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NUMERICAL ASSESSMENT OF BRITTLE STRENGTH OF FIELD WELDS OF THE MAIN GAS PIPELINES AT TRANSPORTATION OF GAS-HYDROGEN BLENDS

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ABSTRACT

Features of the influence of hydrogen degradation of pipe steel on brittle strength of circumferential field welded joints were considered within the framework of analysis of the possibility of using the Ukrainian gas-transportation system for transportation of mixtures of natural gas and hydrogen. Applied for these purposes were the methods of finite-element modeling of the structure stress-strain state during welding and further service together with modern criteria of macroscopic fracture of a cracked body. Results of prediction of brittle strength margin of a typical welded section of the main gas pipeline with postulated surface cracks at transportation of gas-hydrogen mixtures of different composition showed that the areas of the weld and heat-affected zone are the most prone to brittle fracture. However, as regards fatigue strength of welded joints, greater ranges of stress intensity factors in the heat-affected zone under the impact of cyclic loading by inner pressure or bending moment, result in an essential reduction of the residual strength margins at prediction of long-term brittle strength.

KEYWORDS: gas-hydrogen mixture, main gas pipeline, hydrogen degradation, technical condition, brittle strength, cyclic loading

INTRODUCTION

Practical perspective of application of Ukrainian gas-transporting system for transportation of blends of fossil natural gas and green hydrogen requires corresponding substantiation of safety of gas pipeline operation. In addition to control of possible leakages and accumulation of gaseous hydrogen during analysis of technical condition of gas pipelines it is necessary to take into account different aspects of hydrogen degradation of pipe steel. At that one of the most susceptible places are field circumferential welded joints with corresponding residual stress and deformation fields caused by assembly welding under field conditions. This promotes larger tendency to appearance of different types of defects of metal inhomogeneity (lacks of penetration, pitting corrosion, stress-corrosion cracking etc.) and increase of risks of initiation of unallowable damage of structure as a result of effect of static or cyclic operation loading.

Analysis of professional references [1–4] showed that the problem of hydrogen degradation of pipe steels is sufficiently well outlined, however, majority of the works are dedicated to solution of materials science problems of determination of peculiarities of interaction of diffusion hydrogen with metal in certain state, including after welding. The final aim of such investigations is determination of dependencies of degradation of mechanical properties of typical materials as a result of long-term operation in hydrogen medium. Nevertheless, the relevant is a set of problems on analysis of effect of material hydrogen degradation on decrease of bearing capacity and general deterioration of technical state of specific gas pipeline under design operation conditions. In particular, it is known that one of the negative effects of increased concentration of diffusion hydrogen in typical pipe steels of different strength class is decrease of their brittle fracture and fatigue fracture resistance [5]. Similar negative effect has assembly or repair welding. It causes formation of residual tensile stresses in weld metal area and heat-affected zone (HAZ) that promotes initiation and propagation of cracks. However, solution of a complex problem of analysis of reliability of welded joints of pipeline systems in transportation of gas-hydrogen blends (GHB) has insufficient representation.

This work considers an issue of numerical analysis of brittle strength of assembly welds of main gas pipelines (MG) in transportation of GHB with the purpose of determination of peculiarities of effect of hydrogen degradation of pipe metal on their reliability and operability.

INVESTIGATION PROCEDURE

Combination of a technological factor of welding effect and degradation of MG material resistance as a result of excessive hydrogenation complicates analysis of bearing capacity of pipeline in area of circumferential field weld. Therefore, it is reasonable to use the methods of mathematical modeling and computer simulation of the welding processes with corresponding numerical analysis of susceptibility of welded structure to failure that allows consideration of various aspects of external operation effect on properties and

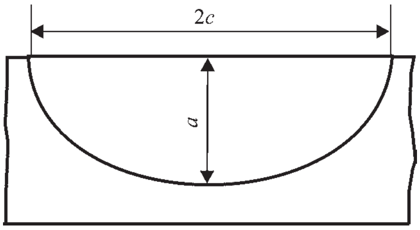

Figure 1. Scheme of surface semi-elliptical crack

boundary condition of structure. A basis of evaluation of brittle strength of welded joints was a principle of "virtual" defects, i.e. the general rules of fracture mechanics of bodies with cracks was used for calculation of a boundary condition of welded joint with postulated crack. An idea of this calculation lies in the fact that in a process of flaw detection of welded joints the small crack-like defects (the most dangerous of which are surface ones, Figure 1) can be missed or they can be formed on the first stages of structure operation. Application of such approach allows considering an effect of welding process on stress-strain state (SSS) in the area of permanent joint as well as interaction of postwelding and service stresses on welded structure reliability.

Prediction of a current and residual SSS in a section of MG welded area was performed using a finite-element analysis of kinetic of nonstationary temperature field in area of effect of welding heat source and corresponding distribution of stresses and strains of pipe metal. Thus, a distribution of temperatures was determined by solution of a heat conduction equation with temperature-dependent thermophysical characteristics of material [6]. Calculation of structure SSS kinetics was realized by means of a consecutive tracing of elasto-plastic deformations from the beginning of welding up to complete cooling of structure and further operation loading in scope of a boundary

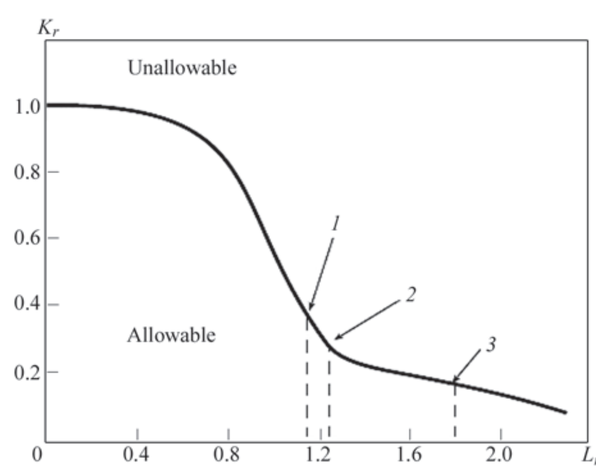

Figure 2. Two-parameter diagram of evaluation of susceptibility to brittle-tough fracture of structures with crack-like defect [9]: *1* — 1.15 (typical low-alloy steels and welded joints); *2* — 1.25 (typical low-carbon steels and austenite welded joints); *3* — 1.8 (typical austenite steels)

problem of nonstationary thermoplasticity [7]. Thus, the components of tensor of strains ε_{ij} and stresses σ_{ij} correlate between each other respectively to the generalized Hooke's law and associated law of plastic flow [8]:

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

where $i, j = r, \beta, z$ in a cylinder coordinate system; δ_{ij} is the Kronecker symbol; $K = (1–2\nu)/E$ is the modulus of three-dimensional compression; E is the Young's modulus; ν is the Poisson's ratio; $G = 0.5E/(1+\nu)$ is the shear modulus; ε_T is the temperature deformation, symbol "*" attributes corresponding change to previous step of tracing; Ψ is the function of material condition, which determines plastic flow condition:

$$\Psi = \frac{1}{2G}, \text{ if } \sigma_i < \sigma_y, \ \Psi > \frac{1}{2G}, \text{ if } \sigma_i = \sigma_y, \\ \sigma_i > \sigma_y \text{ state is unallowable.} \tag{2}$$

where σ_i is the stress intensity; σ_y is the yield limit.

Determination of Ψ function was performed by iteration in each step of a numerical tracing by time or increase of external power load in scope of solution of a boundary problem of nonstationary thermoplasticity [8].

Realization of a method of "virtual " defects for evaluation of brittle strength of MG welded joints with different level of hydrogen degradation of metal lies in a postulation of crack of certain size and orientation in each of assemblies of finite-element partition of pipe surface, in scope of which a total SSS caused by welding and service loads was determined. For each case of a virtual defect it was calculated a residual safety factor of brittle strength n based on corresponding criterion of a boundary condition of body with crack. One of the most widespread criteria is a procedure R6 [9] which is based on a two-parameter diagram of brittle-tough failure of a body with crack (Figure 2) and has the following mathematical description:

$$nK_r\left(L_r\right) = \begin{cases} \left[1 - 0.14\left(nL_r\right)^2\right] \times \\ \times\left\{0.3 + 0.7\exp\left[-0.65\left(nL_r\right)^6\right]\right\}, \\ \text{if } nL_r \le L_{r\max} \\ 0, \text{ if } nL_r > L_{r\max}. \end{cases} \tag{3}$$

where $K_r = K_I/K_{Ic}$, $L_r = \sigma_{ref}/\sigma_y$; K_i are the coefficients of stress intensity; K_{Ic} is the fracture toughness; σ_{ref} are the reference stresses

Calculation of K_I, σ_{ref} present in (3) was carried out according to the algorithms provided in particular in [10].

Analysis of distribution of strength safety factors in a structure section allows evaluating brittle strength of welded joint depending on parameters of welding process, conditions of external force effect and hydrogen degradation of material. One of the key aspects of specific realization of given algorithm is a selection of size of a postulated defect. On the one hand, linear dimension of a crack should not exceed resolution of the flaw detection tools, and on the other hand, be sufficiently large for detection of welded structure susceptibility to brittle fracture. As a conservative approach it is possible to use the standard requirements as for a size of postulated defect or correlate a residual safety factor of pipeline with crack with the design requirements [11].

Evaluation of operability of a MG welded element in addition to hydrogen degradation of material properties requires consideration of possibility of fatigue failure as a result of effect of cyclic load. This type of failure can be considered from point of view of the classical approaches to analysis of long-term strength of welded structures using *S*–*N*-diagrams [12] as well as based on evaluation of allowability of the postulated cracks by the algorithms mentioned above. At that additionally it is necessary to take into account a fatigue growth of sizes of defects for certain operation period. A rate of growth of fatigue crack (increase of its linear sizes) depending on number of cycles of load N with asymmetry of cycle R is calculated according to the Paris's law [13]:

$$\frac{da}{dN} = \frac{C\Delta K^m}{(1-R) - \frac{\Delta K}{K_{Ic}}}, \quad (4)$$

where C, m is the Paris coefficients; ΔK is the range of load intensity coefficient.

PRACTICAL EXAMPLE

The peculiarities of effect of hydrogen in a content of a blend transported by pipeline on strength of field welded joints was investigated by a typical example of straight MG section of $D = 1420$ mm diameter and wall thickness $t = 20$ mm, pipe material — pipe steel 17G1S. Inner pressure of a transported GHB (maximum value $P = 7.5$ MPa) was considered as an external load and additionally a bending moment in pipe axis plane M as for the case of static loading as well as at cyclic one to 10000 cycles. A maximum value of bending moment was taken equal $8.4\cdot10^9$ N·mm that correspond to the values of additional axial stresses comparable with those provoked by the maximum inner pressure. In general case the bending moment of similar type can be caused by different factors depending on type and conditions of operation of a specific pipe section. Thus, for the sections of aerial crossings through artificial or natural obstacles an additional bend is typically formed at wind loads or in passing pipe inspection gears (in particular, at resonance increase of oscillation amplitude). For underwater MG sections similar additional force effect can appear in failure of integrity of distributed ballasting and cyclic effect of undercurrents.

Table 1. Effect of hydrogen in atmosphere on properties of smooth specimens from pipe steel at tensile tests and rate of fatigue crack development [14]

Hydrogen concentration, vol.%	Ultimate strength, MPa	Yield limit, MPa	$C\cdot10^8$	m
0	656.39	523.90	2.25	2.592
5	666.00	518.56	25.7	2.582
10	657.81	525.52	29.8	2.580
20	656.06	524.83	35.1	2.574
50	661.54	523.67	99.3	2.389

In general case the mechanical properties of metal of pipeline element being considered depend on hydrogen concentration ν_H in transported GHB and corresponding level of hydrogen degradation. According to available data [14] the most negative effect of hydrogen on pipe steels is observed on characteristics of fatigue fracture resistance that is quantitatively described by the changes of the Paris coefficients C and m (see Table 1). At that at indicated concentrations of hydrogen in GHB up to 50 % no significant decrease of fracture toughness K_{1c} is observed [15]. Similarly, it was assumed that for low-alloy pipe steels a prevailing factor affecting resistance to fatigue crack development in area of weld metal and HAZ is the significant residual stresses (reaching metal yield limit) and high ΔK, whereas inhomogeneity of the Paris coefficients in a welded structure section is insignificant.

As it was mentioned above, an important parameter in calculation of brittle strength of MG welded element is a value of postulated surface crack $2c\times a$ (see Figure 1). For a case being considered using preliminary calculation it was determined that at $2c\times a =$ $= 3.0\times0.5$ mm a brittle strength margin of pipe on a welded joint periphery made around 1.81 and, thus, conservatively corresponds to the pipeline design requirements (1.79). The cracks of different orientation relatively to pipe axis (longitudinal, circumferential) were studied for a particular consideration of 3D SSS in calculation of brittle strength and minimum safety factor n was selected.

RESULTS AND DISCUSSION

A finite-element analysis of residual SSS in area of welding of circumferential welds allowed taking into account an effect of assembly technological aspect on

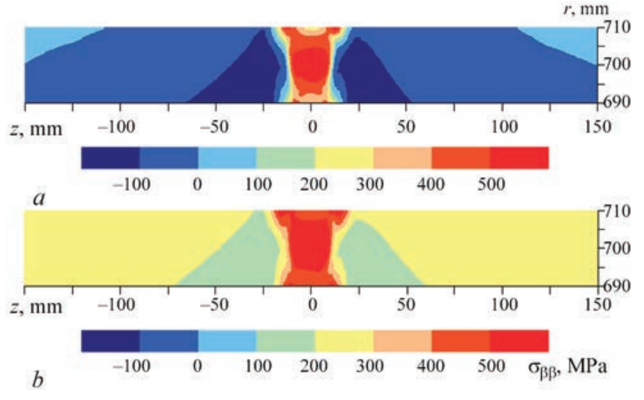

Figure 3. Calculation field of circumferential stresses $\sigma_{\beta\beta}$ in longitudinal pipe section: *a* — residual postwelding state; *b* — under condition of loading by inner pressure 7.5 MPa

reliability and operability of pipeline. Interaction of operation stresses with postwelding ones has a significantly nonlinear nature in both typical directions relatively to pipeline axis, namely circumferential and axial (Figures 3, 4). Inhomogeneity of a stress field at different stages of cyclic load of MG welded section provokes a corresponding spatial distribution of ranges of a stress intensity coefficient ΔK (Figure 5) and, as a result, a change of susceptibility of various sections of structure to brittle fracture in a process of long-term operation. The most susceptible to brittle fracture at static loading is a weld areas and HAZ. They are characterized with high total tensile stresses, caused by interaction of operation and postwelding SSS (Figure 6).

Regarding the fatigue strength of welded joints under effect of cyclic varying inner pressure or bending moment, the larger ranges of values of stress intensity coefficient in HAZ provoke significant decrease of the residual safety factors *n* in prediction of long-term brittle strength. As can be seen from investigation results (Figure 6) hydrogen degradation has the maximum effect on the brittle strength residual safety factor of HAZ metal under conditions of cyclic load by inner pressure:

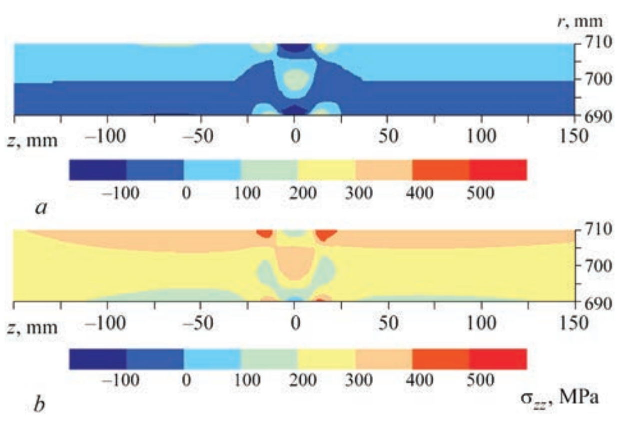

Figure 4. Calculation field of axial stresses σ_{zz} in longitudinal pipe section: *a* — residual postwelding state; *b* — under condition of loading by inner pressure 7.5 MPa and bending moment $8.4\cdot10^9$ N·mm

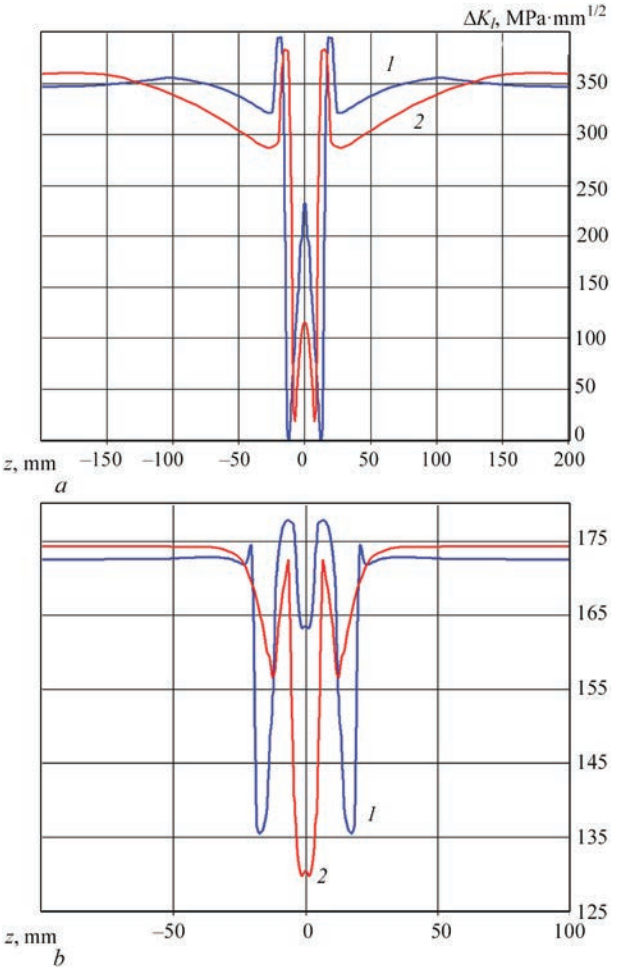

Figure 5. Distribution of values of range of stress intensity coefficient ΔK along inner (*1*) and outer (*2*) surfaces of pipe after 10000 cycles of loading by inner pressure (*a*) and bending moment (*b*)

a total decrease of *n* values exceeds 25 % in comparison with a case of transportation of pure natural gas. At that an effect of cyclic bending moment has not so dramatic influence on pipeline reliability.

The dependencies of a minimum brittle strength safety factor of MG welded element on volume of hydrogen concentration ν_H in a transported GHB in base metal and in HAZ under conditions of cyclic loading by inner pressure and bending moment are quasi-linear, have different angles of inclination (Figure 7) that corresponds to different metal susceptibility to brittle fracture in developed hydrogen degradation and cyclic loading. This effect can also be numerically characterized by a value of fatigue growth of crack size. Thus, in the case of cyclic change of inner pressure depending on hydrogen concentration in a blend the maximum increase of linear dimensions of defect for 10000 cycles of loading is in the range from 0.13 mm (at $\nu_H = 0$ %) to 4.7 mm ($\nu_H = 50$ %), in case of cyclic loading by bending moment from 0.013 to 0.31, respectively.

It is necessary to note that in scope of this investigation the consideration is given particularly to brittle strength of metal of MG welded section, but in area

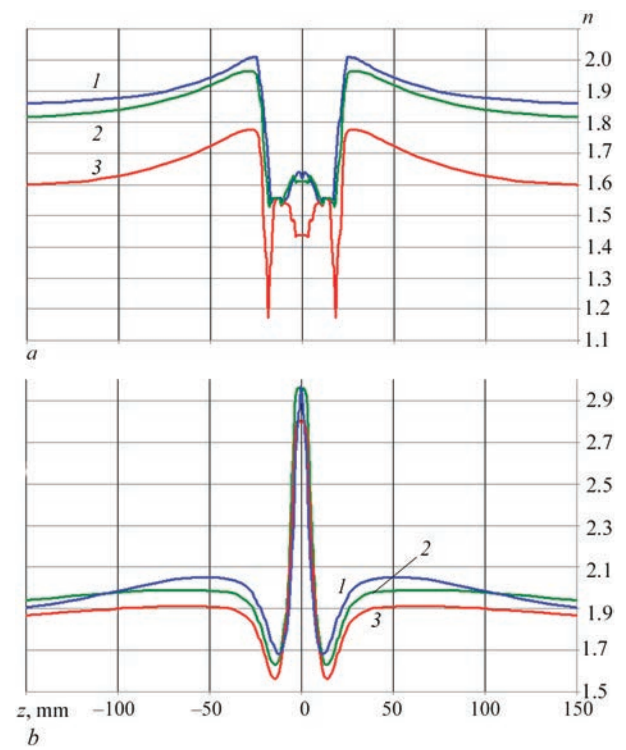

Figure 6. Distribution of values of brittle strength safety factor *n* along outer pipe surface under conditions of static and cyclic loading by inner pressure (*a*) and bending moment (*b*): *1* — static loading (ν_H = 0.5); *2* — cyclic loading (ν_H = 0.0, 10000 cycles); *3* — cyclic loading (ν_H = 0.5, 10000 cycles)

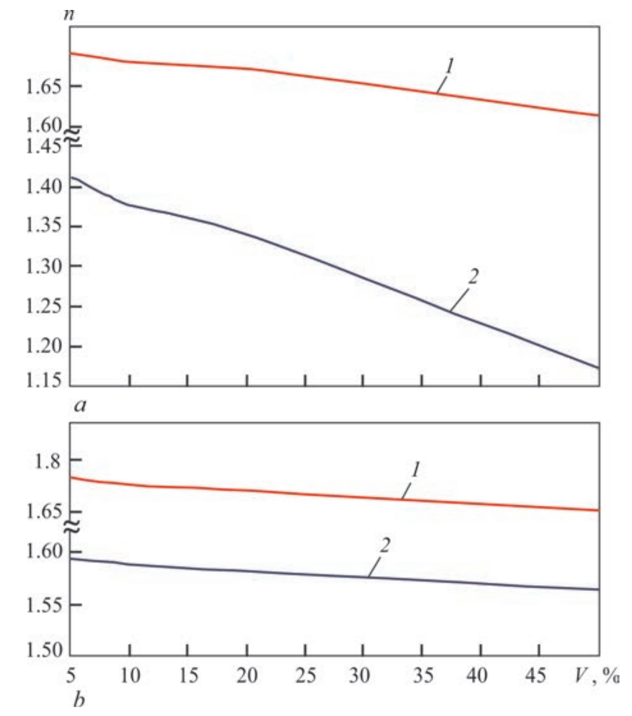

Figure 7. Dependencies of minimum brittle strength safety factor of MG welded element on volume concentration of hydrogen ν_H in transported blend in base metal (*1*) and in HAZ (*2*) under conditions of cyclic loading (10000 cycles) by inner pressure 0–7.5 MPa (*a*) and bending moment $8.4 \cdot 10^9$ N·mm

of welded joint, where stress value reaches material yield limit, the boundary condition and macroscopic failure can distinguish by tough or brittle-tough fracture. However, these types of fracture are not typical in a case of hydrogen embrittlement of metal in long-term operation of pipeline under conditions of continuous contact with hydrogenized medium.

CONCLUSIONS

1. It was developed a numerical procedure for analysis of brittle strength of the MG welded sections in transportation by them of the blends of natural gas and hydrogen. A basis of proposed procedure is a finite-element analysis of structure SSS in welding and further operation loading as well as calculation of a residual safety factor under assumption of presence of a postulated surface crack of certain size. At that the possibility was considered for prediction of brittle strength by static as well as cyclic loading. For this a rate of fatigue growth of defect size by the Paris's law was calculated.

2. A typical example of straight MG section ($D \times t$ = = 1420×20 mm, 17G1S) was used for investigation of a peculiarity of effect of hydrogen degradation of metal on pipeline reliability. Inner pressure (up to P = 7.5 MPa) and bending moment in an axis plane (up to $8.4 \cdot 10^9$ N·mm) was considered as an external loading. It is shown that the most susceptible to brittle fracture is a weld section and HAZ, which are characterized with the high total tensile stresses caused by interaction of operation and postwelding SSS. However, regarding fatigue strength of the welded joints under effect of cyclic loading by inner pressure or bending moment, the bigger ranges of values of stress intensity coefficient in HAZ provoke more substantial decrease of residual safety factors in prediction of long-term brittle fracture.

3. It is shown that the hydrogen degradation has the maximum effect on brittle strength of a welded pipeline under conditions of cyclic load by inner pressure: 10000 cycles of loading promote total decrease of a residual safety factor in HAZ for more than 25 % in comparison with a case of transportation of pure natural gas. At that the cyclic bending moment does not have significant effect of pipeline reliability.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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