Structural Integrity Issues at Repurposing Gas Pipelines for Hydrogen Service

Viacheslav Bogdanov1[0000-0001-9864-9120], Zinoviy Nazarchuk2[0000-0003-0402-0570] and   
Olha Zvirko2[0000-0002-6973-6804]

1 S.P. Timoshenko Institute of Mechanics of the NAS of Ukraine, P. Nesterova St., 3, Kyiv 03057, Ukraine

2 Karpenko Physico-Mechanical Institute of the NAS of Ukraine, Naukova St., 5, Lviv 79060, Ukraine  
olha.zvirko@gmail.com

**Abstract.** The hydrogen economy is advancing yet confronts significant challenges, particularly in hydrogen transportation via pipelines. Ukraine, with its extensive gas transmission infrastructure connected to the European Union, offers a unique opportunity for hydrogen transport. In this study, the challenges for repurposing existing natural gas pipelines in Ukraine for hydrogen transportation are considered. They are mainly related to the risk of hydrogen embrittlement of pipeline steels and deterioration of the mechanical properties of steels due to long-term operation. The influence of gaseous hydrogen on corrosion and hydrogen uptake by steels is studied. The fracture mechanics approaches in meeting the challenges are considered, and the role of hydrogen-induced stress in damaging and strain ageing of pipeline steels is analyzed. The fracture toughness of pipeline steels from the Ukrainian natural gas network under varying specimen displacement rates and hydrogen action using the J-integral method was investigated. A methodology for evaluating the serviceability of pipelines at hydrogen transportation, based on the criterion of operational decrease in fracture toughness of pipeline steels under hydrogen influence, is proposed.

**Keywords:** Steel, Pipeline, Structural Integrity, Hydrogen Embrittlement, Mechanical Properties, Fracture Toughness, *J*-Integral Method, Degradation.

1. Introduction

Hydrogen is a promising green energy carrier with significant potential to decarbonize sectors such as transportation, industry, and energy production. However, realizing this potential requires the development of efficient hydrogen transportation networks. According to the European Hydrogen Backbone initiative, one of the promising and cost-effective approaches is to repurpose existing natural gas pipelines for hydrogen transport [1], leveraging current infrastructure to reduce deployment time and investment [2, 3]. This strategy can accelerate the development of hydrogen infrastructure and support the broader adoption of hydrogen as a sustainable energy source. Ukraine has an extensive gas transmission network connected to the European Union, as well as a potential for green hydrogen production. Therefore, there is a unique opportunity for hydrogen transportation through existing natural gas pipelines in Ukraine.

However, a significant part of both main and distribution gas pipelines in Ukraine has a significant service life and operates in harsh mechanical and corrosion conditions. Therefore, when assessing the possibility of safe transportation of hydrogen through pipelines with a service life of 30 years or more, it is necessary to take into account their degradation in terms of key properties that determine their serviceability [4, 5]. In such an analysis, attention is often paid to the development of damage at the nano-, micro- and macro-levels, which is the main reason for the decrease in resistance to brittle fracture. For pipelines that have been in long-term service, the risk of in-service embrittlement must also be addressed [5–8]. This degradation can increase sensitivity to hydrogen-induced damage and contribute to other operational issues [5]. Therefore, an assessment of the current physical and mechanical properties of steels, primarily resistance to brittle fracture and crack growth, is required for gas pipelines to substantiate their serviceability under hydrogen service. Degree of embrittlement of a metal is usually evaluated by changes in certain mechanical properties (plasticity, impact toughness and resistance to crack growth).

Ensuring the compatibility of operated pipeline steels with hydrogen is one of the primary technical challenges in repurposing gas pipelines for hydrogen service [9]. Hydrogen can induce embrittlement in steel, reduce ductility [3, 6, 10–15], fracture toughness [3, 6, 10, 13, 15–23], fatigue resistance [2, 6, 14, 24–26], and ductile-brittle transition in fracture mode [6, 11, 12, 15, 18, 24, 27]. This can influence on structural integrity of pipelines and increase safety risks. The most sensitive to metal embrittlement are the parameters of crack growth resistance [3, 6, 10, 13, 15–23, 28, 29]. For low-strength and, accordingly, highly ductile steels, the *J*-integral method of nonlinear fracture mechanics is used [3, 13, 19, 28]. Known studies of the mechanisms of interaction of ferritic-pearlite steels with hydrogen were carried out mainly for steels in the as-delivered state [11–27], and do not take into account the influence of long-term operation conditions on changes in the metal state.

Under hydrogen transportation via pipelines, there are different mechanisms of hydrogen evolution and permeation into steels [6, 30]. One contributing mechanism is hydrogen evolution resulting from electrochemical interactions between the metal and moisture condensed on the inner surface of the pipe under climatic changes in temperature. Furthermore, this process can be intensified by transporting gaseous hydrogen due to saturation of the moisture [30]. The other one is dissociation of molecular hydrogen. All these mechanisms can occur in the case of hydrogen transport through existing natural gas pipelines.

The purpose of the work is to analyze the influence of hydrogen on deformation, embrittlement and fracture of operationally degraded pipeline steels, considering operational conditions under hydrogen transportation through existing natural gas pipelines. The presented research results are important for understanding the mechanisms of metal-hydrogen interaction and the fracture resistance of steels under such conditions.

1. Assessment of Degradation Degree of Existing Pipeline Steels

Existing natural gas pipelines are subject to aging and degradation, which implies deterioration of the mechanical properties of pipeline steels. The process is facilitated by hydrogen absorbed under electrochemical interaction between the metal and corrosive environment (condensed moisture inside the pipeline). Hydrogen evolution and permeation into a metal during corrosion cause its embrittlement. One of the most dangerous consequences of hydrogen embrittlement of pipeline steel during long-term operation is a significant decrease in brittle fracture resistance [4, 5, 8, 9], which may lead to pipeline failure. Corrosion, hydrogen uptake, and working stresses during long-term operation, intensified by each other, are the main reasons for in-service degradation of gas pipeline steels.

Pipelines should be periodically assessed and timely repaired because the mechanical properties of steels, associated with safe operation and put in engineering calculations at the design stage, deteriorate under long-term service. Accurate evaluation of the current technical condition of pipeline steel is crucial for addressing reliability and estimating residual service life [31]. These assessments typically need to be conducted without interrupting pipeline operation. To achieve this, a combination of monitoring systems and discrete non-destructive inspection and testing techniques is employed. Degradation of pipeline steels is usually evidenced by mechanical testing of steel specimens machined from the pipe, comparing properties of the as-delivered metal and the operated one [4, 5, 8, 9].

Two stages of pipeline steel degradation, strain aging and dissipated damaging, were identified [4, 8]; and, for the second one, two substages were additionally distinguished [5]: disoriented damaging and damaging oriented in rolling direction. The effect of strain aging on mechanical properties of steels can include increased yield and tensile strength and hardness, and reduced plasticity, fracture toughness and impact strength. However, this tendency of changes in the mechanical properties could be violated if the metal undergoes dissipated damage under operation. In such a case [5], strength, hardness, reduction in area, and fracture toughness of the damaged material are decreased, and elongation is increased. The presence of delaminating cracks oriented transverse to the fracture plane can lead to an increase in impact toughness of material at testing of longitudinal specimens [5].

Changes in brittle fracture resistance for the low-carbon ferrite-pearlite 17H1S steel (API 5L X52 strength grade), commonly used for Ukrainian natural gas pipelines, caused by operation, are presented in Fig. 1. It can be seen that the impact strength of the metal deteriorates due to in-service degradation.

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**Fig. 1.** Impact strength *KCV* of the 17H1S steel (API 5L X52 strength grade) depending on time of operation *t*.

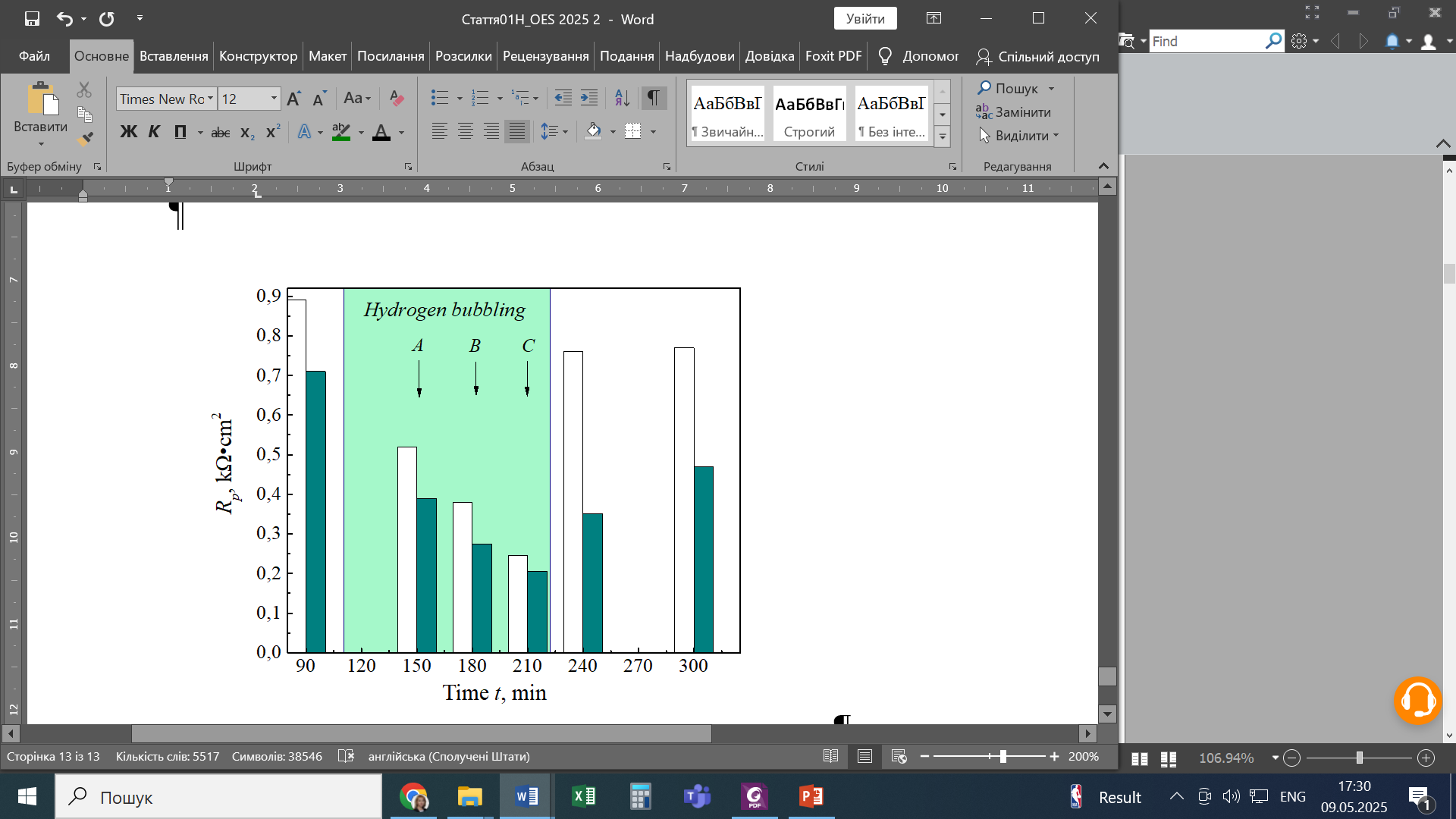
Despite of the fact that impact toughness of pipeline steels, determined on longitudinal specimens, can be increased due to decreasing cohesion between fibers of structure and developing delamination and microcracks orientated along rolling direction, increasing fracture energy, their fracture toughness is always decreased during the whole operation time of pipeline [4, 5, 8].

1. Influence of transported hydrogen on metal-corrosive environment interaction

In a natural gas transmission system, the possibility of hydrogen permeation into pipeline steel from its inner surface due to corrosion with hydrogen depolarization in a layer of condensed moisture containing corrosively active components was demonstrated in [32]. In the case of transportation of gaseous hydrogen, it can affect this process, in particular, the hydrogen adsorption/desorption behavior. To model such an effect, an experimental method was developed involving a study of the electrochemical interaction of a metal with a corrosive environment under bubbling with gaseous hydrogen. Hydrogen was generated directly in the electrochemical cell by electrolysis of water, which simplifies and increases the safety of the experiments compared to using gaseous pressurized hydrogen.

Pipeline steel API 5L X70 was tested in the as-delivered and post-operated (after 37 years of service) states in a test solution simulated condensed moisture inside natural gas pipelines [32] with chemical composition in g/l as follows: 14.44 Na+, 0.60 Ca2+, 0.518 Mg2+, 0.389 Sr2+, 0.14 Ba2+, 0.129 K+, 0.052 NH4+, 0.0025 Li+, 0.001 Al3+, 0.0003 Fe2+, 0.0005 Mn2+, 25.40 Cl–, 0.522 HCO3–, 0.1 Br–, 0.018 SiO32–, 0.0021 I–, 0.0036 F–, 0.005 NO3–, 0.005 SO42–, and 0.005 PO43–.

The polarization resistance of the steel was registered under experiments (Fig. 2). measuring at each stage. The results showed that the steel in the as-delivered state revealed lower corrosion activity (higher polarization resistance) at all stages of the experiment (Fig. 2) compared with the operated one. In particular, in stationary conditions (before hydrogen bubbling), polarization resistance of the steel is 0.89 kOm∙cm2 and 0.71 kOm∙cm2 in the as-delivered and operated states, respectively. The polarization resistance of the steel in both states decreases with increasing hydrogen bubbling intensity, but more noticeably for the operated state (almost three times). A pronounced aftereffect of hydrogen was revealed; the polarization resistance of the steel was only partially restored after the stop of bubbling hydrogen. The effect was much more pronounced for the operated metal – even 90 min after hydrogen bubbling termination, the polarization resistance recovered only up to 65% from its initial value, whereas, for the as-delivered state, it reached 87%.



**Fig. 2.** Polarization resistance *Rp* of the API 5L X70 pipeline steel (white bars – as-delivered state, green bars – post-operated one) depending on time *t* of exposure to a test solution and hydrogen bubbling with different intensities (current densities *i*): *A* – *i* = 14.3 mA/cm2; *B* – *i* = 57.1 mA/cm2; *C* – *i* = 142.9 mA/cm2.

Significant hydrogen uptake by the surface layer of the tested sample was evidenced by hydrogen-induced cracking of the surface of the operated steel. It was associated with the shift of the equilibrium of hydrogen reactions in the system by the available gaseous hydrogen towards the absorbed one according to the following schemes:

H2 ⇄ H2(ads) ⇄ 2H(ads) ⇄ 2H+ + 2 e–; (1)

Hads ⇄ Habs. (2)

These equilibria depend on gaseous hydrogen pressure and the activity of hydrogen ions (pH) in the solution.

Thus, the influence of molecular hydrogen on the interaction of steels with the corrosive environment was manifested in a decrease in their corrosion resistance, as well as in the intensification of hydrogen permeation, which was associated with an increase in the proportion of hydrogen absorbed by the metal.

1. Hydrogen-deformation damaging in low-strength ferritic-pearlite pipeline steels

The various mechanisms of hydrogen influence on the deformability and failure of steels are considered [12], and among them, hydrogen trapping in microdefects, which induces stresses comparable to those from mechanical loading. Absorbed hydrogen can cause stresses in steels [33, 34], resulting in cracking, blistering, delamination, and damage even without mechanical loading [5, 24, 35]. For low-strength pipeline steels, hydrogen-induced stresses create preconditions for the intensification of damage at the nano- and micro-scales. In general, high-strength pipeline steels are mostly highly susceptible to hydrogen embrittlement and hydrogen-induced cracking, while low-strength steels are considered immune to the action of hydrogen. However, for long-term operated (degraded by the mechanism of dissipated damage) steels, this pattern may be different. Analyzing the mechanical situation at the micro-scale, the increased ductility inherent to low-strength steels contributes to the relaxation of peak stresses. This makes it difficult to achieve the critical combination with high hydrogen concentration required for hydrogen-induced cracking. However, long-term operation of steels violates the general regularity – low-strength steels exhibit intensive microdamaging and a high susceptibility to hydrogen-induced cracking at the micro- and macro-scales [5]. That is, low-strength steel, slightly sensitive to hydrogen embrittlement in the as-delivered state, acquires such sensitivity during operation, increasing the risk of pipeline integrity violation during hydrogen transportation.

A hypothesis has been put forward about the facilitating development of dissipated damages in low-strength steels by the mechanism of material deformation under the influence of high-pressure hydrogen recombined in defects. The development of defects is influenced by the components of the microstructure, in particular, non-metallic inclusions, oriented in the rolling direction, at the boundaries with the matrix, where nano-sized pores are formed, which are effective hydrogen traps. Hydrogen, on the one hand, weakens the cohesion between the inclusion and the matrix (Fig. 3a), and on the other hand, accumulates in pores and other discontinuities, which causes delamination between the components of the microstructure and subsequent deformation of the surrounding metal under the pressure of recombined hydrogen. Over time, such defects develop to significant sizes (Fig. 3b). Schematically presented in Fig. 3c microdefect illustrates delamination along the internal contour *1* (in the given example between the non-metallic inclusion and the matrix), while along the external contour *2*, the deformation mechanism of defect development. The distance and, accordingly, the volume of the cavity between the defect contour and the inclusion are insignificant, which facilitates the accumulation of high-pressure hydrogen. Therefore, the development of damages in low-strength steels at the nano- and micro-scales, facilitated by hydrogen, is accompanied by a combination of the deformation mechanism with the decohesive one. As a result, even low-strength steel with a high degree of dissipated damage is characterized by low resistance to brittle fracture (for example, the impact toughness of Charpy specimens from the 17H1S steel (API 5L X52 strength grade) after 40 years of operation is 125 J/cm2 versus 206 J/cm2 for the as-delivered state). Thus, the sensitivity to hydrogen embrittlement of low-strength ferritic-pearlite pipeline steels after long-term operation is associated with the implementation of the hydrogen-deformation mechanism of defect development.

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| *a* | b |
|  | |
| c | |

**Fig. 3.** Fractograms (a, b) and scheme (c) illustrating the decohesion of non-metallic inclusions from the matrix (a), defects of hydrogen-deformation nature (b) and their formation (c): *1* – internal contour of defect; *2* – external contour of defect; NMI – non-metallic inclusion; Н2 – recombined hydrogen.

The decohesive effect of hydrogen facilitates the damage in high-strength steels, while in lower-strength steels, the role of deformation mechanisms in defect development due to high pressure of recombined hydrogen increases.

1. Hydrogen-assisted strain aging of pipeline steels

Strain ageing in pipeline steels could occur under operation since they are subjected to plastic deformation as a result of manufacturing, installation, and service of pipelines, and elevated temperatures of pipelines behind compressor stations.

Strain ageing involves the formation of Cottrell atmospheres – clusters of carbon and nitrogen atoms that accumulate around dislocations, thereby hindering plastic deformation of a metal [37]. The implementation of strain ageing requires a high dislocation density, along with specific temperature-time conditions that allow impurity atoms to diffuse. In the laboratory, strain ageing is typically induced by pre-straining steel samples by 10%, followed by heating at 250 °C for one hour [37]. The resulting changes in mechanical properties generally manifested as embrittlement, indicated by reduced ductility and impact toughness.

The high level of hydrogen-induced stresses in steels can affect their strain aging, leading to embrittlement. In such a case, hydrogen-induced stresses within the steel create localized regions of plastic deformation, which may serve as favorable sites for strain ageing. Since hydrogen diffusion in a steel is a microstructurally selective, the highest internal stresses are expected at sites with the highest local hydrogen concentration, such as along preferred diffusion pathways. In steels, grain boundaries are considered the dominant paths for hydrogen transport [38]. It was assumed that hydrogen induces internal stresses in a steel and, consequently, sites with local plastic deformation induced by hydrogen could be preferable for strain ageing.

To evaluate the effect of hydrogen on strain aging and, consequently, embrittlement of pipeline steel, a set of experiments was carried out. The research object was low-carbon ferrite-pearlite 17H1S pipeline steel (0.17C-Mn-Si, API 5L Х52 strength grade). Samples were cut out in the longitudinal direction from the pipe sections. A series of samples were tested:

1. in as-delivered state;
2. after low-temperature tempering at a temperature of 250 ºС for 1 hour;
3. after electrolytic hydrogen charging and subsequent low-temperature tempering under the same regime.

The steel samples were electrolytically hydrogen pre-charged in an aqueous solution of H2SO4 (pH = 2) at a current density of 50 mА/сm2 for 100 hours at a temperature of 20°С before the specimens were subjected to low-temperature tempering.

The specimens for tensile, impact strength and fracture toughness tests were machined from the steel samples after the abovementioned procedures. The cylindrical smooth tensile specimens had a gage length of 25 mm and a diameter of 5 mm. Tensile tests were carried out at the strain rate ε = 3⋅10-3 s-1 at ambient temperature using tensile specimens to obtain the basic mechanical properties of the material: ultimate strength σUTS, yield strength σY and reduction in area RA. For impact toughness testing, the standard-size (10 mm × 10 mm × 55 mm, working cross-section 10 mm × 8 mm) V-notch specimens were used. Fracture toughness was evaluated by the *J*-integral method according to the ASTM E 1820 standard requirements using single-edge notched bend (SEN(B)) specimens (4x15x160 mm); parameter *Jcr*, the value of the *J-*integral for a crack growth of 0.2 mm, was determined. Susceptibility to stress corrosion cracking was evaluated by reducing the plasticity characteristic RA under tensile testing specimens at the strain rate ε = 10-6 s-1 in the NS4 test solution by the indicator βSCC as follows:

βSCC = , (3)

where RANS4, RAair – reduction in area of specimens after tensile testing in a corrosive environment and air, respectively. The chemical composition of the NS4 solution in g/l was as follows: 0.122 KCl, 0.483 NaHCO3, 0.181 CaCl2∙2H2O, and 0.131 MgSO4∙7H2O.

The test results are presented in Table 1.

**Table 1.** Mechanical properties and resistance to brittle fracture of the 17H1S steel in different states tested in air (numerator) and NS4 solution (denominator).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Steel state | σY, MPa | σUTS,MPa | RA, % | *KCV*, J/cm2 | *Jcr*, N/mm | βSCC, % |
| As-delivered | 428 / 429 | 531 / 529 | 71 / 69 | 129 / - | 322 / - | - / 3 |
| Low-temperature tempered | 433 / 431 | 535 / 538 | 72 / 68 | 125 / - | 330 / - | - / 4 |
| Hydrogen pre-charged with subsequent low-temperature tempering | 435 / 434 | 533 / 537 | 74 / 53 | 131 / - | 286 / - | - / 25 |

Low-temperature tempering had practically no effect on the mechanical behavior of the studied steel (Table 1). However, the steel after electrolytic hydrogen charging and subsequent low-temperature tempering under the same regime was characterized by lower fracture toughness and, especially, higher susceptibility to stress corrosion cracking compared to the untreated one. This indicates that the strain aging of the steel in local microstructural areas, induced by the hydrogen action (hydrogen pre-charged with subsequent low-temperature tempering), did not affect the properties of the steel at the macro scale (ultimate and yield strength, reduction in area, and impact strength), slightly reduced them at the meso-scale (*Jcr*) and most significantly at the micro-scale (susceptibility to stress corrosion cracking βSCC = 25%).

1. Features of the application of nonlinear fracture mechanics approaches for assessing the hydrogen embrittlement of steels

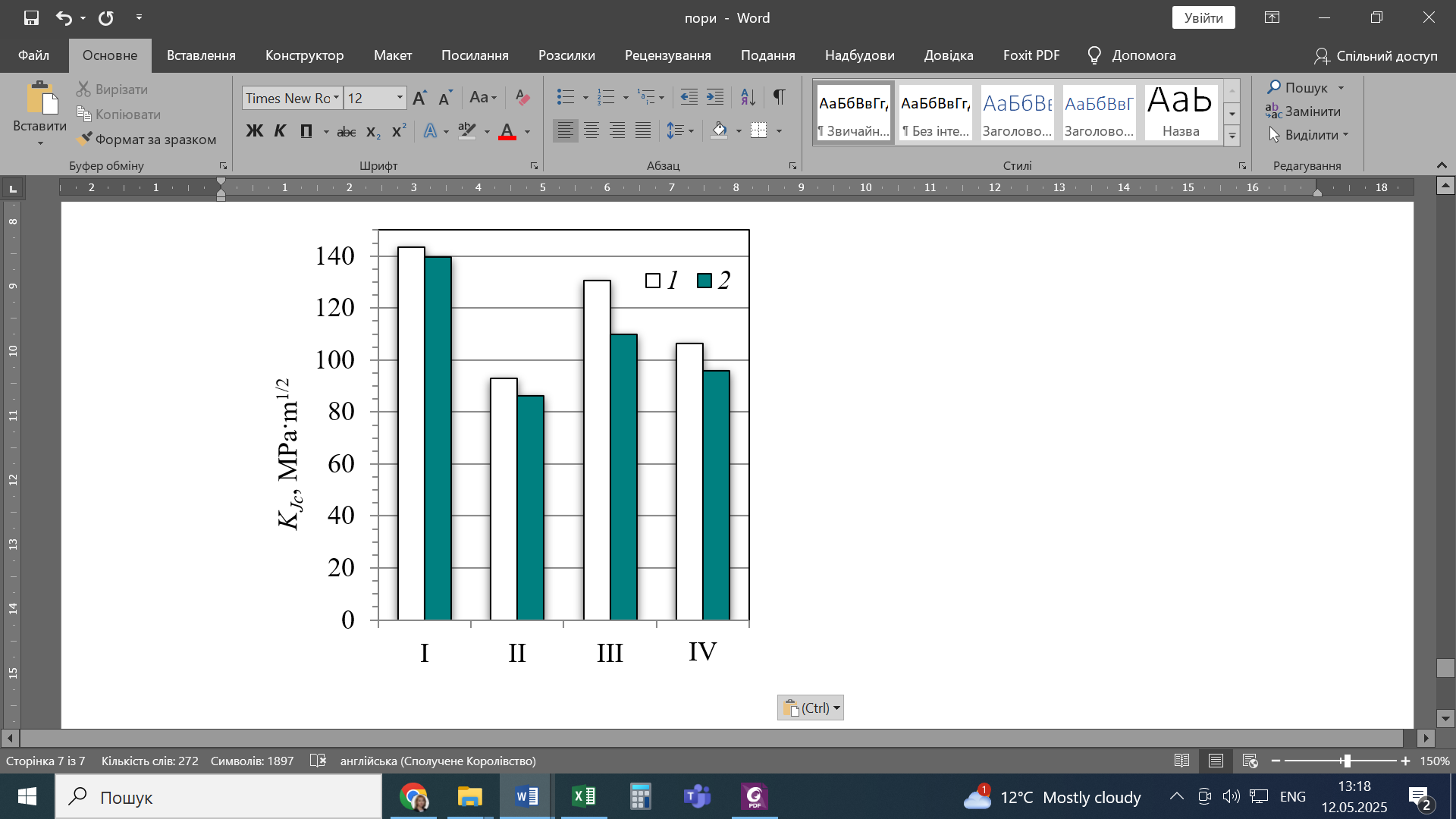
Fracture mechanics approaches are considered the most effective for assessing the resistance to crack growth and brittle fracture of steels [3, 6, 10, 13, 15–23, 28]. Fracture toughness (static crack growth resistance) is most often used as an important calculated mechanical characteristic.

The effect of hydrogen on the fracture toughness of ferritic-pearlite steels of two strength grades was investigated using the *J*-integral method, following the requirements of the ASTM E 1820 standard: 17H1S (API 5L X52 strength grade) and API 5L X67 in the as-delivered state (reserve pipes) and after 38 (17H1S steel) and 34 (X67 steel) years of operation on gas transit pipelines. The pipes had an outer diameter of 1220 and 1420 mm and a pipe wall thickness of 12.0 and 18.7 mm for steels 17H1S and X67, respectively. Mechanical characteristics of steels were as follows: 17H1S in the as-delivered state – σUTS = 568 MPa, *KCV* = 129 J/cm2, in the post-operated state – σUTS = 570 MPa, *KCV* = 103 J/cm2; steel X67 in the as-delivered state – σUTS = 577 MPa, *KCV* = 196 J/cm2, in the post-operated state – σUTS = 576 MPa, *KCV* = 154 J/cm2. The parameters *J*0 corresponding to the start of the crack and fracture toughness, the critical value of the stress intensity factor *KJс*, were determined through the *J*-integral. SEN(B) specimens with dimensions of 4×15×100 mm for the 17H1S steel and 10×18×160 mm for the X67 steel were used. Before bending loading, they were electrolytically hydrogen-charged in a solution of H2SO4 (pH1) + 10 g/l of thiourea at a cathode current density of *i* = 0.05 mA/cm2 for 120 hours for the 17H1S steel and 100 hours for the X67 steel to achieve a uniform distribution of hydrogen throughout the specimen. A feature of the experiments was applying different displacement rates of specimens: the standard 0.5 mm/min and reduced to 0.05 and 0.005 mm/min. It was expected that a decrease in the displacement rate should contribute to the diffusion of hydrogen into the zone in the vicinity of the crack tip and enhance its effect. The test results are presented in Tables 2 and 3.

In general, the fracture toughness of the 17H1S steel in the as-delivered and post-operated states differed slightly (Table 2): its decrease was revealed after long-term service when testing longitudinal specimens, while when testing transverse specimens, slightly higher values were obtained for the operated steel compared to the as-delivered one, both without and after hydrogen pre-charging. The 17H1S steel in the as-delivered state is characterized by pronounced anisotropy of the fracture toughness (the values for the longitudinal and transverse specimens differ by ⁓50%, while for the operated metal, by ⁓23%). For tests under the standard displacement rate (0.5 mm/min), a slight decrease in the fracture toughness *KJc* of the as-delivered 17H1S steel after its hydrogen pre-charging was revealed (Table 2). At the same time, for the steel in the post-operated state, these differences are more significant (Fig. 4).

**Table 2.** Crack growth resistance parameters (*J*-integral at crack initiation *J*0 and fracture toughness *KJc*) of the 17H1S steel depending on its state, orientation of specimens relative to the pipe axis and the influence of hydrogen (displacement rate was 0.5 mm/min).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Steel state | Test condition | Orientation of specimens | *J*0, N/mm | *KJc*, MPa·m1/2 |
| As-delivered | Without hydrogen charging | Longitudinal | 90.2 | 143.4 |
| As-delivered | Without hydrogen charging | Transverse | 38.0 | 93.0 |
| As-delivered | Hydrogen pre-charged | Longitudinal | 85.4 | 139.5 |
| As-delivered | Hydrogen pre-charged | Transverse | 32.7 | 86.3 |
| Operated for 38 years | Without hydrogen charging | Longitudinal | 75.0 | 130.7 |
| Operated for 38 years | Without hydrogen charging | Transverse | 49.8 | 106.5 |
| Operated for 38 years | Hydrogen pre-charged | Longitudinal | 53.1 | 110.0 |
| Operated for 38 years | Hydrogen pre-charged | Transverse | 40.3 | 95.8 |



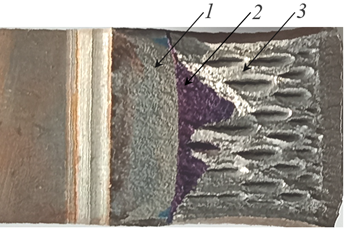
**Fig. 4.** Fracture toughness *KJc* of the 17H1S steel in the as-delivered (I, II) and operated for 38 years (III, IV) states, determined using longitudinal (I, III) and transverse (II, IV) specimens without (*1*) and after hydrogen charging (*2*).

For the API 5L X67 steel, a decrease in fracture toughness of transverse specimens after hydrogen pre-charging was determined, more significant under tests at a lower displacement rate (Table 3). Therefore, crack growth resistance depend on both hydrogen charging and mechanical loading conditions.

**Table 3.** Crack growth resistance parameters, *J*-integral at crack initiation *J*0 (N/mm, in the numerator) and fracture toughness *KJc* (MPa∙m1/2, in the denominator) of the API 5L X67 steel, depending on its state, displacement rate and the influence of hydrogen (transverse specimens).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Steel state | Test condition | Displacement rate, mm/min | | |
| 0.5 | 0.05 | 0.005 |
| As-delivered | Without hydrogen charging | 188.0 / 207.0 | - | - |
| As-delivered | Hydrogen pre-charged | 147.0 / 183.0 | 113.0 / 160.5 | 47.0 / 103.5 |
| Operated for 34 years | Without hydrogen charging | 176.0 / 200.3 | - | - |
| Operated for 34 years | Hydrogen pre-charged | 150.0 / 185.0 | 114.0 / 161.0 | 33.0 / 86.7 |

Similar as for the 17H1S steel (Table 2), in contrast to the generally high sensitivity of fracture mechanics parameters to embrittlement of steels, for the API 5L X67 steel in different states, insignificant differences in values of the *J*-integral at the crack initiation of non-hydrogenated and hydrogen-precharged specimens tested under relatively high displacement rates of 0.5 and 0.05 mm/min were found (Table 3). Such mechanical behavior of steels is unexpected, since the impact toughness values showed a significant difference in resistance to brittle fracture for their different states. It was explained based on fractographic analysis (Fig. 5), which indicated the periodic delaminations on the fracture surface of the specimen of the operated API 5L X67 steel. These delamination cracks were oriented perpendicular to the crack plane and acted as crack dividers. They divide the crack front along its length into subunits, creating a series of mini-specimens that are several times thinner than the tested specimen. The division of the crack front (in this case, by delaminations) weakens the stress state at the tip of the main crack [39, 40] and, accordingly, causes an increase in the fracture toughness. It is known [39] that fracture toughness for the thinner specimens should be higher. This indicates the need to take into account the specific morphology of static growth cracks in operated steels.

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**Fig. 5.** Fracture surface of the SEN(B) specimen of the operated X67 steel after fracture toughness test: 1 – fatigue precrack region; 2 – static crack growth region; 3 – fast final fracture region.

Using the lowest (0.005 mm/min) displacement rate , significantly lower fracture toughness values were obtained for the operated steel specimens after hydrogen pre-charging (86.7 MPa m1/2 versus 103.5 MPa m1/2 for steels in the post-operated and as-delivered state, respectively). This means that the effect of operation of the steel in terms of *J*0 and *KJc* was revealed only under particularly harsh conditions of hydrogen embrittlement associated with a more intense accumulation of hydrogen in the vicinity of the crack tip. It can be assumed that the implementation of lower displacement rates will lead to even more pronounced hydrogen embrittlement of the metal of the zone in front of the crack tip and, accordingly, a further decrease in fracture toughness.

The usage of the *J*-integral method is also effective for the case of the electrochemical mechanism of steel hydrogen charging, which is realized as a result of corrosive interaction with moisture condensed in local areas of the pipeline [5, 32], and is enhanced by saturation with gaseous hydrogen [30]. This simulates the operating conditions of hydrogen transport in areas of moisture condensation on the inner surface of the pipe. The fracture toughness of the 17H1S steel, determined experimentally under such hydrogen charging conditions, is ~ 9% lower than without hydrogen, that is, the metal degrades in terms of crack growth resistance.

Therefore, the assessment of the state of long-term operated gas pipeline steels and their serviceability under hydrogen transportation conditions should, first of all, be based on the criterion of operational reduction of the resistance to brittle fracture under hydrogen exposure, in particular, crack growth resistance determined according to the *J*-integral method. For hydrogen pipelines, the critical value of fracture toughness *KJc*  = 55 MPa∙m1/2 is regulated by the ASME B31.12 standard. Accordingly, gas pipeline steels with fracture toughness above this value can be considered, in a first approximation, suitable for hydrogen transportation. The calculated critical value *J*0 was 13.3 N/mm. Based on the data in Tables 2 and 3, it can be seen that the parameter of *J*-integral for the studied conditions is higher than the critical value of crack growth resistance. Based on the criterion of operational decrease in fracture toughness of pipeline steels under hydrogen exposure, a methodology for evaluating the serviceability of existing natural gas pipelines for hydrogen transportation was developed.

Further research should be focused on determining the crack growth resistance of steels at lower displacement rates of specimens under hydrogen exposure, where the effect of hydrogen may be more significant, as well as on selective studies of steels from various characteristic sections of pipelines for fracture toughness parameters, which are sensitive to hydrogen embrittlement of steels.

1. Concluding Remarks

In the context of the development of hydrogen energy in general the challenges associated with hydrogen transportation by the long-term operated gas pipeline network of Ukraine are considered, should be taken into account when assessing the risk of integrity violations of the existing gas pipeline network in the case of transporting hydrogen.

Existing transmission pipelines are subject to aging and degradation and the degree is likely to increase over time and will be accelerated under hydrogen service. The process is facilitated by hydrogen absorbed under corrosion and transported hydrogen will amplify hydrogen permeation. Thus, in the presence of gaseous hydrogen in corrosive environment, simulating moisture condensation on the pipe inner surface, polarization resistance of the API 5L X70 pipeline steel is significantly reduced (by 3-5 times) and hydrogen permeation is intensified; these effects are more pronounced for the 37-year-operated steel compared with the as-delivered one, and the recovery of corrosion resistance after eliminating the hydrogen factor is less significant.

The implementation of the decohesive-deformation mechanism of damage in low-strength pipeline steels during long-term operation is substantiated, explaining an increase in hydrogen embrittlement susceptibility of steels during the long-term operation.

An assumption about the possibility of implementing strain aging as a stage of operational degradation of pipeline steels under the hydrogen action with no required external mechanical loading is experimentally confirmed; in such a case, hydrogen-induced stresses accompanied by dislocation generation are sufficient for strain aging.

Using experimental studies of the fracture toughness of pipeline steels (API 5L X52 and X67 strength grades), determined by the *J*-integral method, a significant effect of the displacement rate of specimens on the crack growth resistance under hydrogen exposure is defined.

An approach to assessing the serviceability of pipelines under hydrogen transportation conditions is proposed, which is based on the criterion of operational reduction of the fracture toughness of steels under hydrogen exposure, determined by the *J*-integral method.

A methodology for evaluating the serviceability of pipelines for hydrogen transportation, based on the criterion of operational decrease in fracture toughness of pipeline steels under hydrogen influence, is proposed.

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