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NUMERICAL ANALYSIS OF THE REGULARITIES OF THE INFUENCE OF PIPE STEEL DEGRADATION ON THE RELIABILITY OF CORRODED MAIN GAS PIPELINES USED FOR TRANSPORTATION OF GAS-HYDROGEN MIXTURES

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ABSTRACT

Transportation of mixtures of natural gas and green hydrogen is one of the promising ways to use the local gas-transportation system under the conditions of a rapid transition to a sustainable economy. For safe operation of available main gas pipelines at transportation of gas-hydrogen mixtures of different compositions, it is necessary to take into account the negative influence of hydrogen on the mechanical properties of pipe metal, in particular at evaluation of their technical condition by the results of flaw detection. In this work, the principles of safe operation of pipelines with detected defects of local corrosion loss of metal were studied. For this purpose, a numerical procedure was developed for evaluation of brittle strength based on finite element modeling of the stressed state and brittle-ductile fracture criteria. It is shown that under the conditions of static loading degradation of brittle fracture resistance of pipeline metal with the detected defect of local metal loss is relatively small and it can be compensated by a change in service load. Under the conditions of cyclic loading by internal pressure, the principles of lowering of the load-carrying capacity of a corroded pipeline were demonstrated, depending on the actual brittle fracture resistance of the pipe steel.

KEYWORDS: gas-hydrogen mixtures, main pipeline, local metal loss due to corrosion, hydrogen degradation, technical condition, brittle fracture, cyclic loading

INTRODUCTION

One of the most intensively growing sectors of the modern power engineering is the production and use of green hydrogen as an environmentally friendly alternative to fossil hydrocarbons. In particular, this is reflected in the European Union's Hydrogen Strategy, as well as in similar documents of other countries, where it is planned to maximise the use of hydrogen for industrial, transport or domestic needs, which is a part of the transformation of the global economy according to the principles of sustainable development [1–3]. It is important to emphasise here that hydrogen is not a fuel itself, but an energy carrier from renewable energy sources (solar, wind or hydroelectric power plants, geothermal sources, etc.) or a raw material (for the chemical industry). Therefore, one of the key challenges in implementing such approaches for green energy is the transportation of hydrogen gas. Building a new pipeline system for these needs is a large-scale and expensive infrastructure project. Therefore, it is rational to use existing gas transportation systems (GTS). However, it is known that diffused hydrogen has a negative impact on the service properties of pipe steel structures caused by hydrogen degradation of metal [4, 5]. Therefore, the direct use of main and distribution pipelines for transporting pure hydrogen is objectively complicated.

As one of the practically possible ways to use the existing gas transportation network for the needs of hydrogen energy, the transportation of mixtures of natural gas and green hydrogen is being considered and gradually implemented [6]. Depending on the composition of the mixture, i.e., on the partial pressure of hydrogen, different levels of additional technological measures are envisaged to maintain the serviceability of individual GTS components. First of all, this concerns the selection of acceptable operating modes, procedure for planning measures to monitor the technical condition and expert reliability evaluation. One of the typical tasks is to evaluate the admissibility of operational anomalies in the pipeline geometry detected by means of non-destructive testing during periodic flaw detection. In the event of significant metal hydrogenation of a defective pipeline, the use of standardised static strength evaluation procedures may be limited, in particular, as a result of changing the prevailing mechanisms of microscopic and macroscopic fracture that determine the conditions of the boundary state of a structure. For example, when analysing the acceptability of crack-like defects in pipelines (or anomalies formally schematised as cracks, such as non-metallic inclusions, pitting, grooves, lacks of fusion in welds, etc.), the limiting state of structures under the operational load is determined by the material's resistance to brittle fracture [7]. Therefore, when evaluating the technical condition of pipelines with crack-like anomalies, it is necessary to take into account the change in the values of the material fracture toughness K_{Ic} and strength characteristics included in the corresponding limiting state criteria. In the case of analysing the admissibility of three-dimensional material discontinuities, among which the most common are local corrosion losses of metal, the limiting state of the pipeline is typically determined by the criteria of ductile fracture [8]. However, in case of significant metal embrittlement, the mechanisms of metal fracture initiation and propagation in the anomaly area may change to brittle-ductile or brittle. Therefore, depending on the composition of the transported gas-hydrogen mixture (and the corresponding saturation of pipeline metal with diffused hydrogen), standard limiting state criteria may be of limited applicability.

The aim of this work is to determine the principles of the influence of the level of hydrogen degradation of pipe steel (changes in fracture toughness and resistance to fatigue failure) on the limiting state of the main gas pipeline with a detected geometric anomaly of a local surface metal loss due to corrosion under the brittle-ductile fracture mechanism. For this purpose, a numerical procedure for evaluation of the stress-strain and limiting states of corroded pipelines based on the method of postulated defects was proposed.

As was already mentioned above, one of the most common types of operational damage in underground main pipelines is local corrosion metal losses in the area of protective insulation damage. Such geometric anomalies are typically schematised as semi-elliptical surface pipe wall thinning (Figure 1). The presence of a geometric anomaly causes local non-uniformity of stresses in the pipe cross-section under the influence of internal pressure and the corresponding heterogeneity in the material's tendency to damage initiation. According to general concepts, the limiting state of pressure vessels with three-dimensional metal discontinuity defects is determined by the ductile fracture mechanism, which consists in the initiation and propagation of microscopic porosity during plastic deformation of the material under external load [9]. However, in the case of significant hydrogenation of the pipeline material during the transportation of gas-hydrogen mixtures, the brittle fracture mechanism is more significant, especially in the presence of crack nuclei in the metal.

To determine the principles of the influence of the level of hydrogen degradation of pipe steel on the brittle strength of the pipe in a non-uniform field of mechanical stresses, it is rational to use numerical modelling methods along with the corresponding limiting state criteria. Thus, in this research, numerical analysis was carried out on the basis of a finite element model of an elastic-plastic continuous medium by formulating and solving the corresponding boundary value problem using the WeldPrediction software package [10]. An increment of the strain tensor components was considered as the sum of the increments of elastic $d\varepsilon_{ij}^{e}$ and plastic $d\varepsilon_{ij}^{e}$ components, $i, j = r, \beta, z$ (Figure 1):

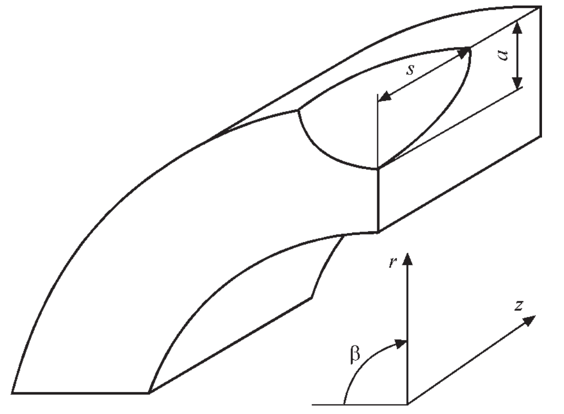

Figure 1. Schematic of pipeline with a surface defect of corrosion wall thinning

$$d\varepsilon_{ij} = d\varepsilon_{ij}^{e} + d\varepsilon_{ij}^{p}. \quad (1)$$

The further analysis of the stress-strain state of the defective pipeline with an increase in the internal pressure was carried out by tracing the accumulation and redistribution of a strain with a gradual increase in loading. During each tracing step, the relationship between the components of the stress (σ_{ij}) and strain (ε_{ij}) tensors was determined using the generalised Hooke's law and the associated plastic flow law [11]:

$$\Delta\varepsilon_{ij} = \Psi\left(\sigma_{ij} - \delta_{ij}\sigma_m\right) + \delta_{ij}K\sigma_m - \\ -\frac{1}{2G}\left(\sigma_{ij} - \delta_{ij}\sigma_m\right)^{*} + \left(K\sigma_m\right)^{*}, \quad (2)$$

where δ_{ij} is the Kronecker symbol, $K = (1–2\nu)/E$, $G = 0.5E/(1+\nu)$; E is the Young's modulus; ν is the Poisson's ratio; the index "*" refers to the variable at the previous step of loading tracing; Ψ is the metal state function, which is determined iteratively based on the actual shape of the yield surface depending on the stress intensity σ_i and yield strength σ_y [11];

$$\Psi = \frac{1}{2G}, \text{ if } \sigma_i < \sigma_y; \\ \Psi > \frac{1}{2G}, \text{ if } \sigma_i = \sigma_y; \quad (3) \\ \text{the state } \sigma_i > \sigma_y \text{ is inadmissible.}$$

At each tracing step, the conditions (3) are implemented, taking into account the history of plastic deformation, including strain hardening.

Simultaneously, at each iteration, the stress field σ_{ij} is calculated for Ψ:

$$\sigma_{ij} = \frac{1}{\Psi}\left(\Delta\varepsilon_{ij} + \delta_{ij}\frac{\Psi - K}{K}\Delta\varepsilon\right) + J_{ij}\,, \qquad (4)$$

where

$$J_{ij} = \frac{1}{\Psi}\left[\left(b_{ij} - \delta_{ij}b\right) + \delta_{ij}K\sigma^*\right],\ \Delta\varepsilon = \Delta\varepsilon_{ii}/3,\ b = b_{ii}/3.$$

The components of the stress tensor satisfy the equation of statics for inner finite elements (FEs) and the boundary conditions for surface FEs. To form a system of linear algebraic equations for the vector of displacement increments in FE nodes, the following functional is minimised at each step of tracing and iterations by Ψ [11]:

$$L_I = -\frac{1}{2}\sum_V\left(\sigma_{ij} + J_{ij}\right)\Delta\varepsilon_{ij}V_{m,n,r} + \sum_\Theta F_i\Delta \boldsymbol{U}_i\Delta S_P^{m,n,r}, \qquad (5)$$

where $\sum_V$ is the sum operator by inner FEs; $\sum_\Theta$ is the sum operator by FEs over S_p surface, on which the components of the force vector F_i are set. A detailed description of equations (1)–(5) and the software implementation for their solution are given in [12].

The evaluation of the actual reliability of the pipeline under the conditions of varying levels of hydrogen embrittlement of the material under a non-uniform stress field caused by internal pressure and local geometric anomaly was carried out using the postulated defects method. This method assumes the presence of small crack-like defects and the further evaluation of their admissibility. To evaluate the brittle strength of corroded pipelines, taking into account the hydrogen degradation of metal, for each postulated defect, the safety factor n is calculated based on the corresponding internal state criterion for a body with a crack. The typically used criterion is the R6 procedure [13], which is based on a two-parameter brittle-ductile fracture diagram (Figure 2) and can be mathematically described as:

$$nK_r(L_r) = \begin{cases} \left[1 - 0.14\left(nL_r\right)^2\right]\left\{0.3 + 0.7\exp\left[-0.65\left(nL_r\right)^6\right]\right\}, \\ \text{at } nL_r \le L_{r\max} \\ 0, \text{ at } nL_r > L_{r\max}. \end{cases}, \qquad (6)$$

where $K_r = K_I/K_{Ic}$, $L_r = \sigma_{ref}/\sigma_y$; K_I is the stress intensity factor; K_{Ic} is the fracture ductility; σ_{ref} are the reference stresses. The calculation of K_I and σ_{ref} is performed according to the algorithms given in [14].

The evaluation of the safety factor n was based on a two-parameter diagram (Figure 2) and consisted of calculating the ratio of the sections' lengths from the beginning of the coordinates to the actual point (K_r, L_r) and its extension to the intersection of the limiting curve.

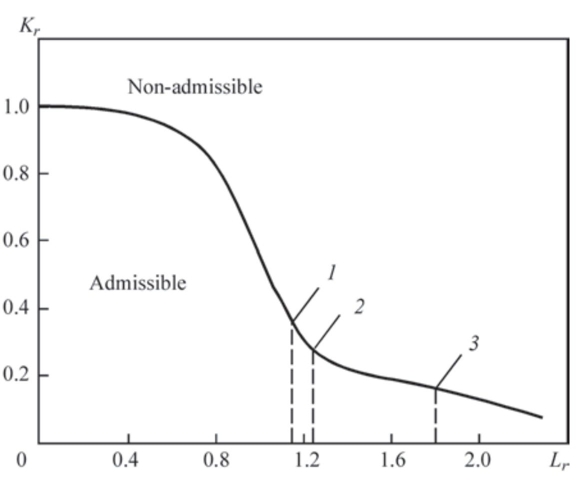

Figure 2. Two-parameter diagram of brittle-ductile fracture of a structure with a crack [13]: *1* — 1.15 (typical low-alloy steels and welded joints); *2* — 1.25 (typical low-carbon steels and austenitic welded joints); *3* — 1.8 (typical austenitic steels)

The use of the developed numerical approach in evaluating the effect of operational load on the corroded element of the main gas pipeline allows not only evaluating the static strength of a structure at different levels of hydrogen degradation, but also taking into account the effect of cyclic loading by internal pressure within the admissible design values. For this purpose, the fatigue growth rate of the postulated cracks was calculated according to the Paris law. If the loading is characterised by a cycle asymmetry with a coefficient R, then the law of growth in crack sizes depending on the number of loading cycles N can be formulated as [15]:

$$\frac{dc}{dN} = \frac{C\left(\Delta K_I\right)^m}{\left(1 - R\right) - \dfrac{\Delta K_I}{K_{1c}}}, \qquad (7)$$

where C, m are the Paris coefficients.

Thus, the fatigue growth of postulated cracks under cyclic loading of a pipeline with local corrosion wall thinning and a certain level of hydrogen degradation of metal properties can be quantified by changing the brittle strength safety factor n.

As an example of using the proposed approach, this work considers a typical rectilinear section of a pipeline with a diameter of $D = 1420$ mm and a wall thickness of $t = 20$ mm, the pipe material is X80 pipe steel. Two types of operating loading were analyzed, namely: static internal pressure of the gas-hydrogen mixture (maximum value $P = 7.5$ MPa) and cyclic change of internal pressure in the range of 5.5–7.5 MPa, with a number of up to 1000 cycles. The actual mechanical properties of the pipeline metal depend on the concentration of hydrogen in the transported mixture and the corresponding level of degradation. According to the available data [16], hydrogen has the most significant negative effect on the resistance of pipe steel to brittle fracture (i.e., a change in K_{1c}) and fatigue failure (which is quantitatively described by changes in the Paris coefficients C and m). At the same time, at a volume concentration of hydrogen in the mixture of up to 50 %, no change in the value of the tensile and yield strength is observed. For pipe steels at hydrogen concentrations in the transported mixture of 5–20 %, Paris coefficients are approximately C = 2.98·10^7, m = 2.580 [17].

As was mentioned above, the size of the postulated crack is an important parameter for the quantitative calculation of pipes for static or fatigue strength. For the considered case, the preliminary calculation showed that when a size of the subsurface elliptical crack is 2.5×0.4 mm, the safety factor of the pipe is approximately 1.92. This conservatively meets the design requirements for the pipeline (1.94). In order to accurately take into account the three-dimensional stress-strain state when calculating the brittle strength, cracks of different orientation relative to the pipe axis (longitudinal, circumferential) were considered, and the minimum safety factor n in the structure cross-section was chosen.

The developed numerical approach to determine the brittle strength safety factor was demonstrated on the example of a characteristic defect of local semi-elliptical corrsion wall thinning (2s = 200 mm, a = 4–12 mm). A comparison was made with standardized algorithms for evaluating the admissibility of such anomalies according to the national standard DSTU-N B V.2.3-21:2008 [18]. This standard is based on the analysis of the residual safety factor of pipelines with local corrosion loss of metal, which makes it appropriate to compare with the proposed calcula-

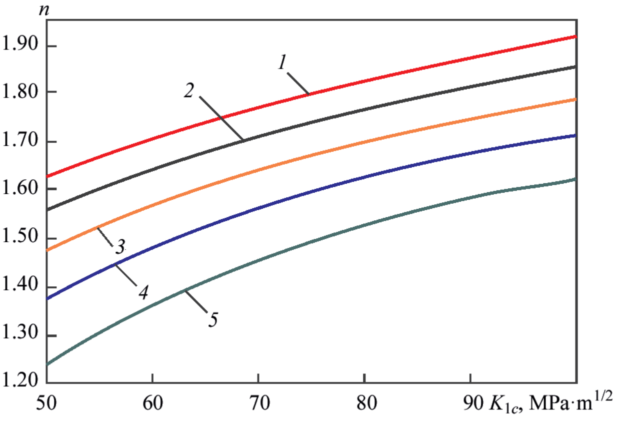

Figure 4. Dependencies of the brittle strength of the pipeline n (1420×20 mm) with local wall thinning (2s = 200 mm) at a pressure of P = 7.5 MPa on the value of fracture ductility K_{1c} of the material and the depth of the defect α, mm: *1* — 4; *2* — 6; *3* — 8; *4* — 10; *5* —12

tions. As shown in Figure 3, the correlation between the developed procedure and regulatory requirements is satisfactory.

The results of the numerical analysis of the effect of the the corrosion damage degree (depth of local wall thinning) of the pipeline on its reliability under static loading by internal pressure and at different K_{1c} values are shown in Figure 4. From these data, it can be concluded about the sensitivity of the brittle strength safety factor of the corroded pipeline to the actual fracture toughness of the material at different depths of the corrosion metal loss, which should be taken into account when analysing its serviceability.

Figure 5 shows the calculated dependences of the brittle fracture resistance value on the depth of local wall thinning a for different values of the operating pressure P in the pipeline, the design allowable safety factor n = 1.617. These results demonstrate a significant safety factor of corroded gas pipelines when transporting gas-hydrogen mixtures under static loading: in the typical operating pressure ranges of 5.5–

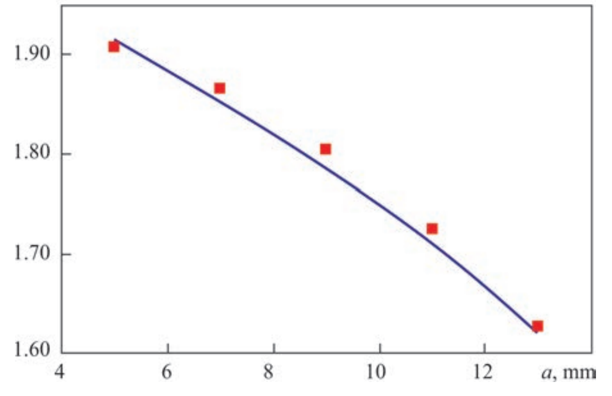

Figure 3. Comparison of the dependence of the brittle strength safety factor n of a pipeline (1420×20 mm) with a defect of local wall thinning (2s = 100 mm) on the depth of the defect a calculated by the method of postulated cracks and according to [18]: ■ — according to DSTU-N B V.2.3-21:2008

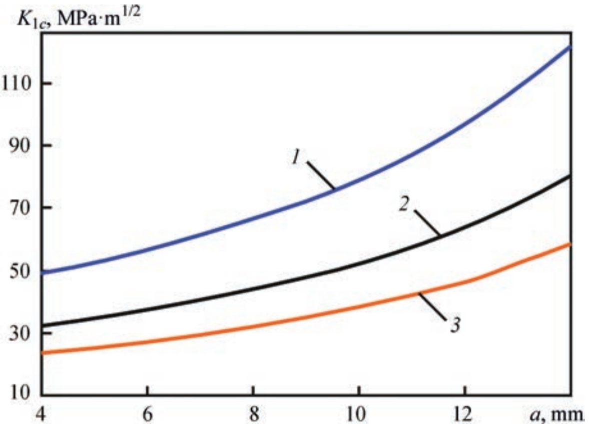

Figure 5. Dependencies of the maximum admissible degradation of the pipeline material (change in K_{1c}) on the depth of the detected local wall thinning a and at different operating pressures P, MPa: *1* — 7.5; *2* — 6.5; *3* —5.5

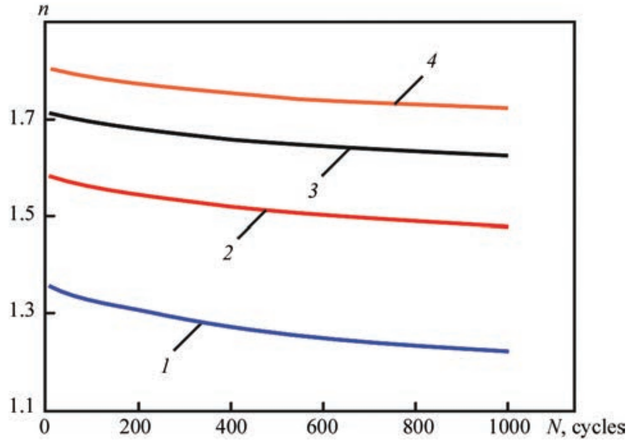

Figure 6. Dependencies of the brittle strength safety factor *n* (1420×20 mm) of a pipeline with a detected defect of local wall thinning ($2s \times a$ = 200×10 mm) on the number of cycles of change in internal pressure from 5.5 to 7.5 MPa and the value of fracture toughness K_{Ic} of the pipe metal, MPa·m$^{1/2}$: *1* — 50; *2* — 75; *3* — 100; *4* — 125

7.5 MPa, a significant reduction in fracture toughness remains acceptable. Thus, the reliability and safety of the operation of a corroded main gas pipeline with a certain level of hydrogen degradation of material properties can be guaranteed by making appropriate adjustments to the operating modes.

For the case of cyclic loading with variable internal pressure (within the design range of 5.5–7.5 MPa), it is necessary to additionally take into account the fatigue growth in the size of postulated cracks. As shown in Figure 6, within 1000 loading cycles, a decrease in the minimum safety factor in the cross-section of the defective pipeline ($2s \times a$ = 200×10 mm) does not exceed 0.2, depending on the value of the fracture ductility K_{Ic}. Therefore, if a particular pipeline has an excessive design strength, the influence of the fatigue mechanism of damage accumulation can be disregarded when evaluating the acceptability of local corrosion-type metal losses.

CONCLUSIONS

1. To predict the reliability of main pipeline elements with geometric anomalies of local semi-elliptical corrosion wall thinning, taking into account the hydrogen degradation of mechanical properties of the material, a numerical procedure for determination of the brittle strength safety factor was proposed. This procedure is based on the finite element analysis of the stress-strain state of the pipeline and the calculation of the brittle strength safety factor based on the postulated cracks method and the two-parameter brittle-ductile fracture criterion. A comparison with the standardised algorithms for evaluating the admissibility of such anomalies in accordance with the national standard DSTU-N B V.2.3-21:2008 was carried out, and a satisfactory correlation between the developed procedure and regulatory requirements was shown.

2. A significant strength safety factor of corroded gas pipelines while transporting gas-hydrogen mixtures under static loading was demonstrated: in the typical ranges of operating pressure of 5.5–7.5 MPa, a decrease in the fracture toughness K_{Ic} remains acceptable. Thus, the reliability and operation safety of a corroded main gas pipeline with a certain level of hydrogen degradation of material properties can be guaranteed by making appropriate adjustments to the operating modes.

3. For the case of cyclic loading with variable internal pressure within the operating range of 5.5–7.5 MPa, fatigue growth in the size of postulated cracks according to the Paris law was additionally taken into account. It is shown that within 1000 loading cycles, a decrease in the minimum safety factor in the cross-section of the defective pipeline (size of thinning defect is 200×10 mm) does not exceed 0.2, depending on the actual value of the fracture toughness K_{Ic}. Therefore, if a particular pipeline has an excessive design strength, the impact of the fatigue mechanism of damage accumulation can be disregarded when evaluating the acceptability of local corrosion-type metal losses.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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