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ASSESSMENT OF DANGER OF LONG-TERM OPERATED COILED TUBING FAILURE

Abstract: The power criterion of the resistance to failure of the metal of coiled tubing (CT) was experimentally evaluated. The conditions are defined under which failure is possible during the operation of CT containing an external semi-elliptical crack. The interconnection of the critical depths of external semi-elliptical cracks from the ratio of their semiaxes is established. It is shown that, during the course of operation, the external transverse semi-elliptical crack with the ratio of semiaxes $(a/c)_i = 1/2$ is the most dangerous for coiled tubing. The experimental and calculation procedures are proposed that give us an opportunity to interpret the results of their technical diagnostics in evaluating the conditions under which the failure of flexible pipes containing outer transverse semi-elliptical cracks is possible during tripping operations.

Keywords: conditions for coiled tubing failure, critical factor of stress intensity, critical depth of external transverse semi-elliptical crack

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1. INTRODUCTION

The increase in oil and gas consumption has led to an increase in the production of hydrocarbon raw materials. One of the most promising directions for the development of drilling techniques as well as the development and repair of wells is a technology based on the use of flexible continuous metal pipes [1] – technology and finished product – pipe wound on the drum (Fig. 1). However, the flexible pipe is the most critical element of a coiled tubing unit (CTU), the destruction of which leads to significant material losses [2].

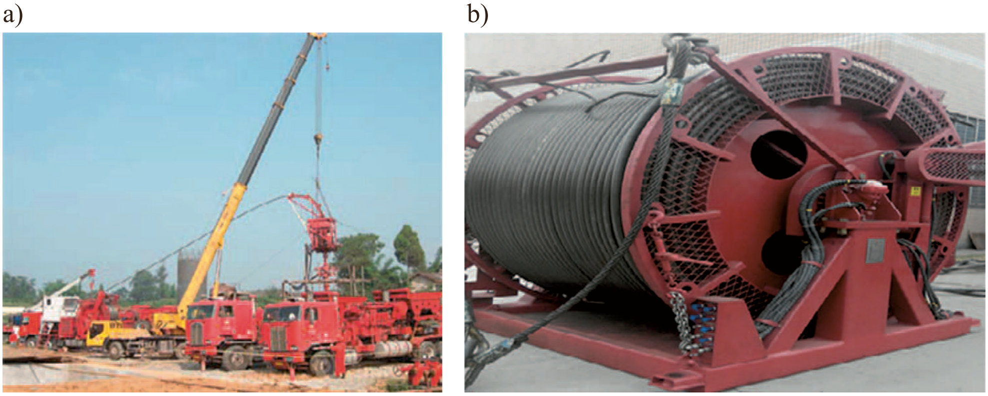

Fig. 1. Coiled tubing unit [2]: a) photo of CTU operation; b) CT wrapped to spool

The appearance of emergency situations in the operation of CTUs is due to the influence of many factors that are associated with significant working pressures during technological operations, the weight of the CT, and the effect of low-cycle bending loads in the elastic-plastic area of the metal pipe, with the influence of corrosive media, and as well as technological mechanical damage, which are concentrators of stress on the outer surface of the pipes; that is, the places of origin and development of crack-like defects [2, 4]. An analysis of CT destruction testifies that the cause was mechanical damage in one third of the cases. Corrosive and corrosion-fatigue damage was in another third of the cases. The remaining third of CT destruction is made up of manufacturing errors, factory technological defects in pipes, and erosion of the CT [2].

In this regard, the problem of assessing the actual and limiting state of CT metal for determining CT lifetime under operating conditions is relevant.

2. BASIC PART

The formation on the outer surface of CT corrosion-fatigue cracks is the reason for its destruction [3, 5, 6]. According to the diagnostic control, such cracks originate at the bottom of corrosive ulcers or technological risks (which are stress concentrators) under the influence of significant cyclic bending loads. They acquire a semi-elliptical shape (*a*/*c*) with semi axes sizes of *a* and *c*, which being developed, cause an emergency situation [6].

In modern engineering practice, the characteristics of the crack resistance of metals are considered as the most adequate basis for evaluating the residual resource and conditions for the destruction of structural elements in the operating environment. In this regard, a methodical procedure for assessing the conditions for the destruction of CT is 1) in the adequate choice of the appropriate design scheme that describes the conditions under which the destruction of CT is possible, and 2) in obtaining experimental data that reflects the conditions for the destruction of the exploited metal of the CT.

It is known [7] that the destruction of an element of a construction with existing cracks occurs when the crack near the peak within a sufficiently large area of stress exceeds the limit value. Since stress intensity factor K_I characterizes the stress field, the criterion of the boundary equilibrium of the body with a crack can be written as follows:

$$K_I = K_{Ic} \tag{1}$$

Value K_{Ic} characterizes the resistance of a solid body to the expansion of the crack in it and defines the cracking resistance with a flat deformation for the static load of the structural element.

In the course of an experimental determination of the conditions of destruction, it is necessary to take into account the fact that CT metal destruction by the development of transverse semi-elliptical cracks occurs under the conditions of flat stress state. In this case, the destruction of CT metal must be evaluated according to the energy [7] criterion: the crack begins to grow if the intensity of released energy J reaches critical value J_c.

$$J = J_c \tag{2}$$

We use method [8] that, by researching, allows us to determine the critical crack resistance J_c of CT metal on the basis of the experimentally obtained diagram of the sample destruction "force – deflection". The value of stress intensity factor K_{Jc} will be calculated according to ratio [8]:

$$K_{Jc} = \sqrt{\frac{J_c \cdot E}{(1-\mu^2)}} \tag{3}$$

where:

J_c – the critical crack resistance,
E – Young module ($E = 2.07 \cdot 10^{11}$ Pa),
μ – the Poisson coefficient (for low-alloy steels $\mu = 0.3$).

Determination of stress intensity critical factor K_{Jc} of long-term-operated CT metal

The research material is a fragment of CT with a diameter of 82.5 mm and a wall thickness of 7 mm that was used during the technological operations of well construction for more than 12 years.

The mechanical characteristics of the long-term-operated CT steel (Tab. 1) were determined according to the standard procedure [9] for testing fivefold cylindrical specimens for tension.

Table 1

Mechanical characteristics of CT steel

Grade of steel	σ_b [MPa]	$\sigma_{0.2}$ [MPa]	δ [%]	ψ [%]
Steel 45	890.7	810.9	7.0	31.5

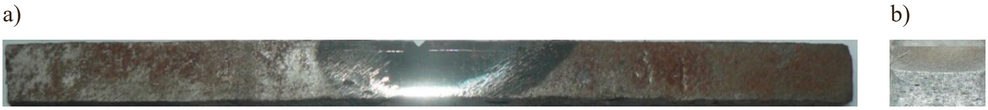

Fig. 2. General view of sample before experiment (a) and area of deformed surface of sample (b) after experiment on study of conditions for spontaneous failure of operated flexible (coiled tubing) pipe

An assessment of the conditions under which the destruction of the metal of flexible pipes occurs was carried out by method [8], experimentally determining value J_c. To do this, five samples from CT fragments with the dimensions of 150.0 mm × 10.0 mm × 7.0 mm were cut. The samples were loaded according to the scheme of a three-point bend at the distance of 30 mm between the supports ($L = 4h$). According to the experimental data, the destruction work was determined (shaded area of the diagram in Fig. 3).

$$A = \int_0^{f_{\max}} P(f)df \tag{4}$$

Value J_c was determined as work A (Fig. 3) spent on the deformation of the specimen with given crack l_{cep} (Fig. 2a) as an element of the construction in which it loses its bearing properties attributed to the net area of the deformed surface of sample S_f (Fig. 2b).

$$J_{Ic} = \frac{A}{S_f} \tag{5}$$

The critical crack resistance characteristics given in this paper (Tab. 2) were represented by stress intensity critical factor K_{Jc}, which was calculated using Equation (3).

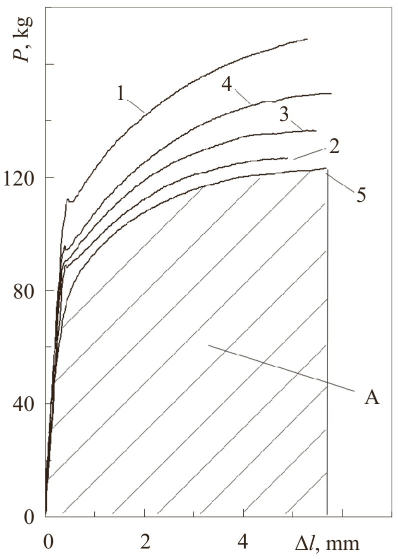

Fig. 3. Diagram of deformation force – compliance ($P - \Delta l$) of samples made from fragments of flexible pipe

Table 2

Value of stress intensity critical factors K_{Jc}

K_{Jc}^{i} [MPa$\sqrt{\text{m}}$]					K_{Jc}^{aver}[MPa$\sqrt{\text{m}}$]
1	2	3	4	5	average
218.8	191.7	211.3	207.8	189.9	203.9

Assessment of strength and risk of flexible pipe failure

In the process of tripping operations, CT undergoes significant low-cycle loads caused by bending moments occurring in the nodes of the CTU as well as the effects of working pressures inside the pipe, the impact of corrosive media, and the weight of the pipe. During a single typical technological cycle (tripping operation), separate areas of CT undergo six times the elastic-plastic deformation (Fig. 4): during lowering – when the tubing is unwound from the drum, bending while passing the guide arc, the straightening in the injector; during lifting – this process is repeated in reverse order. Therefore, the failure of CT during tripping operation is of a fatigue character [6, 10, 11]. The reason for the destruction of CT is the origin and development of external transverse semi-eliptical cracks under the influence of significant fatigue loads (Fig. 5).

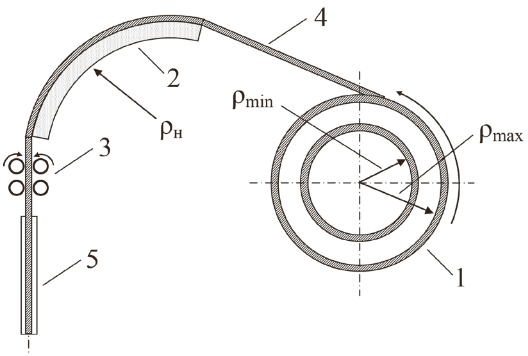

Fig. 4. Scheme of supplying flexible pipe into well
1 – drum, 2 – arch guide, 3 – injector, 4 – flexible pipe, 5 – well

An assessment of the conditions for the destruction of an element of CT with an external transverse semi-elliptical crack of given dimensions (a/c) being under the action of load will be carried out by using the appropriate analytical dependences [12] to determine stress intensity factor K_I. The obtained calculation data is compared to the results of the calculation and experimental evaluation of the destruction of the exploited CT metal. Moreover, the main parameters that allow us to determine the conditions for the destruction of the CT element are as follows:

- depth (a_c) and form (a/c) of the external transverse semi-elliptical cracks in CT;
- axial normal stresses arising from working pressures (σ_m) and bending loads (σ_b).

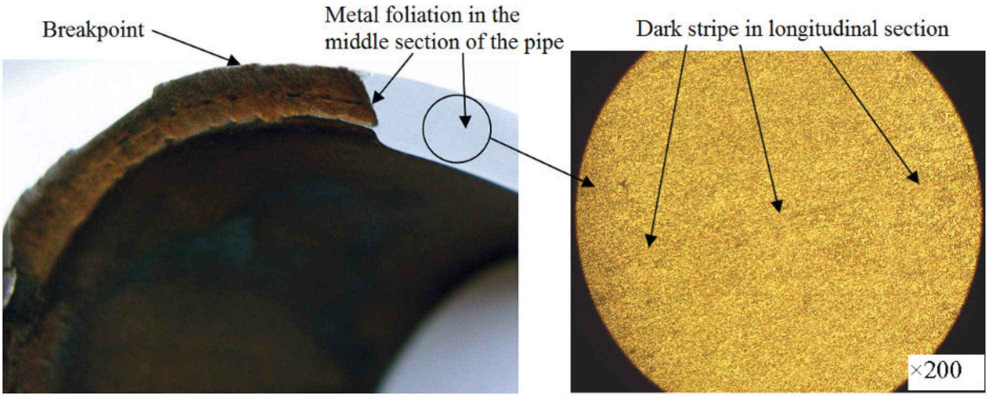

Fig. 5. General view of CT crack nucleus [6]

Consider the case of the destruction of a long-term-exploited flexible pipe (D = 82.5 mm, t = 7.0 mm) that contains an external transverse semi-elliptical crack that is under the influence of working pressures (p) and bending loads (σ_b).

In order to determine the conditions under which the failure of the explored flexible pipe with the outer transverse semi-elliptical (a/c) crack with a depth of (a/t) is possible, let us consider the calculation scheme shown in Figure 6.

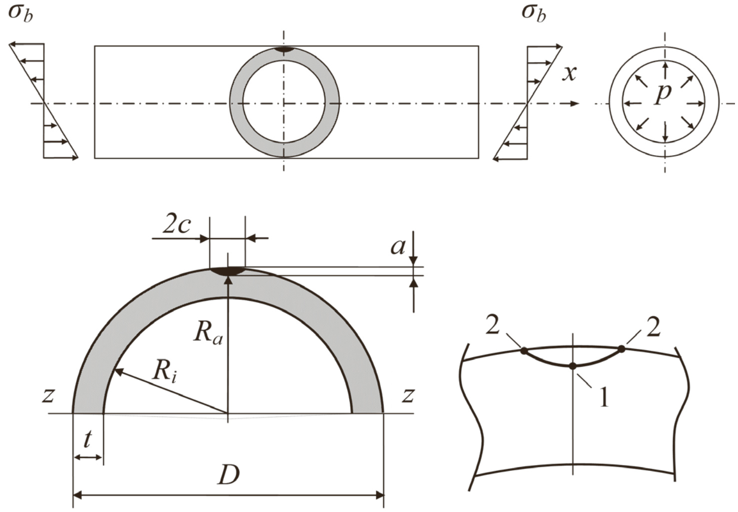

Fig. 6. Hollow cylinder with external transverse annular crack under axial load

When calculating the values of stress intensity factor K_1 in the characteristic points of the 1 (a) and 2 ($\pm c$) of the front of the outer transverse semi-elliptical (a/c) crack with a depth of (a/t) (Fig. 6), we use dependence [6]:

$$\begin{cases} K_a = \tau\left[\left(X_0 + Y_0\dfrac{a}{t}\right)\sigma_m + \left(X_1 + Y_1\dfrac{a}{t}\right)\sigma_b\right] \\ K_c = \tau\left[\left(Z_0 + U_0\left(\dfrac{a}{t}\right)^2\right)\sigma_m + \left(Z_1 + U_1\left(\dfrac{a}{t}\right)^2\right)\sigma_b\right] \end{cases} \tag{6}$$

where:

$$\sigma_m = \frac{p}{\left(\dfrac{R_a}{R_i}\right)^2 - 1}, \quad R_a = R_i + t - a, \quad \tau = \frac{\sqrt{\pi\dfrac{a}{Q}}}{f},$$

$$Q = 1 + 1.464\left(\frac{a}{c}\right)^{1.65},$$

$$f = 1 - 0.385\frac{t}{R_a}\frac{c}{t}\left[2.14\left(\frac{a}{c}\right) - 1.557\left(\frac{a}{c}\right)^2 + 0.417\left(\frac{a}{c}\right)^3\right],$$

$$X_0 = 1.135 - 0.135\left(\frac{a}{c}\right),$$

$$Y_0 = 0.5 - 0.663\left(\frac{a}{c}\right) + 0.266\left(\frac{a}{c}\right)^2 + \left[0.713 - 1.286\left(\frac{a}{c}\right) + 0.651\left(\frac{a}{c}\right)^2\right]\frac{t}{R_a},$$

$$X_1 = 1.093 - 0.1\left(\frac{a}{c}\right),$$

$$Y_1 = 0.936 - 1.758\left(\frac{a}{c}\right) + 0.903\left(\frac{a}{c}\right)^2 - \left[0.598 - 0.417\left(\frac{a}{c}\right)\right]\frac{t}{R_a},$$

$$Z_0 = 0.56 - 0.555\left(\frac{a}{c}\right),\ Z_1 = 0.556 - 0.584\left(\frac{a}{c}\right),$$

$$U_0 = 0.876 - 0.465\left(\frac{a}{c}\right) - \left[0.86 - 0.217\left(\frac{a}{c}\right)\right]\frac{t}{R_a},$$

$$U_1 = 0.943 - 0.518\left(\frac{a}{c}\right) - \left[2.382 - 2.226\left(\frac{a}{c}\right) + 0.9\left(\frac{a}{c}\right)^2\right]\frac{t}{R_a}.$$

According to the flow diagram (Fig. 4), we determine the maximum value of the stresses in the metal of the FP due to the bend according to dependence [13], taking into account that the radius of the curvature of the neutral layer is equal to the radius of the outer wrap of the CT on the drum (which can decrease with $\rho_{\max} = 2248$ mm to $\rho_{\min} = 1780$ mm) and the radius of curvature in the guide arch is equal to $\rho_H = 3050$ mm [13]:

$$\sigma_b^{\max} = \frac{M_b}{I_z}R_a\left[1 - \frac{0.25}{\left(\frac{t\cdot\rho_{\min}}{R_i^2}\right)^2 + \frac{1}{12}}\right] \tag{7}$$

The critical depth of external transverse semi-elliptical crack a_c (Tab. 3) was determined from dependence (6), providing $K_a = K_{Jc}$, considering the form of semi-elliptical crack $(a/c)_i$ and the minimum value of the radius of the outer wrap of the CT $\rho_{\min} = 1780$ mm.

Table 3

Values of critical depths of semi-elliptical crack *a*

$(a/c)_i$	$a_c^{K_a}$ [mm]	$a_c^{K_c}$ [mm]
1/2	1.68	3.36
1/1.5	2.20	3.30
1/1	2.45	2.45

3. CONCLUSIONS

The experimental and calculation procedures are proposed for assessing the conditions under which the failure of flexible pipes containing external transverse semi-elliptical cracks is possible during tripping operations.

An experimental estimation of stress intensity critical factor K_{Jc} of the metal of the exploited flexible pipe is carried out; in particular, for the investigated flexible pipe with a diameter of 85 mm and a wall thickness of 7 mm and made of steel 45 (σ_b = 890.7 MPa, $\sigma_{0.2}$ = 810.9 MPa) $K_{J_C} = 203.9\ \mathrm{MPa}\sqrt{\mathrm{m}}$.

It has been established that the critical depth depends on the form of the crack. The most dangerous is the external semi-elliptical crack with the ratio of semiaxes (a/c) = 1/2.

The obtained results can be used to interpret the technical diagnostics of exploited flexible pipes.

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