipe occurs under the influence of significant operating loads, high operational pressures and under the condition of achieving transverse closed or semi-elliptic cracks that nucleate and propagate in the places of stress concentrators due to the damage by rotor wedges [1, 3], the critical sizes or the presence in pipe metal structural inhomogeneities (non-metallic inclusions, cavities, wrinkling and capillaries) [5], as well as in the case of breaking the technology of tripping operations, such as lifting on one sling [1, 3]. Other stress concentrators, such as corrosion pits and microcracks on the inner or outer surface can be the cause of drill pipes failure on their body, which also lead to the nucleation and propagation of macrocracks [4, 9].

Thus, the destruction of the elements of drill strings is due to the specificity of drilling. Moreover, at large depths, it is determined by the dominant influence of the corresponding force factors, that is, the magnitude, direction and nature of the operational loads that arise during the drilling operations and tripping operations, which determine the development of cracks in the places of damage in the cross-section of the pipe body (fig.2) [6] or a tool joint [4, 5].

The provision of reliable and safe operation of the DS requires increased attention to the evaluation of the defects detected during the technical diagnosis and the analysis of operational conditions when making the appropriate engineering decision.

Since in the process of tripping operations, caused by the influence of workloads, the most common is the failure of DS in the cross-section by its fracture, then the important issue is to determine the conditions of destruction.

In this regard, the calculation and experimental evaluation of the conditions under which the potentially possible transverse failure of DS elements is an actual scientific and technical problem.

The purpose of the work

Estimation of operational loads influence and degradation of metal properties of DP containing external or internal annular cracks on the conditions of their destruction during tripping operations is based on approaches of fracture mechanics.

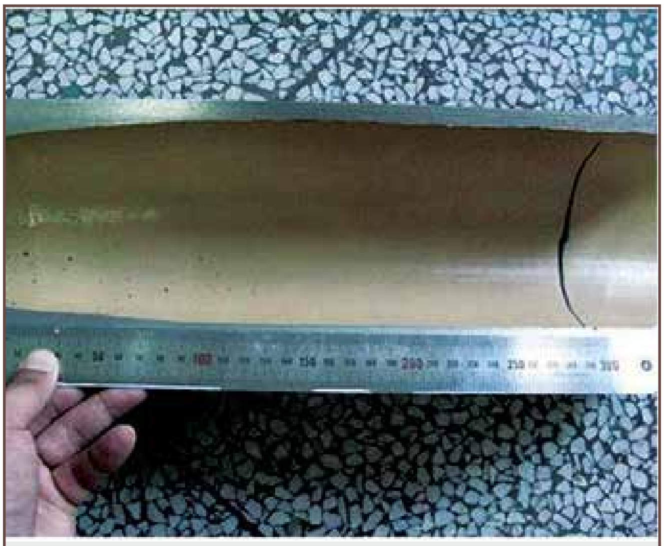

Fig.2. Morphology of the initial surface of the crack [6]

1. Methodological procedure for research and calculations

1.1. Evaluation of loading capacity of the upper end of ds

In the process of tripping operations the determination of the load of the upper end of the DS, is very important, that is, the load on the hook of the drawworks, which makes it possible to more accurately determine their durability [1]. The static weight Q of DS was determined from the ratio [12]:

$$Q = k \cdot \delta \cdot \left(Q_b + Q_{td} + Q_{dc}L_{dc} + Q_{dp}L_{dp}\right) \cdot \left(1 - \frac{\rho_{dm}}{\rho_m}\right) \quad (1)$$

where k - coefficient, which takes into account the friction forces of the string of drill pipes to the wall of the well, (k=1.5÷2.0);

δ - coefficient, which takes into account the increase in the weight of the pipes due to the weight of joint elements availability (for the coupling and tool joint connection δ=1.1);

Q_b - the weight of the bit, H (bit DRS 214.3-M1 -Q_b =651 H);

Q_{td} - weight of the turbodrill, H (turbodrill A7GTSH - Q_{td} =44250);

Q_{dc} - weight of 1 m of the drill collar, H (Q_{dc} =1631);

Q_{dp} - weight of 1 m of DP with welded tool joints, H(DP127·9-Q_{dc}=257, DP 127·8-Q_{dc}=230.5);

L_{dc}- length of the drill collar, m;

L_{dp}- length of the DP, m;

ρ_{dm} - specific gravity of the drilling mud, kg/m^3 (ρ_{dm}=1240 kg/m^3);

ρ_m - specific weight of DP material, kg/m^3 (ρ_m=7850 kg/m^3).

In the study of dynamic processes that occur in DS during tripping operations dynamic models are used due to which maximum loads and stresses being the greatest in the upper section of DS are determined. At the same time, the solutions of equations of DS vibrations are complex and require calculations of bulky rows, which greatly complicates their use in engineering calculations [13, 14]. To simplify the proces calculation schemes of DS, in which the distributed masses are replaced by reduced discrete masses, interconnected with elastic elements [15-20].

This approach gives a certain error, depending on how the masses were reduced, which according to the research of Z.Kerimov [13-16] in some cases is lower by 42.3%, while in others - by 26.5% higher than the exact solution. However, this reduced rigidity wasn't taken into account. If reduced rigidity is considered, then this error according to the research of B.Malko [21] is 3.2% of the exact solution, which is admissible under engineering calculations, and allows us to use the two-mass model, taking into account the reduced masses and rigidity, in the first approximation, for determining the stresses in the upper sections of the DS during tripping operations.

To study the effect of dynamic loads during tripping operations we used a two-mass model, the calculation scheme of which is presented in figure 3, in which the distributed masses are replaced by discrete masses m_1 and m_2, being connected to each other by elastic element with reduced rigidity C_{12}.

The operations of lifting and lowering the DS were considered separately. In particular, to calculate the effect of dynamic loads during DS lifting [22] a calculation scheme (fig.3a) was used. Differential equations of mass motion have the form:

$$\begin{cases} m_1 \cdot \ddot{S}_1 = F - (S_1 - S_2) \cdot C_{12} \\ m_2 \cdot \ddot{S}_2 = (S_1 - S_2) \cdot C_{12} - Q \end{cases} \quad (2)$$

where S_1, S_2 - respectively, the movement of the DS upper and lower ends;

F - force corresponding to the reduced force to hook on the shaft of the drawworks (fig.3) is determined separately for lifting and lowering stages.

In particular, for the lifting stage ((fig.3a) the equation of motion (2)), we assume that the force F increases according to the linear law:

$$F = Q + q_F t$$

where $q_F = F_M / t_M$ - the characteristic of the force growth, being determined by the parameters of the tire-type pneumatic clutch, is described in detailes in work [21];

F_M - maximum value of force, which the clutch can transfer;

t_M - full time of the growth of force to the maximum value;

t - current time of the growth of force from $F = Q$ to $F = F_M$.

$C_{12} = \frac{C_w \cdot C_p}{C_w + C_p}$ - consolidated rigidity of the travelling block wirelines ($C_w = \frac{E_w \cdot A_w \cdot (U_{pb} - 2)}{h_t}$)

and drilling string pipes ($C_p = \frac{2 \cdot E_{dp} \cdot A_{dp}}{L_{dp}}$);

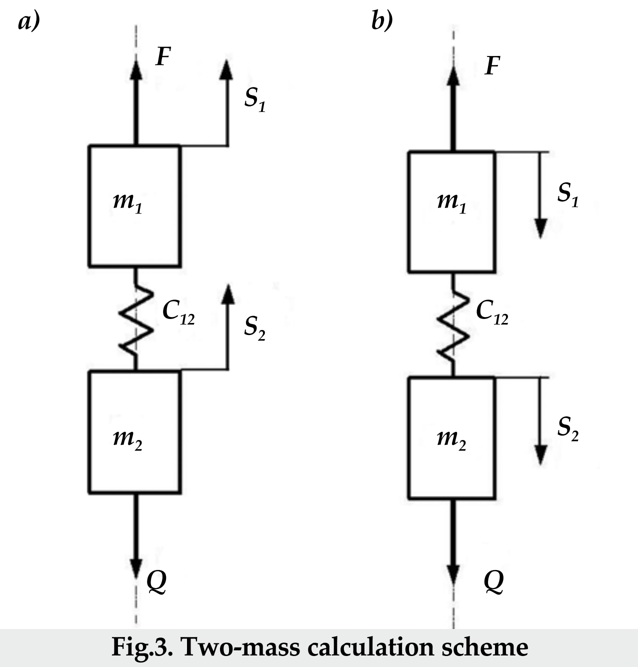

Fig.3. Two-mass calculation scheme of lifting a) and lowering; b) srtings of drill pipes

$m_1 = I_{wd} \cdot \left(\frac{U_{pb}}{r_p}\right)^2 + m_{tb} + m_p + m_w$ - consolidated mass of the drum of the drawworks and the travelling block;

m_{tb} - mass of travelling block (5000 kg);

$m_p = \frac{I_p \cdot U_{pb}}{6 \cdot r_p^{\,2}} \cdot \left(U_{pb}+1\right) \cdot \left(2U_{pb}+1\right)$ - consolidated mass of travelling block pulleys and the crown block;

$m_w = \frac{U_{pb}^{\,3} \cdot h_t \cdot q_w}{3g}\left(1 + \frac{3H}{U_{pb} \cdot h_t}\right)$ - consolidated weight of the wireline;

$m_2 = m_{wb} + \frac{1}{3} m_{dp}$ - consolidated mass of DP m_{dp} and weighted bottom m_{wb};

U_{pb} - multiplicity of the pulley block (10);

I_{wd} - moment of inertia of the winch drum (2250.0 kg/m^2);

I_p - moment of inertia of the pulley (75.25 kg/m^2);

h_t - length of the intermediate branch of the travelling block wireline (35 m);

r_p - radius of winding wireline on the winch drum (0.835 m);

E_w - modulus of elasticity of the wireline (1.2×10^{11} H/m^2);

E_{dp} - modulus of elasticity of DP material (2.1×10^{11} H/m^2);

A_{dp} - the cross-sectional area of the wireline (5.64×10^{-4} m^2);

A_w - the cross-sectional area of the DS pipe, m^2;

H - length of the driving side of the wireline (45 m);

q_w - weight of the linear meter of the wireline (50.0 kg/m).

To the system of equations (2) we add the initial conditions:

$$S_{12} = S_1 - S_2 = \frac{Q}{c_{12}}, \quad \dot{S}_{12} = \dot{S}_1 - \dot{S}_2 = V_{12} \qquad (3)$$

where V_{12} - speed of DS lifting.

Given that the force in the elastic element is determined by its deformation

$$FC = C_{12} \cdot (S_1 - S_2) = C_{12} \cdot S_{12}$$

let's put down one equation instead of the system of equations (2):

$$\frac{m_1 m_2}{C_{12}} \ddot{S}_{12} = m_2 F - \left(m_1 + m_2\right) \cdot S_{12} + m_1 Q \qquad (4)$$

The solution of this equation [22] considering the expression for F and the initial conditions (3) has the form

$$S_{12} = \frac{1}{p}\left(V_{12} - \frac{q_F}{m_1 p^2}\right)\sin pt + \frac{q_F t}{m_1 p^2} + \frac{Q}{C_{12}}$$

where $p = \sqrt{\frac{C_{12}\left(m_1 + m_2\right)}{m_1 m_2}}$.

The force in the elastic connection varies according to the law:

$$F_c = \frac{C_{12}}{p}\left(V_{12} - \frac{q_F}{m_1 p^2}\right)\sin pt + \frac{q_F t C_{12}}{m_1 p^2} + Q \qquad (5)$$

When calculating the force F_C, considered was the fact that the speed of DS lifting is interrelated with its length, that is, the load acting on the hook and is determined according to the regulation of the machine-manual and manual time for the rise and descent of pipes.

The results of the calculations of effort Q in the period of drilling string tripping operations according to equation 1 allows obtaining graphical dependence of the value of the static weight on the length of DS (fig.4, curves 1, 2).

The results of calculating the dynamic effort when lifting DS in accordance with equation 4, taking into account optimal rates of lifting the drill string, allows obtaining a graphical dependence of the magnitude of the strength of the elastic coupling on the length of the DS (fig. 4, curves 3, 4).

Determination of the force F_C during lowering (fig.3b) has its own peculiarity. The operation of DS lowering into the well is one of the most responsible in the performance of tripping operations and consists of three stages: acceleration, DS steady motion and braking [13,21]. The influence of dynamic loads during DS lowering was determined by using the calculation scheme (fig.3b).

Differential equations of motion are recorded:

$$\begin{cases} m_1 \cdot \ddot{S}_1 = (S_1 - S_2) \cdot C_{12} - F \\ m_2 \cdot \ddot{S}_2 = Q - (S_1 - S_2) \cdot C_{12} \end{cases} \qquad (6)$$

where, the force F which is characterized by the action of the braking moment on the tape brake,

can be established due to various laws, which are determined by the subjective characteristics of drill operators [13, 21]. Therefore, in the calculations we adopted the following:

- stage of acceleration: the movement of the srting downward will begin when the value of force F will be equal to the DS pipes weight Q.

$$F = Q\,(1 - t/t_1)$$

where t_1 - the time of the braking force completion.

- stage of stabilized motion: $F = 0$

- stage of braking: the braking force F increases and changes according to the linear law:

$$F = q \cdot t$$

where $q = F_{\max}/t_m$ - the intensity of the braking force growth from 0 to the maximum value of $F_{\max}$;

t_m - time of the growth of force.

Initial conditions are added to the system of equations (6)

$$S_{12}(0) = S_2(0) - S_1(1) = Q/C_{12}$$

$$\dot{S}_{21}(0) = \dot{S}_2(0) - \dot{S}_1(0) = 0$$

At each of the stages of the DS descent, the system (6) was solved considering initial conditions. Moreover, under the initial conditions for each next

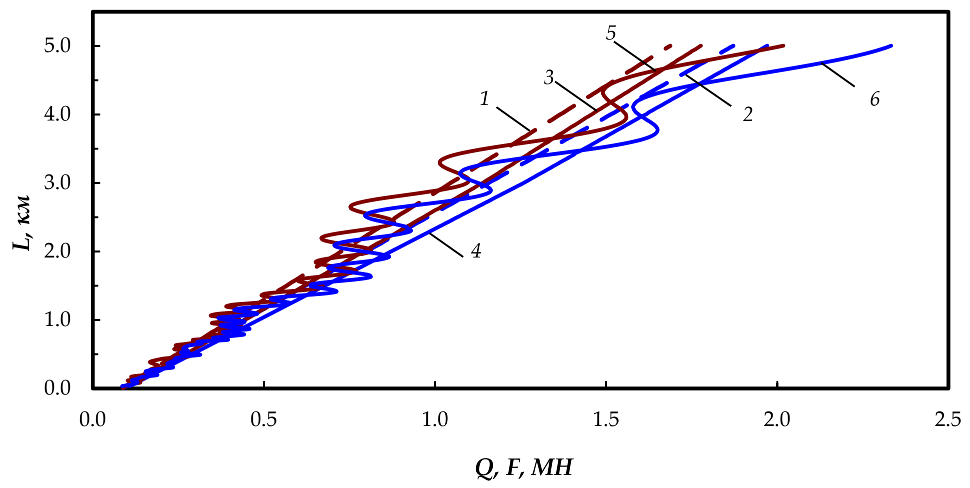

Fig.4. General scheme for determining the characteristic depth of the transverse annular crack [27]

stage, the deformation and velocity of the elastic element are taken at the end of the previous one.

The main attention in the DS pipes lowering is drawn to the dynamic processes taking place at the final stage of the movement, that is, during the period of braking [24, 25] and are described by the system of equations 6.

The solution of the system of equations 6 [22] has the form

$$S_{21} = A \cdot \sin pt + B \cdot \cos pt + \frac{q \cdot t}{p^2 \cdot m_1} + \frac{Q}{p^2 \cdot m_2}$$

which allows us to calculate the strength of the elastic connection, varying according to the law

$$F_C = \left(A \cdot \sin pt + B \cdot \cos pt + \frac{q \cdot t}{p^2 \cdot m_1} + \frac{Q}{p^2 \cdot m_2} \right) \cdot C_{12} \quad (7)$$

Constant integration of A and B is found taking into account the initial conditions

$$A = \frac{1}{p} \cdot \left(V_{21}(t_2) - \frac{q}{p^2 \cdot m_1} \right); \qquad B = S_{21}(t_2) - \frac{Q}{C_{12}} \quad (8)$$

where $S_{21}(t_2)$, $V_{21}(t_2)$ – deformation and velocity of the elastic element at the end of the second stage of the string movement, which we find by substituting the values t_2=t_2 into the expressions.

$$S_{21} = \frac{V_{12}(t_1)}{p} \cdot \sin pt + (S_{21}(t_1) - \frac{Q}{p^2 \cdot m_2}) \cdot \cos pt + \frac{Q}{p^2 \cdot m_2} \quad (9.1)$$

$$V_{21} = V_{21}(t_1) \cdot \cos pt - (p \cdot S_{21}(t_1) - \frac{Q}{pm_2}) \cdot \sin pt \quad (9.2)$$

The results of calculations of the dynamic force during the descent at the stage of braking considered strings of drill pipes according to equation 6, taking into account equations of deformation 9.1 and velocity 9.2 of the elastic element at the end of the second stage of the string motion, allows us to obtain a graphical dependence of the value of the coupling elastic force on the length of the DS (fig.4, curves 5, 6).

1.2. Evaluation of the failure conditions of ds elements with available crack-like defects of targeted shapes

An assessment of the conditions for the failure of DS elements containing an external or internal annular crack and are under the action of the axial load was carried out using appropriate analytical dependences [27] to determine the parameters of the stress intensity coefficients K_I and the rate of their change (dK_I/d_t). In this case, the index «resistance of the structural element to the crack propagation» was determined, that is, the depth of the crack $(a/t)^*$, at which the rate (dK_I/d_t) of change of the coefficient K_I of stresses intensity sharply increases [27]. The magnitude $(a/t)^*$ is a characteristic parameter, in which achievement the likelihood of DS failure dramatically increases. For its determining according to the method [27], a dimensionless dependence of the following type was built

$$\frac{\sqrt{t}}{\sigma} \frac{dK_I}{da} = F\left(\frac{a}{t}\right) \quad (10)$$

where σ - the applied external load; t - thickness of the structural element at the point of fracture.

With step a/t=0.01 the current values were calculated dK_I/d =F(a/t) (fig.5) and three points were determined in the vicinity of which the following conditions were executed:

$$\begin{aligned} &(dK_I/da)_{i+1} - (dK_I/da)_i = 0.01 \to (a/t)_1 \to 1 \\ &(dK_I/da)_{i+1} - (dK_I/da)_i = 0.10 \to (a/t)_2 \to 2 \\ &(dK_I/da)_{i+1} - (dK_I/da)_i = 1.00 \to (a/t)_3 \to 3 \end{aligned} \quad (11)$$

Due to the arguments of these points by the coordinates of the points L (0.5·[$(a/t)_1$+$(a/t)_2$], $(dK/da)_L$ and M (0.5·[$(a/t)_2$+$(a/t)_3$], $(dK/da)_M$ were determined. From the defined points L and M (fig.5) tangents were made. The argument of the intersection point of these tangents is the value of the depth of a characteristic defect $(a/t)^*$, at which the rate of change (dK_I/d) of the intensity stresses coefficients K_I dramatically increases.

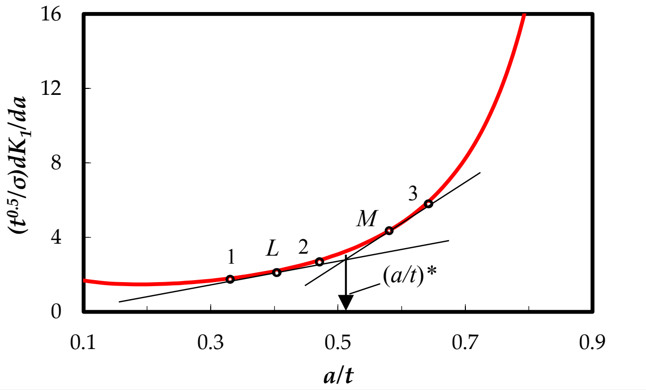

Fig.5. General scheme for determining the characteristic depth of the transverse annular crack [27]

1.3. Evaluation of the conditions of DS elements failure

For an adequate assessment of the conditions of the DS failure during tripping operations it is necessary to obtain experimental data that would reflect the change in the properties of the DS metal during their prolonged operation, that is, to take into account the process of drill pipes metal degradation (aging).

The failure of DS metal was evaluated according to the pover [28] criterion: the crack should begin to spread if the intensity of released energy J reaches a critical magnitude J_C.

$$J_* = J_C \qquad (12)$$

The critical crack resistance J_C of DS metal was determined according to the method [29]. The significance of the stress intensity factor K_{J_c} was calculated using the ratio [29]

$$K_{J_c} = \sqrt{\frac{J_C \cdot E}{(1-\mu^2)}} \qquad (13)$$

where J_C - critical crack resistance;

E - Jung module ($E = 10^{11}$ Pa);

μ - Poisson coefficient (for low-alloy steels μ=0.3).

In addition, the cause of destruction in some cases [1-5, 9] is the formation of corrosion-fatigue cracks both on the external or internal surface of the DS and the elements of their threaded connections. According to the diagnostic control data, such cracks originate at the bottom of corrosive pits, technological lines, near stress concentrators (for example, the first stage recess of both the outer and inner threads of the tool joint) or in the zone of thermal impact of the drill pipe with the welded joints. At first, they acquire a semi-elliptical shape (a/c) with pumice sizes a and c, however, developing in the process of operation, form transverse annular cracks with a relative depth (a/t), where t - the thickness of the drill pipe wall. Therefore, it is necessary to apply the appropriate calculation scheme [30], which describes the conditions under which the destruction of the DS is possible. It should also take into account the weight of the instrument (a bit) and the DS, which includes a kelly (square rod), a drill pipe, tool joints, couplings, an adapter, a DS centralizer and weighted drill pipes (WDP), i.e. static load, and also consider the impact of dynamic processes during tripping operations.

Estimated data were obtained using the results of calculation and experimental tests for the evaluation of the destruction of non-operated (127 · 9) and operated (127 · 8) metal of drill pipes. Moreover, the main parameters that allow us to determine the conditions for the destruction of the drill string elements are:

- the depth of the inner or outer circular transverse cracks in the drill pipe a_c;
- the weight of the DS.

2. Results of calculation and experimental researches and their discussion

2.1. Determination of critical crack resistance jc of DS metal

The material of the study was the fragments of non-operated or short-term operated (hereinafter - reserve) and operated (for 23 years) drill pipes with a conventional diameter of 127 mm of strength group «L».

The chemical composition of the investigated steels is given in table 1.

The mechanical characteristics of the reserve and continuously operated (for 23 years) drill pipes (see Table 1) made of steel (36G2S) were determined according to the standard procedure [31] by testing cylindrical specimens on stretching. Their values are given in table 2.

For the experimental determination of the value J_C five samples were cut out from the fragmentation

Table 1

Chemical composition of the studied steel drill pipes

Steel 36G2S (reserve)								
Mass fraction of elements, %								
C	Mn	Si	V	Cu	Al	Ni	S_{max}	P_{max}
0.36	1.68	1.02	0.12	0.09	0.22	0.08	0.014	0.012
Steel 36G2S (reserve)								
Mass fraction of elements, %								
C	Mn	Si	V	Cu	Al	Ni	S_{max}	P_{max}
0.38	1.52	0.92	0.09	0.13	0.04	0.09	0.018	0.016

Table 2

Mechanical characteristics of reserve (1) and operated (2) drill pipes (36G2S steel)

№	$\sigma_в$, MPa	$s_{0,2}$, MPa	δ, %	ψ, %
1	623.5	545.4	20.3	57.4
2	790.0	605.0	12.5	27.0

of both the reserve drill pipe and continually operated drill pipe of the strength group «L» with the dimensions 100.0 · 10.0 · 9.0 mm.

Scheme of cutting samples is shown in figure 6a. The basis for the experiments was a technique [29], however, taking into account the potential danger of existing defects, we used a non-standard sample (fig.6b,d) based on the size of the explored drill pipes. Experiments were conducted in the open air at temperature (T=20 °C). The samples were loaded according to the scheme of three point bends (fig.6c) at a distance between the supports 36 mm. The loading speed on the sample was 1.67·10^{-5} mm/c and remained constant during all tests.

The characteristics of critical crack resistance (tabl.3) were presented as a critical stress intensity factor K_{J_c}, which was calculated by using equation 13.

2.1. Evaluation of the conditions of the drill pipe failure with the external transverse annular crack being under the effect of the axial load

To determine the conditions under which the destruction of the studied drill pipe of the strength groups «L» containing the outer transverse annular crack with the depth (a/t), the calculation scheme depicted in figure 7a was considered.

In the calculation of the values of the stress intensity factor K_1 of along the front of the outer transverse annular crack (fig.7a), dependence [32] was used:

$$K_I = \sigma \cdot \sqrt{\pi \cdot \alpha} \cdot \frac{F}{\sqrt{Y}} \tag{14}$$

where

$$F = \frac{1 - R_{ia}^2}{\left[1 - \left(1 - R_{ia}\right)\frac{a}{t}\right]^2 - R_{ia}^2}$$

$$R_{ia} = \frac{R_i}{R_i + t}$$

$$Y = 0.8 + \left(1 - R_{ia}\right) \cdot \frac{a}{t} \cdot \frac{H}{\left[1 - \left(1 - R_{ia}\right) \cdot \frac{a}{t}\right]}$$

$$H = 4 + 1.08 \cdot \frac{R_{ia}}{\left(1 - R_{ia}\right) \cdot \left(1 - \frac{a}{t}\right)}$$

Table 3

The value of critical stress intensity factors K_{J_c}

Pipe	Group of strength	Time of operation, years	K_{J_c}, $MPa\sqrt{m}$					$K_{Jc}^{av.}$, $MPa\sqrt{m}$
36G2S	L	0	145.2	144.7	142.7	135.3	146.2	142.8
		23	105.8	98.8	99.9	96.9	93.6	99.0

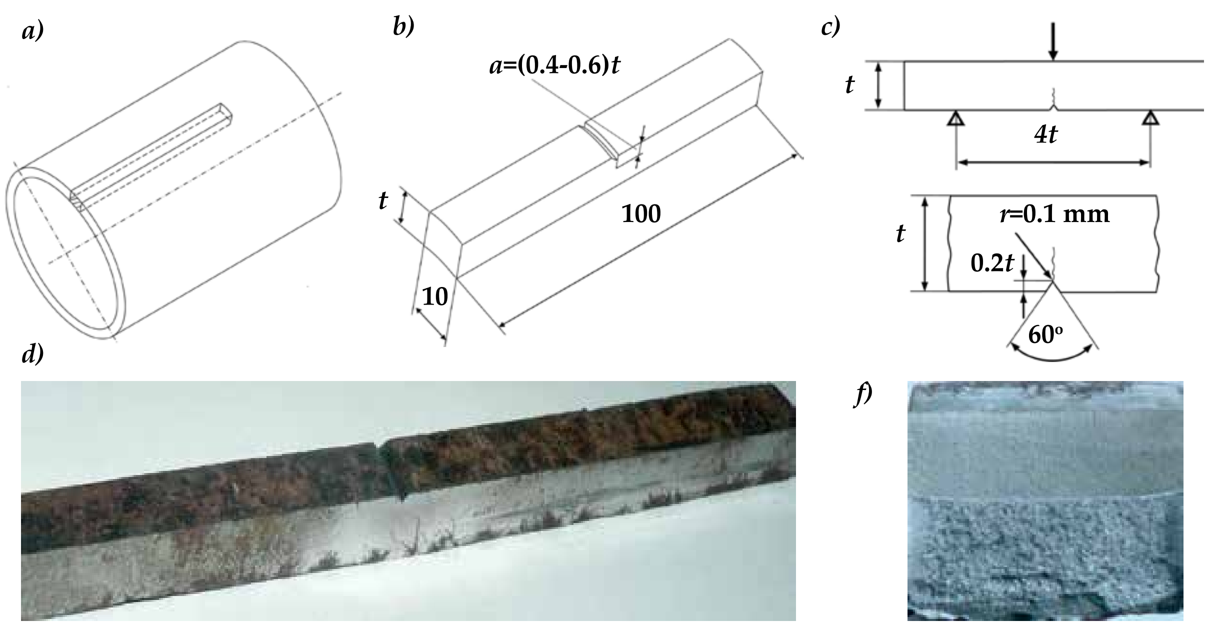

Fig.6. The cutting out pattern a) and the sample load c), its dimensions b) and overall view (d) and the distorted surface of the sample f) after the static crack resistance test

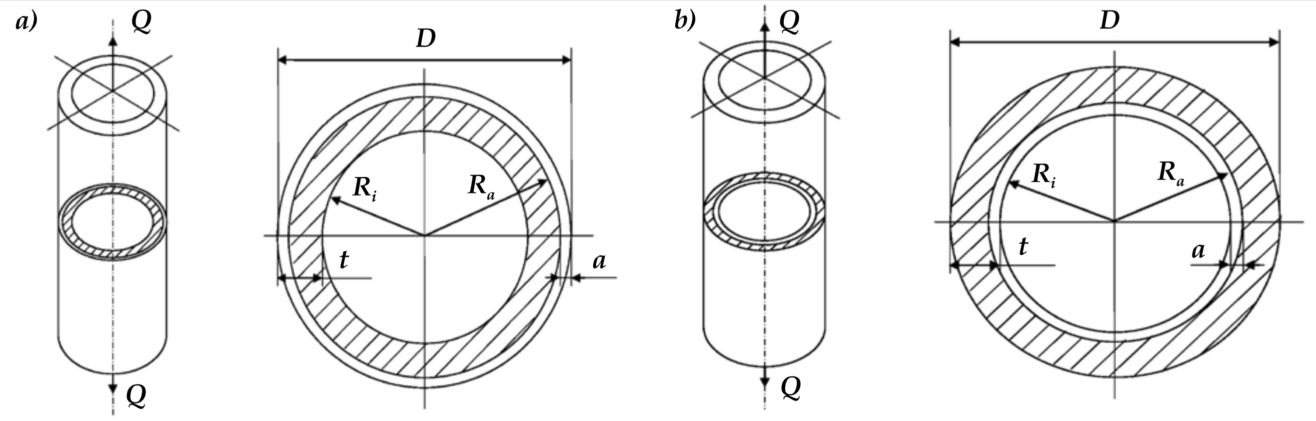

Fig. 7. Hollow cylinder with the external a) and internal b) transverse annular crack under the action of axial load [32]

The critical depth of the outer transverse annular crack a_C was determined from dependence (14), provided that $K_I = K_{Jc}$, taking into consideration given depth of the well, that is, the weight of the DS

$$a_C = \frac{K_{Jc} \cdot Y}{\pi \cdot \sigma^2 \cdot F^2} \qquad (15)$$

where $\sigma = Q/S_f^*$, S_f^* – the area of destruction.

To determine the characteristic depth of the fatigue crack $(a/t)^*$, at which the rate of change (dK_I/da) in the stress intensity factor K_I increases dramatically, dependence [32] was used:

$$\frac{dK}{da} = 0.5 \cdot \sigma \cdot \sqrt{\frac{\pi}{a}} \cdot \frac{F}{\sqrt{Y}} + \sigma \cdot \sqrt{\frac{\pi \cdot a}{Y}} \cdot \frac{dF}{da} - 0.5 \cdot \sigma \cdot \sqrt{\pi \cdot a} \cdot \frac{F}{Y^{1.5}} \cdot \frac{dY}{da} \qquad (16)$$

where

$$\frac{dF}{da} = \frac{2 \cdot (R_{ia} - 1) \cdot \left[\frac{a \cdot (R_{ia} - 1)}{t} + 1 \right] \cdot (R_{ia}^2 - 1)}{t \cdot \left\{ \left[1 - (1 - R_{ia}) \cdot \frac{a}{t} \right]^2 - R_{ia}^2 \right\}}$$

$$\frac{dH}{da} = 1.08 \cdot \frac{R_{ia}}{t \cdot (1 - R_{ia}) \cdot \left(1 - \frac{a}{t}\right)^2}$$

$$\frac{dY}{da} = \frac{(1 - R_{ia})}{t \cdot \left[1 - (1 - R_{ia}) \cdot \frac{a}{t} \right]} \cdot \left\{ H + a \cdot \frac{dH}{da} + \frac{H \cdot a \cdot (1 - R_{ia})}{t \cdot \left[1 - (1 - R_{ia}) \cdot \frac{a}{t} \right]} \right\}$$

Consideration was given to the case of reserve D=126 mm, t=9.0 mm and operated D=126 mm, t=8.0 drill pipes of the strength group «L» failure. For these cases, the corresponding dimensionless dependence of type 3 (fig.8a) was constructed and on its basis, the relative depth of the characteristic defect, which for the cases under consideration is $(a/t)^*$=0.535.

Using dependence (15), we established the relationship between the critical depth of the outer transverse annular fatigue crack a_c/t and the dynamic force F (fig.9), which depends on the length of the DS, taking into account the features of metal destruction (fig.6) of the studied drill pipes of the strength group «L».

The results of the calculations presented graphically (fig.9) give grounds to conclude that external transverse annular cracks are critical for non-operated drill pipe metal of the strength group «L» during the descent to a depth from 2900 m to 5000 m (1.2 MH ≤ F ≤ 2.3 MH) cracks in range of 4.8 mm ≤ F ≤ 3.2 mm (fig.9, curve 1, section I (C'A')) are critical, while at depths from 400 m to 2900 m fatigue cracks with a depth of a^*=4.8 mm (fig.9, section II (BC`)) are dangerous.

For the metal of the operated drill pipe of the strength group «L» during the descent at depths from 1700 m to 5000 m (0.79 MH ≤ F ≤ 2.0 MH) external cross-sectional annular cracks in range of 4.3 mm ≥ a_c ≥ 2.2 mm are critical (fig.9, curve 2, section I (CA)), whereas at depths from 400 m to

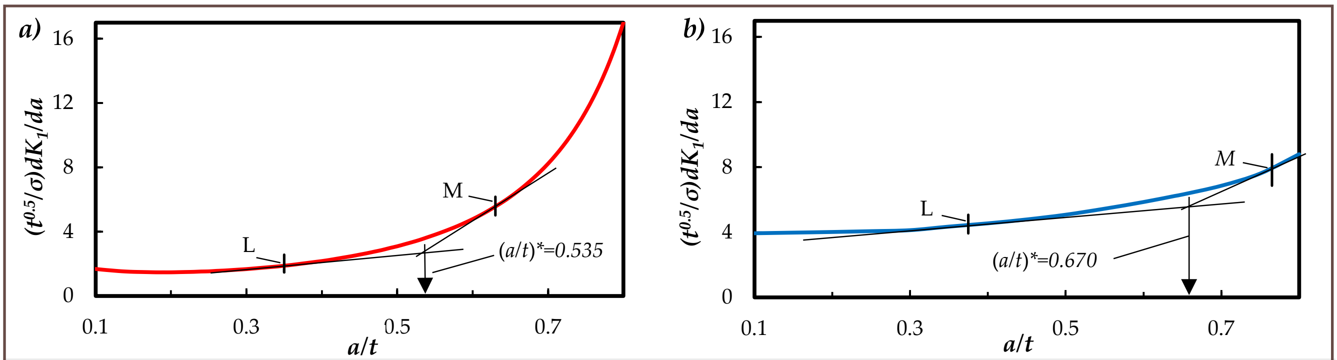

Fig.8. Estimation of the characteristic depth of the external a) and internal b) transverse annular crack in the wall of the reserve and operated drill pipes of the strength group «L» according to the axial load

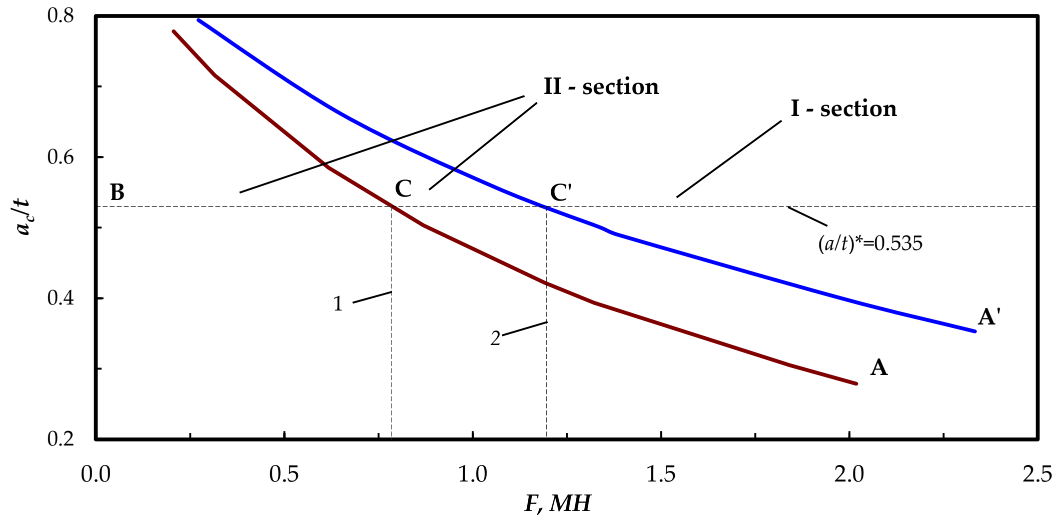

Fig.9. Interconnection of the critical (a_c/t) depth of the outer transverse annular crack in the wall of the operated (1) and reserve (2) drill pipes of the strength group «L» and the force of the elastic coupling (*F*) during the descent of the DS

1700 m fatigue cracks with a depth of a^*=4.3 mm are dangerous (fig.9, part II (BC)).

2.2. *Evaluation of the conditions of the drill pipe failure with the internal transverse annular crack being under the effect of the axial load*

To determine the conditions under which the destruction of the studied drill pipes of the strength group «L» containing the internal transverse annular crack (fig.7b) with *a* depth $(a/t)^*$ is possible, dependence [32] which determines the value of the stress intensity factor K_I on the top of such crack was used:

$$K_2 = \sigma \cdot \frac{F}{\sqrt{1-\frac{a}{t}}} \mp \sqrt{\pi \cdot a} \qquad (17)$$

At the same time, the rate of change (dK_I/da) in the stress intensity factor K_I is equal to

$$\frac{dK_{Ia}}{da} = \sigma \cdot \frac{dF}{da} \cdot \frac{\sqrt{\pi \cdot a}}{\sqrt{1-\frac{a}{t}}} + \frac{\sigma \cdot F}{2 \cdot t} \cdot \frac{\sqrt{\pi \cdot a}}{\left(1-\frac{a}{t}\right)^{\frac{3}{2}}} + \frac{1}{2} \frac{\sigma \cdot F}{\sqrt{1-\frac{a}{t}}} \cdot \sqrt{\frac{\pi}{a}} \qquad (18)$$

where the function *F* and the rate of its change *dF/da* are determined by functional series, which depend on the ratio R_I/R_a [32] ($R_a = R_I + a$).

The characteristic depth of the internal transverse annular crack $(a/t)^*$ for the investigated fragments of the reserve and operated drill pipes of the strength group «L» (*D*=126 mm, *t*=9.0 mm) and (*D*=126 mm, *t*=8.0 mm) was determined. For this purpose, the dimensionless dependence of the type

$$\frac{\sqrt{t}}{\sigma} \frac{dK_I}{da} = F\left(\frac{a}{t}\right)$$

(fig.8b) and the place with a sharp increase in the rate of change (dK_I/da) of the stress intensity factor K_I was established during drill pipes desent. In accordance with the method described above [27], the coordinates of the points L $\left(0.5 \cdot \left[(a/t)_1 + (a/t)_2\right],\ (dK/da)_L\right)$ and M $\left(0.5 \cdot \left[(a/t)_2 + (a/t)_3\right],\ (dK/da)_M\right)$ were determined.

The characteristic depth of the internal transverse fatigue crack for the investigated reserve drill pipe of the strength group «L» is equal to a^*=6.0 mm, and the operated drill pipe of the same strength group is equal to a^*=5.4 mm.

The interconnection between the critical depths of the internal transverse fatigue crack *ac/t* for the investigated drill pipes and the dynamic force *F* depending on the depth of the well has been established.

The results of the calculations (fig.10) give grounds to conclude that during lowering for the reserve drill pipe of the strength groups «L» at depths from 1200 m to 5000 m (0.56 MH ≤ *F* ≤ 2.3 MH) for the drill pipe metal critical are the internal transverse annular cracks in the range 6.0 mm ≥ a_c ≥ 3.0 mm (fig.10, curve 1 (C' A'), section I), whereas at depths from 400 m to a depth of 1200 m for the reserve drill pipe of the strength group «L» internal transverse annular cracks with a length a^*=6.0 mm are more dangerous (fig.10, section II (B' C')).

For the operated drill pipe of the strength group «L» at depths from 500 m to 5000 m (0.31 MH ≤ *F* ≤ 2.0 MH) critical for the drill pipe metal are inner transverse annular cracks in the range 5.4 mm ≥ a_c ≥ 2.0 mm (fig.10, curve 2 (CA), section I), and for the operated drill pipe of this strength group at depths from 400 m to 500 m, internal transverse annular cracks with a depth of a^*=5.4 mm are dangerous (fig.10, section II, (BC)).

3.3. *Discussion*

The obtained results allow us to interpret a significant increase in the number of failures of drill string elements during tripping operations, described in [1-5].

The analysis of the results of the performed calculation and experimental studies testifies that in order to assess the conditions for the destruction of reserve and long-term operated drill pipes of the strength group «L» containing transverse annular

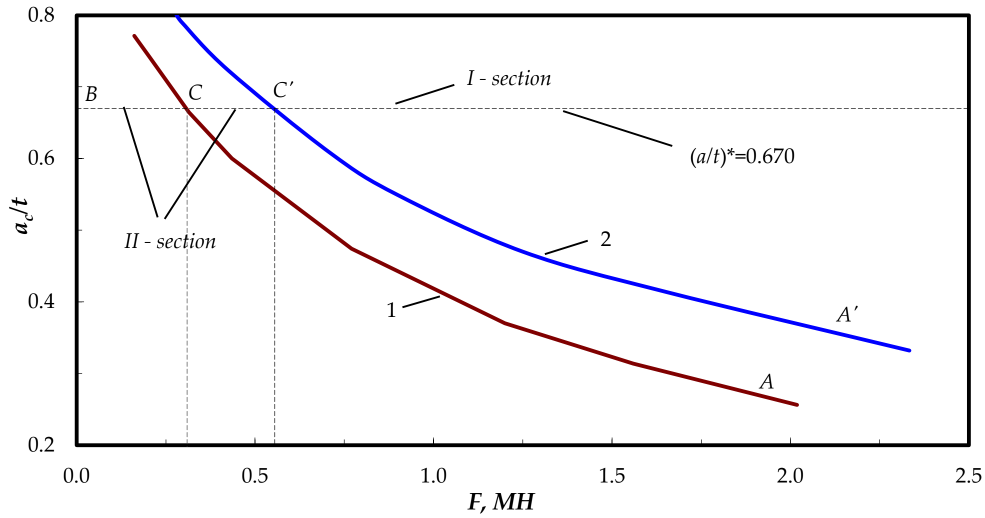

Fig.10. Interconnection of the critical (a_c/t) depth and internal transverse annular crack in the wall of the operated (1) and the reserve (2) drill pipes of the strength group «L» and the strength of the elastic connection (*F*) at the descent of the DS

cracks, it is necessary to take into account:

- impact of dynamic loads;
- durability of drill pipes operation, i.e. metal degradation;
- the nature of the placement of the transverse annular crack (external or internal);
- at the small depths of drilling, the index of «structural element resistance to crack growth».

Note, that the value of the critical stress intensity factor K_{J_c} as a characteristic of the power criterion for the drill pipes metal fracture depending on the operating time decreases with increasing durability of their operation. In this connection, the depth at which it is necessary to take into account the magnitude of K_{J_c} – section I (CA and C'A') in figures 9 and 10. Thus, for reserve pipes containing an outer circular crack it is 2900 m, and for 23-year operated pipes it decreases to 1700 m. For reserve pipes that contain an inner circular crack it is 1200 m, and for 23-year operated pipes it decreases to 500 m.

Thus, the determining factor, which leads to a significant increase in the number of DS failures with external transverse annular cracks during the descent of 23-year operated drill pipes and reserve pipes at depths in the range of 1600 – 2900 m, and for similar drill pipes containing internal transverse annular cracks during tripping operations at depths in the range of 500 - 1200 m is the loss of drill pipes metal resistance to cracks propagation.

Moreover (tabl.4, 5), external circular cracks are more dangerous for reserve pipes at depths up to 2000 m, whereas internal transverse annular cracks are more dangerous within the range of depths from 2000 m up to 5000 m. For 23-year operated pipes, external circular cracks are at a depth of up to 1200 m, whereas internal transverse annular cracks are more dangerous in the depth range from 1200 m to 5000 m.

It should be noted that the determining factor stipulating the predominant influence of external circular cracks at low depths (up to 2000 m for reserve pipes and up to 1200 m of operated 23 years pipes) is the characteristic depth of the fatigue crack *a**, while at greater depths the determining factor

Table 4

The values of the depth of the critical a_c (characteristic (a^*)) external transverse annular cracks for drill pipes of the strength group «L»

Critical external transverse annular crack a_c (a^*), mm					
L, m	Static weight of drilling string *Q*		*L*, m	Dynamic force of elastic coupling *F*	
	reserve	operated		reserve	operated
500	7.2 (4.8)	6.0 (4.3)	400	7.1 (4.8)	6.4 (4.3)
1000	6.6 (4.8)	5.4 (4.3)	1000	6.3 (4.8)	5.2 (4.3)
2000	5.6 (4.8)	4.4 (4.3)	1700	5.5 (4.8)	4.3(4.3)
2100	5.5 (4.8)	4.3 (4.3)	2000	5.3 (4.8)	4.2
3000	4.8 (4.8)	3.7	2900	4.8 (4.8)	3.6
4000	4.3	3.0	4000	3.8	2.8
5000	3.8	2.7	5000	3.2	2.2

that substantiates the conditions for the DS failure during tripping operations is the magnitude of the critical stress intensity factor K_{Jc}.

In addition, it is necessary to pay attention that the dynamic loads compared with the static ones during lowering operated pipes, containing the outer circular crack affect more at depths exceeding 1700 m, and for drill pipes with an internal circular crack - this effect is manifested from 700 m (tabl.4, 5).

Table 5

The values of the depth of the critical a_c (characteristic (a*)) internal transverse annular cracks for drill pipes of the strength group «L»

Critical external transverse annular crack a_c (a*), mm					
L, m	Static weight of drilling string *Q*		*L*, m	Dynamic force of elastic coupling *F*	
	reserve	operated		reserve	operated
500	7.2 (6.0)	5.7 (5.4)	400	6.8 (6.0)	5.7 (5.4)
700	7.0 (6.0)	5.4 (5.4)	500	6.7 (6.0)	5.4 (5.4)
1000	6.5 (6.0)	5.0	700	6.5 (6.0)	4.8
1250	6.0 (6.0)	4.7	1200	6.0 (6.0)	4.4
1400	5.9	4.4	1400	5.5	4.2
1700	5.5	4.2	1700	5.2	3.9
2000	5.3	4.0	2000	5.0	3.7
3000	4.6	3.4	2900	4.4	3.1
4000	4.0	2.8	4000	3.7	2.5
5000	3.7	2.3	5000	3.0	2.0

Conclusions

1. An experimental and calculation procedure was proposed for evaluating the conditions of critical fracture during tripping operations of operated drill pipes with an external or internal transverse annular crack.

2. An experimental evaluation of the critical stress intensity factor K_{Jc} of the metal of reserve and long-term operated drill pipes for the strength group «L» was carried out.

3. It was established that the failure of reserve drill pipes of the strength group «L» with an external transverse annular crack at depths exceeding 2900 m is determined by the critical crack growth resistance of the pipes metal, and at depths up to 2900 m – it is an indicator «of the structural element resistance to the crack growth». While for drill pipes with an internal transverse annular crack at depths from 1200 m to 5000 m, it is determined by the crack growth resistance of the pipes metal, and at depths up to 1200 m - it is an indicator «of the structural element resistance to the crack propagation" .

4. It was shown that the failure of the long-term operated drill pipes of the strength group «L» with an external transverse annular crack at depths of more than 1700 m is determined by the critical crack growth resistance of the pipes metal, and at depths up to 1700 m - it is an indicator «of the structural element resistance to the crack propagation». For similar drill pipes with an internal transverse annular crack at depths of up to 5000 m, it is determined by the crack growth resistance of the pipes metal, and at depths up to 500 m – it is an indicator of «the structural element resistance to the crack propagation».

5. Estimation of the conditions of equally loaded drill pipes critical failure during tripping operations confirms that dynamic loads compared with static ones at the descent of operated drill pipes containing the outer circular crack more significantly affect at the depths over 1700 m, and for drill pipes with an inner circular crack this effect becomes apparent from 700 m.

6. It has been shown that internal transverse annular cracks during descending operated drill pipes at depths exceeding 1400 m are more dangerous than external ones, while at depths up to 1400 m outer cross-sectional circular cracks are more dangerous.

7. The results obtained can be used to interpret the results of technical diagnostics of both prolonged and short-term operated drill pipes.

References

1. Pokhmursky, V. I., Kryzhanivsky, Ye. I., Ivasiv, V. M., et al. (2006). Mechanics of fracture and strength of materials: reference manual /Ed. Panasyuk, V. Vol. 10. Strength and durability of oil and gas equipment. Lviv-Ivano-Frankivsk: *Institute of Physics and Mechanics named after. G.V. Karpenko National Academy of Sciences of Ukraine; IFNTUOG.*

2. Artym, V., Yatsyniak, I., Hrytsiv, V. (2012). Analysis of corrosion-fatigue failure of drill string elements. *Exploration and Development of Oil and Gas Fields*, 2(43), 197-202.

3. Ivasiv, V., Hrydzhuk, Ya., Yurych, L. (2014). Analysis of the causes of drilling string elements failure. *Technological Audit and Production Reserves,* 6/4(20), 15-17.

4. Macdonald, K., Bjune, J. (2007). Failure analysis of drillstrings. *Engineering Failure Analysis,* 14(8), 1641-1666.

5. Zamani, S., Hassanzadeh-Tabrizi, S., Sharifi, H. (2016) . Failure analysis of drill pipe: A review. *Engineering Failure Analysis,* 59, 605-623.

6. Fangpo, L., Yonggang, L., Xinhu, W., Caihong, L. (2011). Failure analysis of J127mm IEU G105 drill pipe wash out. *Engineering Failure Analysis,* 18, 1867–1872.

7. Macdonald, K. (1994). Failure analysis of drill string and bottomhole assembly components. *Engineering Failure Analysis,* 1994, 1(2), 91–117.

8. Vaisberg, O. (2002). Fatigue of drillstring: state of the art. *Oil and Gas Scientific Technology*, 57(1), 3–37.

9. Kryzhanivskyi, E. (1990). Investigation and increase of fatigue resistance of drilling strings during rotary drilling of wells. Doctor's degree thesis. Moscow.

10. Information bulletin on accidents, complications and lack of work during well drilling in the Drilling Department «UKRBURGAZ» for 2015.

11. Information bulletin on accidents, complications and lack of work during well drilling in the Drilling Department «UKRBURGAZ» for 2016.

12. Saroyan, A. (1990). Theory and practice of the drilling string operation *Moscow: Nedra.*

13. Kerimov, Z. (1970). Dynamic calculations of the drill string. *Moscow: Nedra.*

14. Kalinin, S. (1975). Dynamics of the hoisting system of drilling rigs. *Lviv: Vyshcha Shkola.*

15. Kerimov, Z., Aliyev, A. (1981). On a task of optimizing tripping in drilling tools into a well. *Izvestiya vuzov. «Oil and Gas»*, 7, 20-23.

16. Kerimov, Z., Balakishiev, N. (1965). On the determination of the reduced mass of a drilling string. *Izvestiya vuzov. «Oil and Gas»*, 10, 31-34.

17. Kulizade, K., Saidov, A. (1963). Investigation of the starting mode of drawworks, taking into account the mechanical characteristics of the driving engine. *Izvestiya vuzov. «Oil and Gas»*, 7, 23-28.

18. Kulizade, K., Saidov, A., Kokov, P. (1965). The influence of the main parameters of the hoisting mechanism on its dynamics. *Izvestiya vuzov. «Oil and Gas»*, 6, 97-100.

19. Radzhabov, N. (1996). Scientific and practical methods of improving the design and forecasting the life of the main components and mechanisms of drilling and repair facilities. *PhD dissertation. Baku.*

20. Tarasevich, V. (1968). Basics of improving the performance of drilling rigs. *Moscow: Nedra.*

21. Malko, B. (1999). Dynamic characteristics of operating mechanisms of drilling and oil-field facilities and their optimization. *PhD dissertation. Ivano-Frankivsk.*

22. Malko, B. (1996). Acceleration of the travelling block with the drilling string during their lifting. Exploration and Development of Oil and Gas Fields. *Series «Oilfield Equipment»*, 33, 91-96.

23. Malko, B. (2002). Equation of the drilling string movement during descent into the well. *Exploration and Development of Oil and Gas Fields*, 2(3), 71-73.

24. Kharchenko, E. (1991). Dynamic processes of drilling rigs. *Lviv: Svit.*

25. Yurtayev, V. (1987). Dynamics of drilling rigs. *Moscow: Nedra.*

26. Malko, B., Ivasiv, V., Kozak, F., Ferynuk, M. (1998). Coefficient of dynamics of the drilling rig hoisting system // Exploration and development of oil and gas fields. *Series «Drilling Oil and Gas Wells»*, 2(35), 122-131.

27. Panasyuk, V., Dmytrakh, I., Toth, L., et al. (2014). A method for the serviceability and fracture hazard for structural elements with crack-like defects. *Materials Science*, 49(5), 565-576.

28. Rice, J. (1968). A path independent integral and the approximate analysis of strain concentration by notches and cracks. *Journal of Applied Mechanics,* 35, 379-386.

29. ASTM E1737-96. (1996). Standard test method for J-integral characterization of fracture toughness. *American Society for Testing and Materials.*

30. Vytyaz, O., Hrabovskyj, R. (2017). Express-evaluation of conditions of operated drill pipe elements failure during tripping operations. *Bulletin of the NTU «KhPI». Series «New Solutions in Modern Technologies»*, 7(1229), 30-38.

31. Friedman, Ya. (1974). Mechanical properties of metals. Mechanical tests. Design durability /in 2 vol. *Moscow: Mechanical Engineering.*

32. Harris, D. (1967). Stress intensity factor for hollow circumferentially notched round bars. Transactions of ASME. *Journal of Basic Engineering*, 89, 634-645.

Оценка условий разрушения труб бурильных колонн при спуско-подъемных операциях

Е.И.Крыжановский, О.Ю.Витязь, В.В.Тирлич, Р.С.Грабовский, В.И.Артым
Ивано-Франковский национальный технический университет нефти и газа, Ивано-Франковск, Украина

Реферат

Проведена экспериментальная оценка силового критерия разрушения металла резервных и продолжительно эксплуатируемых бурильных труб. Определены условия, при которых при спуско-подъемных операциях возможных разрушениях исследованных бурильных труб, содержащие внешние или внутренние поперечные кольцевые трещины. Установлена взаимосвязь между глубиной критических внешних или внутренних поперечных кольцевых трещин в бурильных трубах и весом бурильной колонны с учетом влияния динамических нагрузок при спуско-подъемных операциях. Показано, что внутренние поперечные кольцевые трещины при спуске эксплуатируемых бурильных колонн на глубинах более 1.4 км более опасны, чем внешние, в то время как на глубинах до 1.4 км более опасны внешние поперечные кольцевые трещины.

Ключевые слова: критический коэффициент интенсивности напряжений; критический размер внешней или внутренней поперечной кольцевой трещины; характеристическая глубина внешней или внутренней поперечной кольцевой трещины.

Endirmə-qaldırma əməliyyatları zamanı qazma kəmərinin borularının dağılma şərtlərinin qiymətləndirilməsi

E.İ.Krıjanivskiy, O.Yu.Vityaz, V.V.Tirliç, R.S.Xrabovskiy, V.İ.Artım
İvano-Frankovsk Dövlət Neft və Qaz Texniki Universiteti, İvano-Frankovsk, Ukrayna

Xülasə

Ehtiyatda olan və sürəkli istimar edilən qazma borularının metalının dağılmasının güc meyarı eksperimental olaraq qiymətləndirilmişdir. Endirmə-qaldırma əməliyyatları zamanı xarici və ya daxili eninə həlqəvi çatları olan tədqiq edilən qazma borularının mümkün dağılma şərtləri müəyyən edilmişdir. Endirmə-qaldırma əməliyyatları zamanı dinamiki yüklərin təsirinin nəzərə alınması ilə, qazma kəmərinin çəkisi ilə qazma borularında olan kritik xarici və ya daxili eninə həlqəvi çatların dərinliyi arasındakı qarşılıqlı əlaqə təyin edilmişdir. Göstərilmişdir ki, istismar boru kəmərinin 1.4 km-dən daha böyük dərinliklərə endirilməsi zamanı daxili eninə həlqəvi çatlar, 1.4 km-ə qədər olan dərinliklərdə isə xarici eninə həlqəvi çatlar daha təhlükəlidirlər.

Açar sözlər: gərginlik intensivliyinin kritik əmsalı faktoru; xarici və ya daxili enenə həlqəvi çatların kritik ölçüsü; xarici və ya daxili eninə həlqəvi çatlaqın xarakterik dərinliyi.