INFLUENCE OF HYDROGEN CONCENTRATION AND CRACK GEOMETRY ON THE RESIDUAL LIFETIME OF PIPELINE STEELS

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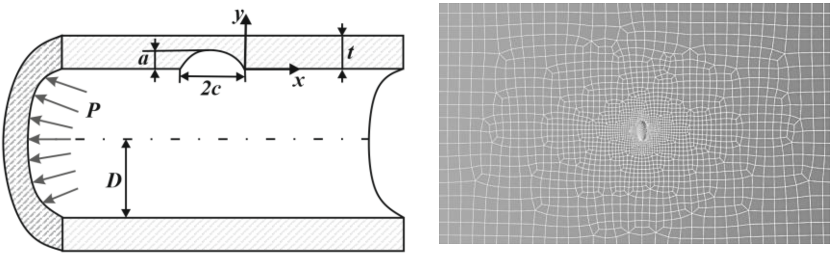
The paper presents a finite element model for estimating the residual durability of pipe steels in the hydrogen environment. The model takes into account hydrogen diffusion, defect geometry, and loading conditions. The results show that both hydrogen concentration and internal pressure significantly reduce the fatigue crack growth resistance, providing useful data for the diagnosis and design of safe hydrogen transport systems.

Keywords: hydrogen embrittlement, pipeline steels, fatigue crack growth, finite element modelling, residual lifetime.

Introduction. Hydrogen is considered one of the key environmentally friendly energy sources of the future. Its widespread use in transport, energy and industry can significantly reduce carbon dioxide emissions and other harmful effects on the environment. However, the interaction of hydrogen with metals has a number of negative consequences. The most dangerous phenomenon is the hydrogen embrittlement (HE), which significantly reduces the mechanical strength and durability of structural materials [1]. Particular attention is paid to pipeline steels, as they are used to transport gases and liquids under high pressure. Under such conditions, even small defects caused by corrosion or erosion can turn into critical areas of stress and hydrogen concentration [2]. The residual durability of pipelines determines their safety, and assessing this parameter is a key task of engineering diagnostics [3]. In many cases, defects take the form of internal semi-elliptical cracks, which are difficult to model due to the uneven distribution of stresses and hydrogen in their vicinity. Therefore, it is important to create mathematical models that take into account the crack geometry, hydrogen diffusion and loading conditions.

Model and methods. The work uses an approach based on the finite element modelling (ANSYS 2024R2), which allows both the stress-strain state of the material and hydrogen mass transfer processes to be taken into account. A schematic representation of a pipe segment with an internal semi-elliptical crack is shown in Fig. 1. A mesh was refined in the vicinity of the crack tip, which provides a more accurate description of the local stress field to ensure the adequacy of calculations.



a) *b*)

Fig. 1. Schematic model of a pipe segment with a semi-elliptical crack (a) and division into finite elements with thickening in the vicinity of the crack.

The stress intensity factor K_I is the key parameter for describing the crack behaviour. Its value is determined by the Newman–Radju formula:

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

where σ – the membrane stress, *a* – the crack depth, *F(a/c)* – the geometric factor [3]. The threshold and critical values of *ΔK*, as well as the Paris coefficients *A* and *n*, are approximated as functions of hydrogen concentration C_H. This allows us to estimate how hydrogen affects the resistance of the material to crack propagation.

Parameter	Analytical form
Threshold swing KIN	$\Delta K_{\mathrm{th}}(C_H) = 7.13 + 11.9\exp(-16C_H)$
Critical swing KIN	$\Delta K_{\mathrm{fc}}(C_H) = 16.65 + 14.1\exp(-6.36C_H)$
Paris coefficient	$A(C_H) = 10^{-10} + 1.3\cdot10^{-9}\exp(-0.5C_H) + 10^{-8}\exp(-13.6C_H)$
Paris index	$n(C_H) = 4.39 + 0.59\ln C_H$

The crack growth rate was calculated using the modified Paris law, which takes into account the current hydrogen concentration in the defect vicinity. For this purpose, integration from the threshold to the critical crack depth was performed, which made it possible to estimate the number of load cycles to failure:

$$\frac{da}{dN} = A(C_H)\left[K_I(a)\right]^{n(C_H)} \tag{2}$$

Hydrogen diffusion was described by the total concentration, which includes diffusible hydrogen C_L (defined by the Fick's equation) and trapped hydrogen C_T (described by the Oriani model [2]). The latter depends on plastic deformations and the structure of steel [4]. Thus, the model covers both thermodynamic and mechanical aspects of the process.

$$C_H = C_L + C_T \tag{3}$$

Results. Modelling showed that the maximum hydrogen concentration is formed near the crack tip. This is explained by the fact that high local stresses create additional traps for hydrogen atoms diffusing into the metal. The crack growth rate in the calculations was determined by the modified Paris law, which depends on the current hydrogen concentration.

$$N_{fc} = \int_{a_{th}}^{a_{fc}} \frac{da}{A(C_H)\left[K_I(a)\right]^{n(C_H)}}\,, \tag{4}$$

The results of the calculations indicate that as the internal pressure in the pipe increases, the residual durability decreases sharply.

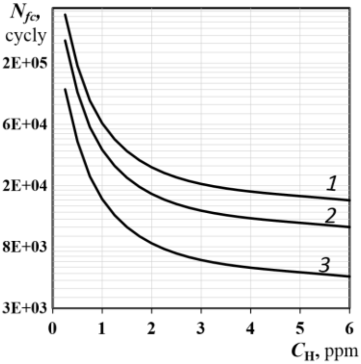


Fig. 2. Dependence of residual durability N_{fc} on hydrogen concentration at different internal pressures: P = 8 MPa (line *1*); P = 10 MPa (*2*); P = 15 MPa (*3*).

The dependencies in Fig. 2 show that at a pressure of 8 MPa, the durability of pipes with defects is significantly higher than at 15 MPa. This indicates that an increase in pressure significantly accelerates destruction even at the same hydrogen concentration.

The influence of hydrogen concentration is also decisive: even a slight increase in concentration leads to a decrease in the number of cycles before fracture [5].

Conclusions. The proposed model comprehensively takes into account hydrogen diffusion processes, defect geometry and loading conditions. This makes it possible to assess accurately the residual durability of pipeline steels. The obtained results can be used for engineering diagnostics of pipelines operating in the hydrogen environment; when planning repairs and replacement of pipeline system components; and for optimising design solutions, taking into account resistance to hydrogen embrittlement.

Further research may be directed towards experimental verification of the model, as well as expanding its application to different steel grades and operating conditions. This will allow the creation of reliable criteria for assessing the safety of hydrogen systems and increasing their efficiency.

1. *Gangloff, R. P. Hydrogen-assisted cracking of high strength alloys. In: Milne, I.; Ritchie, R. O.; Karihaloo, B. (eds.) Comprehensive Structural Integrity, Vol. 6: Environmentally Assisted Fracture. Elsevier, 2003, pp. 31–101. DOI: 10.1016/B0-08-043749-4/06134-6.*
2. *Oriani, R. A. Hydrogen diffusion and trapping in steels. Acta Metallurgica, 1970, 18(1), 147–157. DOI: 10.1016/0001-6160(70)90078-7.*
3. *ASTM E647-15e1. Standard Test Method for Measurement of Fatigue Crack Growth Rates. ASTM International, 2015. DOI: 10.1520/E0647-15E01.*
4. *Krom, A. H. M.; Koers, R. W. J.; Bakker, A. Hydrogen transport near a blunting crack tip. Journal of the Mechanics and Physics of Solids, 1999, 47(4), 971–992. DOI: 10.1016/S0022-5096(98)00064-7.*
5. *Dutkiewicz, M.; Hembara, O.; Ivanytskyi, Y.; Hvozdiuk, M.; Chepil, O.; Hrynenko, M.; Hembara, N. Influence of hydrogen on the fracture resistance of pre-strained steam generator steel 22K. Materials, 2022, 15(19), 6596. DOI: 10.3390/ma15196596.*