THE EVALUATION OF PIPE-LINE CARRYING CAPACITY USING FRACTURE MECHANICS CRITERIA

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ABSTRACT

The strength of pipe-lines having longitudinal cracks is considered. By means of the fracture tests of full-size pipe sections with crack-type defects, conducted at climatically low temperatures, and on the base of data obtained in the studies on fracture toughness of pipe steels, the pipe-line structural crack resistance vs breaking hoop stress is shown. Basing on this relationship, a criterion for assessment of the carrying capacity of pipe-lines with longitudinal cracks, working at climatically low temperatures, is proposed.

KEYWORDS

Pipe; crack-type notch; low temperature; critical stress intensity factor; critical breaking stress; correction to plasticity.

INTRODUCTION

Theoretical bases of elastic-plastic mechanics of failure for practical use are developed insufficiently, for up to the present time there exists no solution of the problem of crack equilibrium state under the developed plastic deformation of order of a few hundreds per cent at the crack tip. Presently, however, there is an urgent need to evaluate the structure carrying capacity low limit in case this structure has the cracks of such dimensions and directions for which it's impossible to use positive sides of linear elastic fracture mechanics.

The specific problem of this paper is to define the breaking stress value of a pipe-line with a longitudinal crack according to laboratory test results of cracked specimens, provided that crack lengths in structure and specimen are equal. The pipe material - low-alloyed steel I6Г2САФ (C-0.I6; Mn-I.5I; Si-0.4; S-0.05), pipe radius - R=6I0 mm, wall thickness t=I2 mm, crack length 2l=75 mm. As to generalized fracture diagram, I6Г2САФ steel specimens (thickness t=I2 mm) with the same crack length fail in conditions of general yield even at the test temperature -70°C. Besides, the choice of the crack size has been influenced by the fact, that it is often met in pipe-lines of a large diameter.

Usually, pipe-line strength is rated on maximum value of internal pressure under failure. But such an approach is practically hardly acceptable for the strength evaluation of pipe-lines with crack defects. According to Ref.[I] the development of fracture mechanics outlines two approaches for cracked pipe strength evaluation. The first one presents the direct computation of critical hoop stress failure $\sigma_{\theta c}$ at the moment of initial crack propagation in pipe (diameter 2R, thickness t) with longitudinal crack 2l long by formula:

$$\sigma_{\theta c} = \bar{\sigma}\left(1+1{,}61\frac{\ell^2}{Rt}\right)^{-\frac{1}{2}} \quad ; \qquad (I)$$

where $\bar{\sigma}$ -some mean stress of unhardening material plastic flow. The stress $\bar{\sigma}$ must be $\sigma_{0,2}<\bar{\sigma}<\sigma_{в}$; as a first approximation one can use the expression [2]

$$\bar{\sigma} = 1{,}23\,\sigma_{0,2} \ . \qquad (2)$$

Formula (I) is suitable only to predict $\sigma_{\theta c}$-value at failure of pipes made from strong materials with short through cracks (2). The empirical relationship for breaking stress predictions has been obtained in consequence with test results of pipes with crack-type longitudinal surface notches of d depth [3] :

$$\sigma_{\theta c} = \bar{\sigma}\frac{\left(\frac{t}{d}\right)-1}{\left(\frac{t}{d}\right)-\left(1+1{,}61\frac{\ell^2}{Rt}\right)^{-\frac{1}{2}}} \ . \qquad (3)$$

The next approach to evaluation of pipe strength according to cracked specimens test results is based on the account of singularity formed at crack tip. This approach is more universal. In general view it employs the following formula for the strength estimation of pipe with longitudinal crack [3]:

$$\sigma_{\theta c} = \frac{K_c}{\sqrt{\pi \ell \varphi}}\cdot M^{-1} \qquad (4)$$

where Kc - critical stress intensity factor, conventionally associated with generalized specific crushing energy by modulus of elasticity; φ - correction to plasticity; M - constructive parameter allowing for stress increase due to bending of cylindrical vessel with longitudinal crack 2l long. On this base it is possible to estimate the critical stress intensity factor by full-scale test data of real pipe-line sections:

$$K_c = \frac{\sigma_{\theta c}\sqrt{\pi \ell \varphi}}{M} \qquad (5)$$

if the conditions $\left(\frac{K_c}{\sigma_{0,2}}\right)^2\cdot\frac{1}{\ell}>7$ and $\left(\frac{\sigma_{\theta c}}{\sigma_{0,2}}\right)^2 < \left(\frac{1{,}23}{K}\right)^2$ of Ref.(I) are satisfied. In conducting full-scale tests values $\sigma_{\theta c}$ and 2l are known. Folias' coefficient M depends on the known geometrical parameters of a pipe and crack-like defect. Test results of full-dimensional pipe sections are given in Ref. [2,3] . We have processed these results and represent them as a relationship from formula 5 :

$$\left(\frac{\sigma_{\theta c}}{\sigma_{0,2}}\right)^2 = \left[\left(\frac{K_c}{\sigma_{0,2}}\right)^2\cdot\frac{1}{\ell}\right]\cdot\frac{1}{\pi\varphi\cdot M^2} \ . \qquad (6)$$

The value $\left(\frac{K_c}{\sigma_{0,2}}\right)^2\cdot\frac{1}{\ell}$ represents an estimation parameter of fracture resistance of pipe with longitudinal notch 2l long. Relation $\left(\frac{\sigma_{\theta c}}{\sigma_{0,2}}\right)^2$ represents a constructive parameter of pipe with longitudinal notch. As a result of pipe full-scale test data processing, given in Ref. [2,3] the relationship of these parameters has been plotted Fig. I . The legitimacy of this relationship has been confirmed by the authors of this paper in conducting tests of a few high pressure vessels and experimental tubes made from I7ГIC (C-0.I7; Si-0.5; Mn-0.9; S-0.04; P-0.035), I4Г2САФ (C-0.I4; Mn-I.6; Si-0.4; S-0.05) and I4Х2ГМР (C-0.I; Si-0.I7; Mn-0.9; Cr-I.5; Mo-0.5) steels under natural low temperature conditions of Yakutsk-town.

While approximating the linear part of empirical relation (see curve I in Fig. I), the authors have suggested the equality:

$$\left(\frac{K_c}{\sigma_{0,2}}\right)^2\cdot\frac{1}{\ell} = 1{,}7 + 8{,}75\left(\frac{\sigma_{\theta c}}{\sigma_{0,2}}\right)^2 \qquad (7)$$

that may be used to get equations for rough estimation of pipeline carrying capacity on the basis of characteristics, established during laboratory tests of craked specimens.

To estimate the strength $\sigma_{\theta c}$ of a pipe-line with the above-mentioned geometry (Fig. 2) the authors have used the test results of flat specimens with central crack 75 mm long at temperature range from -70°C to 20°C. Besides, the account for plasticity, defined from deformational representations [I]

$$\varphi_1 = \left(\frac{\pi\sigma_p^0}{2\bar{\sigma}}\right)\ln\sec\left(\frac{\pi\sigma_p^0}{2\bar{\sigma}}\right) \qquad (8)$$

has been used for plotting curves 4 and 5.

The account for plasticity φ_2 for curve 6 plotting is evaluated on the basis of energy approach. The sense of φ_2 estimation is in use of load-general displacement diagram and empirical formula:

$$\varphi_2 = 2\frac{v_c}{v_0} - 1 \ ; \qquad (9)$$

where v_c -general displacement at maximum loading; v_0 -displacement corresponding to the point on prolongation of curve elastic part up to maximum loading.

When plotting the curve 4 on Fig. 2 the Kc-value has been counted according to maximum values of generalized specific energy of failure, obtained in tests of flat specimens from steel I6 2CA with central crack. The Kc-value has been assumed to be a constant over the whole temperature range under study. In case of curve 5 plotting the Kc-value has been determined according to model [I] , but in case of curve 6 the authors use schemes of failure specific energy estimation.

The curves 2 and 4 on Fig. 2 characterize two forms of cracked pipe failure. The first one corresponds to general yield, the second one - to initiation and propagation of brittle crack, i.e. to large-scale failure of pipe material. At test temperature drop the use of formula (I) for estimation has no sense and that's why must be restricted by the low limit of temperature scale. As to the formula (4) it must be restricted by the upper temperature limit, when the use of Kc-value has no sense due to loss of brittle properties of specimen material. The criterion $\left(\frac{K_c}{\sigma_{0,2}}\right)^2 \cdot \frac{1}{\ell}$ for determination of these bounds is not suitable here, for if $\left(\frac{K_c}{\sigma_{0,2}}\right)^2 \cdot \frac{1}{\ell} < 7$ the value $\sigma_{\theta c}$ by formula (I) passes above the curve 2.

To some extent the curves 3 and 6 allow evaluation of the transition from cracked pipe failure under yielding to brittle fracture without crack propagation. In a first approximation the curve 6 characterizes this transition more correctly, because at temperatures -70°C and 20°C it is more close to curves 4 and 2 than curve 5, correspondingly. As to the fact, $\sigma_{\theta c}$ -value of curve 6 is less than value at temperature 20°C, it can be explained in the following way. At this temperature the I6 2CA steel tube with radius 6I0 mm, wall thickness I2 mm and longitudinal crack of 75 mm fails under the conditions of partial, but not general yielding. The difference between these two conditions is, that in the first case the yielding of material is observes only in the zone before crack, while in the second case the whole of material in the area of crack is strained above the yield point before failure. Curve 6 in Fig. 2 evaluates $\sigma_{\theta c}$ -value more precisely as the fact shows that curve 2 in Fig. I plotted with the use of φ_2 -correction is more closely to curve I, than when using φ_1 -value.

In general case, if failure is inadmissible under given conditions, when R/t<70 and under preset crack length and cofigurations as a criterion of the pipe carrying capacity low limit one can choose the inequality

$$\sigma_\theta = \frac{PR}{t} \leqslant \sigma_{0,2} \sqrt{0{,}114 \left(\frac{K_c}{\sigma_{0,2}}\right)^2 \cdot \frac{1}{\ell} - 0{,}194} \qquad (I0)$$

where P -working pressure in a pipe.

In that case of predetermined working pressure value, one needs to choose material, which mechanical properties and crack resistance satisfy the criterion (I0). Besides, points connecting values $\left(\frac{K_c}{\sigma_{0,2}}\right)^2 \cdot \frac{1}{\ell}$ and $\left(\frac{\sigma_{\theta c}}{\sigma_{0,2}}\right)^2$ lie above the straight

line I for any surface crack size relations (Fig. 3). As mentioned before, it is possible to determine Kc-value according to test results of flat plates with central crack of a given length using correction for plasticity by formula (9).

As to the defect of size 2l in criterion (I0), it must be taken equal to minimum defect value and determined according to the level of non-destructive testing in the industry, allowing for the defect detection margin.

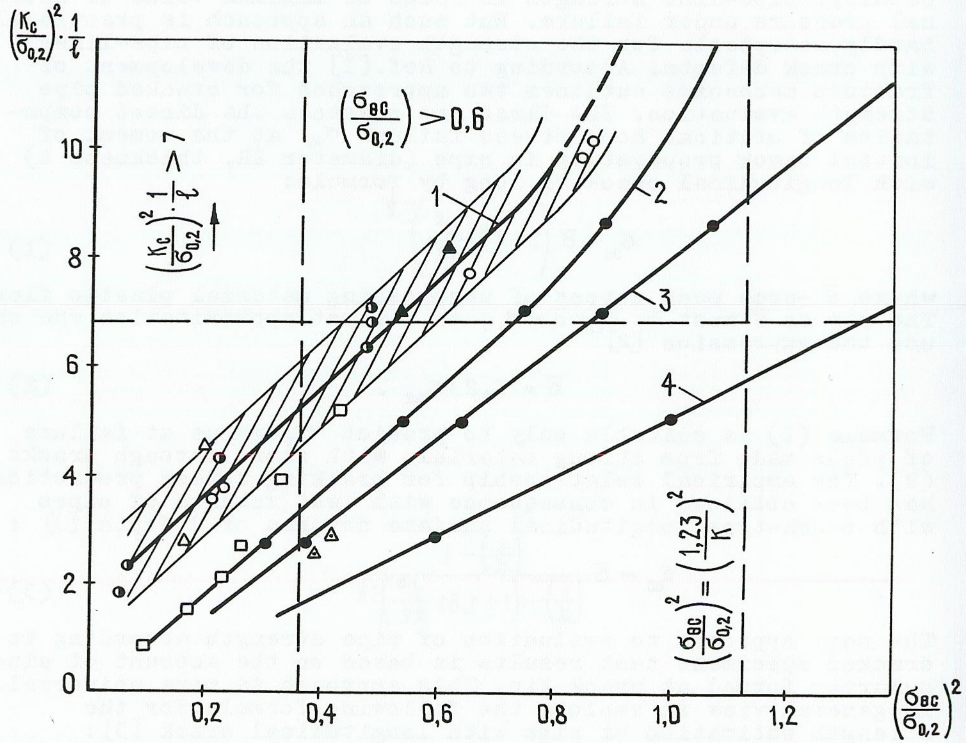

Fig. I. Relation between tube material resistance to $\left(\frac{K_c}{\sigma_{0,2}}\right)^2 \cdot \frac{1}{\ell}$ -value extention and tube constructive parameter $\left(\frac{\sigma_{\theta c}}{\sigma_{0,2}}\right)^2$.
Curves: I - averaging the full-scale tests results of pipes with through cracks;
2 - plotted using φ_2 ;
3 - plotted using φ_1 at σ_p^D ;
4- plotted using φ_1 at σ_p^H.

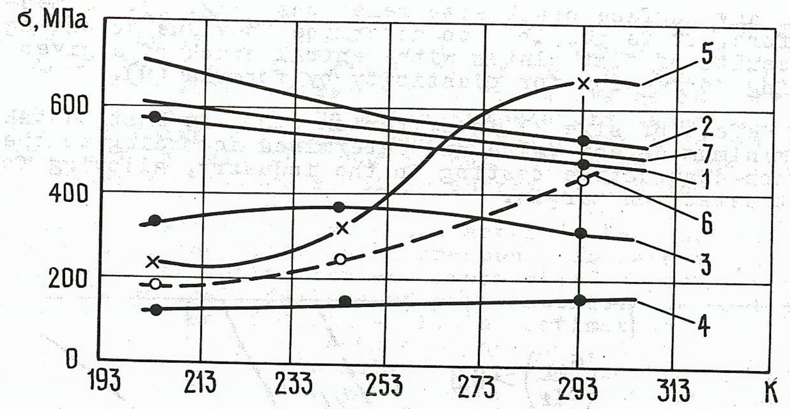

Fig. 2. Relation between failing stress and test temperature of specimens with central crack and tube with longitudinal crack.
Curves: I – $\sigma_{0,2} = f(T^{\circ}K)$;
2 – $\sigma_{BC} = 1{,}23\,\sigma_{0,2}\,M^{-1}$;
3 – nominal failing stress of cracked specimen σ_p^H ;
4 – $\sigma_{BC} = (K_c/\sqrt{\pi \ell \varphi}) \cdot M^{-1}$;
5 – $\sigma_{BC} = (K_c/\sqrt{\pi \ell \varphi_2}) \cdot M^{-2}$;
6 – $\sigma_{BC} = (K_c/\sqrt{\pi \ell \varphi_2}) \cdot M^{-1}$;
7 – specimen failing stress at crack stress-section σ_p^0.

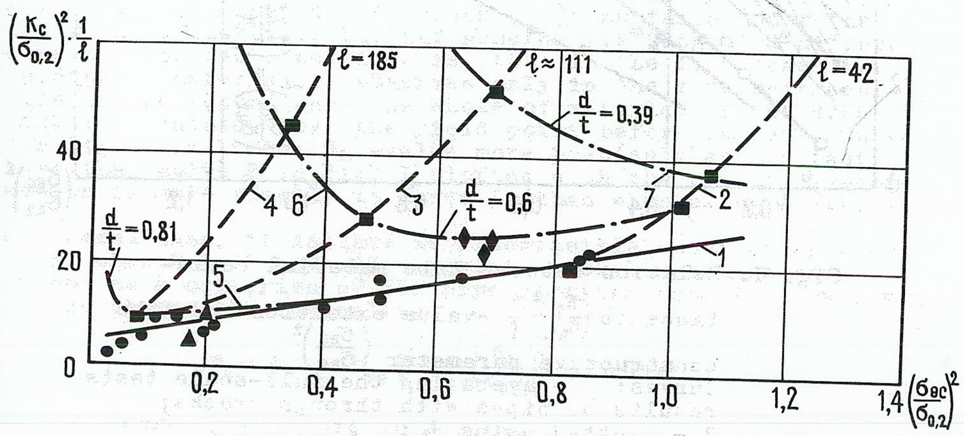

Fig. 3. Relation similar to Fig. I. Curves 2–7 are the full-scale test results of tubes with surface cracks at constant relation between crack depth d and tube wall thickness t.

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