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.

**Keywords:** pipeline, crack-like defects, residual lifetime, hydrogen concentration

**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) \(K_1\) rate change near the crack tip of length \(a\) during its growth in the given element, i.e.

\[
\lambda = \frac{dK_1}{da} .
\]

A certain value of the defect size \(a_\ast\), starting from which the rate of SIF \(K_1\) change increases sharply is present on the dependence \(dK_1/dK_1 = F(a)\). 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.:

\[
N_{fc} = \int_{a_{th}}^{a_{fc}} \frac{da}{F(\Delta K_1)}.
\]

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; \( F(\Delta K_1) \) is a known SIF \( \Delta K_1 \) 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

\[
K_{la} = F\sigma\sqrt{\pi a} 0.97 \left( \frac{R_a^2 + R_i^2}{R_a^2 - R_i^2} - 1 + 0.5 \sqrt{\frac{a}{r}} \right) \frac{t}{R_i} 1.07,
\]

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

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

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 ($p = 7 \text{ MPa}$) of the transported hydrogen-containing product. The outer diameter of the pipe $D = 610 \text{ mm}$, the thickness of the pipe wall $t = 11 \text{ mm}$. 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 ($\Delta K_{th}$, $\Delta K_{fc}$, 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.

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

**Results and Discussion.** 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 $C_H = 0.074 \text{ ppm}$ to $C_H = 5.462 \text{ ppm}$). 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 $C_H = 5.462 \text{ ppm}$, i.e., $N_{fc} = 1.564 \times 10^4$ 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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