ASSESSMENT OF THE RESIDUAL LIFETIME OF A DEFECTIVE PIPELINE AT DIFFERENT HYDROGEN CONCENTRATIONS IN THE METAL

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The residual lifetime of a pipeline with an axial semi-elliptical crack on the outer surface was estimated. It was established that lifetime significantly decreases with an increase in the hydrogen concentrations in the metal of the pipeline. Similar tendencies are also visible with a change in the a/c relation (defect shape). That is, more elongated semi-elliptical cracks are more dangerous as compared to deeper defects. In general, of all the considered cases, the most dangerous is an elongated (a/c = 0.25) axial semi-elliptical crack on the outer surface of the pipe at a hydrogen concentration in the metal of the pipeline C_H = 5.462 ppm.

Introduction. The possibility of using the existing gas transportation network for transportation of gas-hydrogen mixtures is being actively discussed [1, 2] in many countries of the world, including Ukraine. This intensifies the researches related to the assessment of the risk of hydrogen embrittlement of long-term operated pipelines with defects. At the same time, the concentration of hydrogen in the material is considered [1, 2] to be the main factor which determines the metal working capacity under these operating conditions. Especially taking into account the fact that the hydrogen concentration in the metal increases with the increase in the service life.

An element of a rectilinear section of a defective pipeline under the internal pressure with an axial semi-elliptical crack on its outer surface at different volume concentrations of hydrogen in the metal is evaluated below.

Problem Formulation and Model. The work [2] formulated a criterion for evaluating the strength and reliability of structures with crack-like defects based on the proposed “resistance of the structural element to crack growth” indicator, which is a characteristic of the stress intensity factor (SIF) K_I rate change near the crack tip of length a during its growth in the given element, i.e.

$$\lambda = dK_I / da \ . \tag{1}$$

A certain value of the defect size a_*, starting from which the rate of SIF K_I change increases sharply is present on the dependence $dK_I / dK_I = F(a)$. This value is characteristic for evaluation of residual lifetime of a pipeline with crack-like defects.

The concept outlined above was applied to cyclic (fatigue) loading conditioned the internal pressure of the transported product of the long-term operated pipeline element with an axial semi-elliptical crack on the outer surface of the pipe (Fig. 1). The estimation of the residual lifetime of a pipeline with a defect (crack) with the account of different hydrogen concentrations in the metal of the pipe C_H was carried out according to the well-known formula [2], which foresees the achievement of conditions for the spontaneous (catastrophic) fracture of the structural element, i.e.:

$$N_{fc} = \int_{a_{th}}^{a_{fc}} \frac{da}{F(\Delta K_I)} . \quad (2)$$

where N_{fc} is the number of load cycles before the fracture of the structural element; a_{th} and a_{fc} are the threshold and critical size of the crack, respectively; $F(\Delta K_I)$ is a known SIF ΔK_I function, which describes the fatigue crack growth rate in the pipe material under given test conditions and known hydrogen concentration in the metal C_H .

To determine SIF in this case (Fig. 1), the relation [2, 3] was used

$$K_{Ia} = F\sigma\sqrt{\pi a}\,0.97\left(\frac{R_a{}^2 + R_i{}^2}{R_a{}^2 - R_i{}^2} - 1 + 0.5\sqrt{\frac{a}{t}}\right)\frac{t}{R_i}1.07 , \quad (3)$$

where $F = \dfrac{M_1 + M_2\left(\frac{a}{t}\right)^2 + M_3\left(\frac{a}{t}\right)^4}{\sqrt{Q}}$; $\sigma = \dfrac{pR_i}{t}$; $M_1 = 1.13 - 0.09\dfrac{a}{c}$;

$$M_2 = -0.54 + \frac{0.89}{0.2 + \frac{a}{c}};\ M_3 = 0.5 - \frac{1}{0.65 + \frac{a}{c}} + 14\left(1 - \frac{a}{c}\right)^{24};\ Q = 1 + 1.464\left(\frac{a}{c}\right)^{1.65} .$$

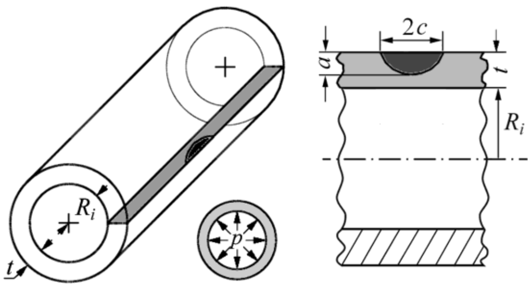


Fig. 1. A pipe under the internal pressure with an axial semi-elliptical crack on the outer surface: a is the crack depth; $2c$ is the crack width; R_i is the inner radius; t is the thickness of the cylinder wall; p is the internal pressure.

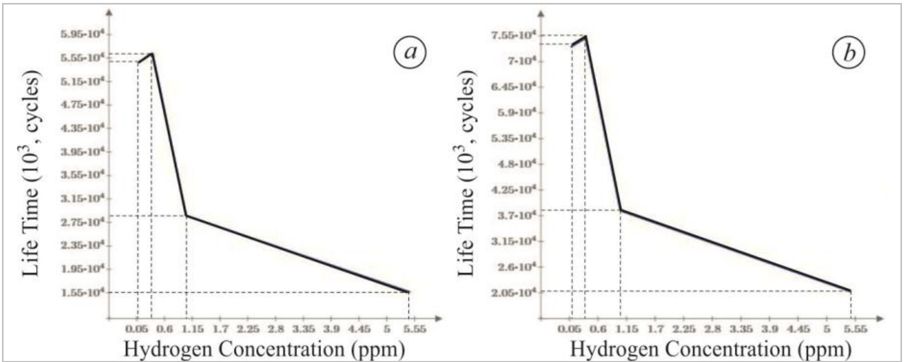
Since SIF K_I has the dimension $\text{MPa}\sqrt{\text{m}}$, and the geometric dimensions of the pipe are given in millimeters, then the obtained result during the calculation of K_I, is multiplied by $\sqrt{10^{-3}}$.

Numerical Experiment. Calculations were made for the linear section of the gas pipeline under the internal pressure (p = 7 MPa) of the transported hydrogen-containing product. The outer diameter of the pipe D = 610 mm, the thickness of the pipe wall t = 11 mm. For the specified type of defect, three variants of its shape (relations of the ellipse axes) were considered for different hydrogen concentrations in the metal (Fig. 1, Table 1). Calculations were made using the basic characteristics of crack resistance of low-alloyed pipe steel (ΔK_{th}, ΔK_{fc}, as well as the A and n constants) determined experimentally for each indicated above hydrogen concentrations in the metal of the pipeline.

Table 1. Results of the Numerical Experiments

Defect shape	Hydrogen concentration in the metal, C_H ppm	a_{th}, mm	a_{fc}, mm	N_{fc}, $\times 10^3$, cycles
$\frac{a}{c} = 0.25$	0.074	0.22	1.12	5.468×10^4
	0.361	0.10	0.61	5.634×10^4
	1.030	0.10	0.53	2.864×10^4
	5.462	0.10	0.52	1.564×10^4
$\frac{a}{c} = 0.5$	0.074	0.30	1.51	7.312×10^4
	0.361	0.13	0.81	7.498×10^4
	1.030	0.13	0.70	3.810×10^4
	5.462	0.13	0.69	2.080×10^4
$\frac{a}{c} = 0.75$	0.074	0.40	2.05	9.926×10^4
	0.361	0.18	1.10	1.018×10^5
	1.030	0.18	0.95	5.171×10^4
	5.462	0.18	0.95	2.824×10^4

Results and Discission. It was established (Table 1, Fig. 2) that the residual lifetime of a pipe with an axial semi-elliptical crack on the outer surface significantly decreases with an increase in the hydrogen concentrations in the metal (from C_H = 0.074 ppm to C_H = 5.462 ppm). Similar tendencies were also evident with a change in the a/c relation (defect shape). That is, more elongated (a/c = 0.25) semi-elliptical cracks are more dangerous as compared with deeper (a/c = 0.75) defects (Fig. 1, Table 1, Fig. 2). In general, among all the considered cases, the most dangerous is an elongated (a/c = 0.25) axial semi-elliptical crack on the outer surface of the pipe at a hydrogen concentration in the metal of the pipeline C_H = 5.462 ppm, i.e., $N_{fc} = 1.564\times10^4$ thousand cycles.



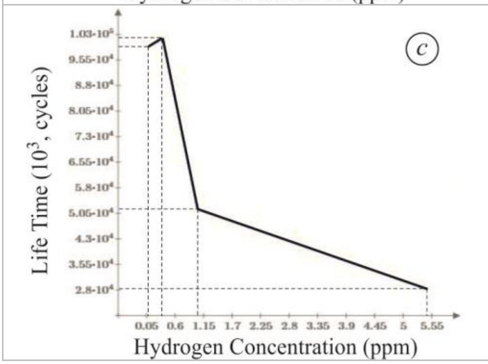


Fig. 2. Residual Lifetime of the Pipe **vs.** the Hydrogen Concentration in the Metal for the Pipeline with the Axial Semi-Elliptical Crack of Different Shape on the Outer Surface of the Pipe: (*a*) $a/c = 0.25$; (*b*) 0.50; (*c*) $a/c = 0.75$.

Conclusions. It was established that the residual lifetime of the pipe with the axial semi-elliptical crack on the outer surface significantly decreases with the increase in the hydrogen concentrations in the metal of the pipeline. Similar tendencies are also evident with the change in the a/c relation. That is, the more elongated semi-elliptical cracks are more dangerous as compared with deeper defects.

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