https://doi.org/10.37434/tpwj2022.06.07

FEATURES OF ANALYSIS OF THE TECHNICAL STATE AND SUPPORT OF RELIABILITY OF THE MAIN GAS PIPELINES AT TRANSPORTATION OF GAS-HYDROGEN MIXTURES (REVIEW)

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ABSTRACT

Analytical review of the features of operation, expert analysis of the technical state, and support of the reliability of the main gas pipelines at transportation of natural gas and hydrogen mixtures through them was performed. Proceeding from modern concepts of hydrogen degradation of pipe steels, conditions are considered which are required for safe use of the currently available gas transportation system for this purpose, in particular, with different hydrogen concentration in the mixture. Additional requirements were formulated as to evaluation of the acceptability of typical defects, and procedure of their repair by pressure welding methods.

KEYWORDS: gas-hydrogen mixture, main gas pipeline, hydrogen degradation, technical state, reliability, repair

INTRODUCTION

Use of hydrogen and other renewable gases as a mean of energy transfer from remote sources (first of all, solar and wind electric stations, biomaterial processing stations etc.) becomes more and more widespread, in particular, in scope of EU Hydrogen Strategy to 2050 adopted by European Committee [1]. It is caused by a series of factors of economical, ecological and technological nature, including intensive development of “green” energy. Thus, usage of “green” technologies for energy production is related with certain localizing of the energy generating capacities depending on their type (places of installation of large area solar panels, wind generators etc.), that requires solution of a problem of generated energy transportation to general networks. Construction of the new power lines requires significant financial expenses that increases total cost of “green” energy. Therefore, one of the possible ways of its transportation to the end user is usage of a branched gas pipeline system for transportation, first of all, of “green” hydrogen, generated by electrolysis of water or its other types, shown in Figure 1 [2, 3]. Such an approach is reasonable from point of view of higher efficiency of energy transfer in pipeline hydrogen transportation, increase of part of renewable energy in a general scope of power generating capacities, decrease of industry dependence on fossil hydrocarbons, in particular natural gas [4].

However, direct use of a gas transportation system (GTS) for hydrogen transportation is related with

Green hydrogen
- Green hydrogen is produced by the electrolysis of water;
- The process is powered by zerocarbon electricity (e.g., wind and solar power);
- It is clean, but is too expensive for widespread use;
- The cost of electrolysers and renewable energy is expected to fall over the next decade, making green hydrogen more viable;
- Green hydrogen is the ideal long-term, zero-carbon way to produce hydrogen

Blue hydrogen
- Blue hydrogen is produced from fossil fuels (typically natural gas), but emissions are dealt with using carbon capture and storage (CCS) technology;
- With abundant natural gas and coal available, blue hydrogen could help to scale the hydrogen economy, however, this is dependent on wider adoption of CCS;
- Blue hydrogen could act as a stepping stone from grey/brown to green hydrogen

Grey/brown hydrogen
- Grey hydrogen is typically produced from natural gas in a process called steam methane reformation;
- Brown hydrogen is produced from the gasification of coal;
- These are the strongly dominant methods in use today;
- They are relatively cheap, but emit large amounts of CO_2

Figure 1. Example of hydrogen classifying by the methods of its industrial production [2]

increase of the risks of accidents since design conditions of the main and distribution pipelines do not consider high concentration of this element in gas being transported from point of view of material selection, operation conditions, maintenance order. Use of the mixtures of natural gas and hydrogen [5–7] is reasonable for the purpose of utilization of existing GTS for hydrogen transportation without significant changes in the pipeline design. Negative effect of hydrogen on strength and performance of the pipeline can be allowable under condition of selection of specific concentration of hydrogen in such a gas-hydrogen mixture (GHM). Nevertheless, in selection of the operation parameters as well as sequence of technical diagnostics performance, analysis of technical state, maintenance of working capacity and guarantee of GTS reliability it is necessary to consider not only materials science aspects of hydrogen effect on the main gas pipeline (MGP) material, but also apply corresponding approaches of mechanical engineering. The latter allows considering the peculiarities of state of the main pipeline structural elements in transportation of GHM in context of corresponding standards and norms.

The aim of present review is a generalization of the data on peculiarities of operation, analysis and maintenance of MGP state and performance during transportation of natural gas and hydrogen mixtures.

PECULIARITIES OF HYDROGEN EFFECT ON THE MAIN GAS PIPELINE MATERIAL

It is known that steel of a buried gas pipeline can be hydrogenated from a pipe outer surface in the area of protective insulation damage due to soil corrosive effect as well as inner one due to electrochemical interaction of condensed moisture that contains hydrogen or as a result of dissociation of hydrogen gas [8]. The applied aspects of a hydrogen negative effect on mechanical properties of metals and long-term operation structures are under constant attention of the operating organizations of different branches of industry as well as research groups all over the world. This allowed determining and generalizing the nature of hydrogen damage of typical pipe steels, however, understanding of its mechanisms [9] is insufficient. Thus, hydrogen degradation of the steel properties depends on their strength. High-strength steels are more susceptible to hydrogen influence than low-strength ones at that change of elastic properties is insufficient, however, ductility, parameters of resistance to different types of failure (ultimate strength, fracture toughness, threshold of strength intensity factor, fatigue crack growth rate) can deteriorate with increase of hydrogen concentration [10].

It is known that an integral concentration of diffusion hydrogen is to some extent a qualitative indicator of a condition of material hydrogenation, because the more important factor is a localized concentration on a tip of already existing material discontinuity defects, where atomic hydrogen can recombine to molecular state [11]. The recombination results in a formation of high local hydrostatic pressure inside the traps that leads to increase of internal microstresses. This promotes formation and development of distributed damage of the material as well as macrodefects on different mechanisms [12–14], namely hydrogen stress cracking (HSC); hydrogen-induced cracking (HIC/HAC); stress oriented hydrogen-induced cracking (SOHIC); soft zone cracking (SZC); stepwise cracking (SWC); sulphide stress cracking (SSC); blistering; stress corrosion cracking (SCC).

The nature and scale of the negative effect of hydrogen depend on various factors, including composition of pipe steel, distribution and morphology of phases, grain structure, segregation and distribution of alloying elements and impurities. Therefore, to evaluate the reliability of MGP elements under conditions of GHM transportation it is necessary to consider separately the effect of excessive hydrogen saturation of assembly welds metal (WM) and heat affected zone (HAZ) on a limiting state of the pipeline under design load conditions. The results of experimental investigations of the specimens from WM, HAZ and pipe steel base metal showed that at different level of hydrogenation the most sensitive to negative effect of hydrogen is HAZ metal in which coarse grain columnar structure is formed [15]. At that the highest degradation is observed in the fatigue characteristics of HAZ metal, which should be taken into account when determining the possibility and conditions of GHM transportation via specific sections of GTS.

A special phenomenon, typical for long-term operation structures at transportation of the hydrogen-containing substances, is accumulation of material scattered damage [16, 17]. The process of accumulation of such type of damage (metal ageing) is divided on several steps [18]. Ageing, strength and hardness of metal rise in stage I and characteristics of ductility and brittle fracture resistance reduce. In stage II for determination of material ductile characteristics it is necessary to consider its actual net section. In this case opening of the multiple microdefects under tensile stress has a significant effect on the obtained results of laboratory experiments that results in an error during determination of actual ductility. The latter could also be a reason for decrease of strength and hardness of the material.

TYPICAL PROBLEMS FOR RELIABILITY ENSURING IN THE MAIN PIPELINES AT TRANSPORTATION OF HYDROGEN AND NATURAL GAS MIXTURES

The requirements to conditions of operation of the existing GTS of Ukraine are based on a complex of standards and norms that regulate different aspects of design, analysis of technical state and order of pipeline maintenance. Reprofiling main pipeline systems for GHM transportation requires consideration of the peculiarities of effect of hydrogen increased concentration on operation characteristics of GTS elements. So, it is established, that high hydrogen flowability, on the one hand, increases energy efficiency of GHM pumping and, on the other hand, provokes rise of a risk of transported gas leakage [19]. From point of view of pipeline integrity management the following reasons of local leakage appearance [20] are usually considered, namely corrosion damage; material defects; defects of technological nature; operation or design errors; distributed load, other loads, equipment malfunction etc.

The results of calculation of a risk factor (for different pipeline materials) and total risk (taking into account probability of appearance of critical situation) of accident due to leakage of transported GHM with different volumes of hydrogen content (0–50 %) (Table 1) show that the highest risks take place in the area of corrosion damages and technological defects (dents, bends, corrugations etc.) [21]. Technological defects that appear, in particular, during construction or technical works on separate sections of the pipelines at open excavations, do not virtually change in the process of pipeline operation in contrast to corrosion damages which are typical for GTS of Ukraine due to its general wear-out. Therefore, increase of corresponding risks by 15–20 % (at hydrogen concentration up to 20 %) has to be justified by additional calculations of the risks of a limit state of separate sections of pipelines with the detected defects of corrosion thinning for the moment of diagnostics as well as under conditions of defect development in process of MGP further operation. Excessive strength of a pipeline section with corrosion damages should be sufficient in order to compensate corresponding increase of the risks in GHM transportation. It should be noted that provided calculations consider different types of pipeline materials (pipe steel, polymers etc.), therefore these indices in relation to Ukrainian GTS are to be considered more as qualitative. However, they notably demonstrate effect of hydrogen of different concentration in GHM content on a tendency of the main pipelines to leakage failure.

The fact that most of the main pipelines lied under ground, to some extent, reduces the possible consequences of gas or GHM leakage. Nevertheless, analysis of the possibility of application of separate section of existing GTS requires consideration of a pipeline location in relation to other infrastructure objects such as residential houses, bridges, roads and railways, power supply networks etc. The construction standards [22], which determine the requirements to lying of main pipelines, include the dependencies of a distance from pipeline axis to an object of certain type depending on pipeline diameter and its class (see example Table 2). However, it is natural to expect that the fatal consequences of ignition or explosion of GHM (first of all, human casualties) are higher than in the case of natural gas. Therefore, it is necessary to formulate more rigid conditions as for mutual location of main or gas distribution pipeline and other objects or constructions.

The available results of investigation of a risk of fatal consequences of explosion of GHM with different concentration of hydrogen [21] showed that a typical peculiarity is increase of risks from accidents at more significant localizing of high risks to direct place of leakage. Thus, (as shown in Figure 2) at the distance around 265 m from the axis of pipeline with GHM leakage the risks of fatal consequences due to

Table 1. Calculated failure risk of MGP depending on failure nature and composition of gas-hydrogen mixture [21]

Accident reason	Probability, %	Risk factor, %				Total risk, %			
		Natural gas	<20 % H_2	20–50 % H_2	>50 % H_2	Natural gas	<20 % H_2	20–50 % H_2	>50 % H_2
Corrosion damage	36.42	24.54	29.54	29.54	44.54	8.94	10.76	10.76	16.22
Material defect	6.98	34.16	39.16	39.16	54.16	2.38	2.73	2.73	3.78
Distributed load	8.47	25.58	35.58	35.58	45.58	2.17	3.01	3.01	3.86
Defect of technological nature	15.39	50.00	60.00	70.00	70.00	7.69	9.23	10.77	10.77
Other load	1.86	10.00	15.00	15.00	30.00	0.19	0.28	0.28	0.56
Malfunction of equipment	6.75	30.00	35.00	35.00	50.00	2.02	2.36	2.36	3.37
Error in design or operation	2.53	30.00	35.00	35.00	50.00	0.76	0.89	0.89	1.27
Other	21.60	10.00	15.00	15.00	30.00	2.16	3.24	3.24	6.48
Total	100.00	214	264	274	374	26	33	34	46

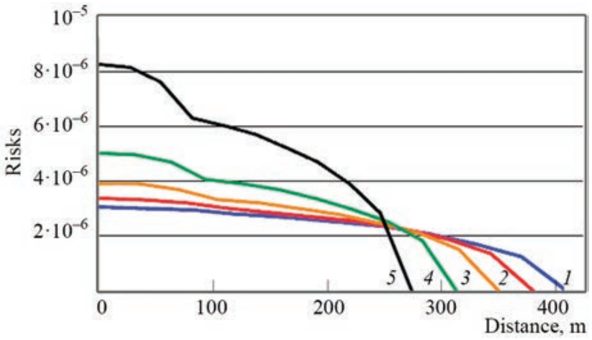

Figure 2. Dependence of risk (for 1 year) of fatal case as a result of accident on distance to pipeline (914 mm diameter, 7 MPa pressure) at different hydrogen concentration in GHM being transported: *1* — pure natural gas; *2* — 25 % of hydrogen; *3* — 50 % of hydrogen; *4* — 75 % of hydrogen; *5* — pure hydrogen [21]

ignition virtually do not depend on hydrogen concentration and equal that for natural gas, and at larger distances high volatility of hydrogen even reduces corresponding risks. However, for smaller distances it is necessary to introduce additional adjustments to existing requirements [22]. This additional adjustment to the distance for hydrogen concentration in GHM up to 25 % makes approximately 100 m, and at 50 % of hydrogen it is around 150 m. If location of the infrastructure objects on separate sections of the pipeline does not fulfil such more rigid requirements, direct usage of these sections for transportation of GHM without previous relocation of pipeline or protection of corresponding objects is unacceptable. The same conclusions should be used for parallel pipeline lines, that are located in the immediate proximity one from another as well as when planning laying of new MGP along the existing ones.

Special attention shall be given to the pipelines, where fatigue failure is possible, namely sections at the exist of compressor stations, underground, underwater or aboveground passages through natural and artificial barriers etc. It is known fact that conditions of increased hydrogen concentration provoke increase of material tendency to spontaneous development of fatigue cracks [23]. Therefore, in order to use these MGP sections for GHM transportation it is necessary to reduce a period of monitoring of their technical state for the purpose of detection of appearance of crack-like defects. This is in particular refers to the places of assembly and repair welding, where additional residual tensile stresses in a weld area and HAZ promote increased susceptibility to crack nucleation under conditions of external cyclic loading.

According to the requirements [22] main pipelines and their sections are divided on categories depending on conditions of laying, pipe dimension-type and operation parameters. Depending on the category of specific section (B, I, II, III, IV) the safety factors of operation conditions are determined in strength and resistance calculations, norms of amount of welded joins, that are subjected to non-destructive testing, testing parameters etc. In order to guarantee corresponding safety of pipelines in GHM transportation it is necessary to change the category of specific sections. In particular, it is related to aerial crossings and crossings through railway rails and roads as the places of increased danger. The standard [22] determines for this case an increase for one category and check of virtual correspondence of these sections to increased category.

PROCEDURE OF EVALUATION OF MAIN GAS PIPELINE TECHNICAL STATE TAKING INTO ACCOUNT INCREASED CONCENTRATION OF HYDROGEN IN A MIXTURE BEING TRANSPORTED

Periodic technical diagnostics of MGP state includes non-destructive testing activities, in particular flaw detection, and following expert analysis of corresponding bearing capacity of the specific sections to design conditions. The main scope of information on

Table 2. Example of reference distances from the axis of buried gas pipeline to different objects depending on class and diameter of pipe [22]

Objects, constructions, buildings	Minimum distance from gas pipeline axis, m							
	Pipeline class							
	I							II
	Nominal diameter of pipe, mm							
	< 300	300–600	600–800	800–1000	1000–1200	1200–1400	≤ 300	> 300
Cities and other settlements; separate industrial enterprises; separate buildings with mass accumulation of people; airports	100	150	200	250	300	350	75	125
Territories of gas-distribution stations	50	75	100	125	150	175	50	75
Mouths of oil, gas and artesian wells	30	50	100	150	175	200	30	50
General network railways	75	125	150	200	225	250	75	100

condition of kilometres-long sections of a linear part of pipelines is obtained based on the results of in-line inspection (ILI). It lies in running of series of pigs together with a product being transported [24, 25]. Today there is a wide spectrum of ILI tools which allow with sufficient accuracy to determine, measure and quantitatively evaluate defects of different type. Besides, in addition to increased danger of a flaw detector operation in a hydrogen medium, their application is related with the same complex of problems of negative effect of hydrogen on metal component properties that are typical for pipeline metal. Therefore, the flaw detectors used in GHM with hydrogen content more than 10 % should be made of materials with the highest resistance to hydrogen degradation. Also the negative effect of hydrogen on long-term integrity of constant magnets of rear-earth metals is known [25, 26]. It is necessary to be considered in usage of corresponding elements, in particular at magnetic flux leakage (MFL).

In case of detection of the discontinuity defects it is necessary to make a decision as for their allowability and planning the activities on restoration of bearing capacity of the pipeline. The allowability of defects (two-dimension — cracks, three-dimension — corrosion damages, shape defects etc.) of main pipelines in Ukraine is regulated with the reference document [27], which contains a complex of the requirements and algorithms of static strength calculation of the pipeline sections with certain type defects. Fields of application [27] allow its usage for evaluation of the gas pipeline state in GHM transportation, but this requires certain formal corrections.

Thus, comparison of the calculation and design values of the safety factor of pipeline specific section is used as a criterion of a limit state in static strength calculations. At that in accordance with the design requirements [22] the pipeline safety factor is determined, also, corresponding to a category of specific pipeline section, which, as was shown above, should be corrected in case of GHM transportation. Thus, the minimum allowable safety factor can also be recalculated that can change the conclusions as for bearing capacity of the defective pipeline section.

An expert conclusion as for allowability of certain found defect of MGP lies, in particular, in determination of this defect category, namely: minor, moderate, major, critical ones. Corresponding to a determined category it is recommended to carry out repair operations, decrease pressure of product being transported or limit an operational life with additional monitoring of a state of defective section every 6 or 2 months and once and twice a year. A period of the additional monitoring in case of GHM transportation can be changed due to insufficient information on intensity of defect development. A proof is necessary that for the specified period the natural increase of the defect will not result in change of its category.

A separate task of analysis of actual MGP state by flaw detection results is determination of its life. For this it is necessary to take into account the next damaging factors, namely degradation of mechanical properties of material, corrosion damage, stress-corrosion, cyclic loading.

Degradation of material properties from point of view of resistance to various types of failure under conditions of increased hydrogen concentration in the product being transported, on the one hand, requires the more conservative expert analysis of defect allowability and, on the other hand, needs a determination of time intervals of additional inspection or removal of found defects. As it was mentioned above, hydrogen has the largest effect on strength parameters (yield stress σ_y and ultimate strength σ_t), crack resistance (fracture toughness K_{Ic}, K_{Jc}) and fatigue strength (threshold value of stress intensity factor ΔK_{th}, fatigue crack growth rate da/dN). Specific current values of the indicated physical-chemical characteristics of pipeline material in the area of found defect are to be determined by means of performance of corresponding laboratory investigations with available samples of pipe metal that allows considering additional negative effect of hydrogenation in GHM transportation. However, performance of corresponding number of the laboratory tests is difficult to realize in practice, therefore, during calculations of static strength and life it is agreed to use certain conservative values of the corresponding parameters. Approaches recommended in [27] as for interpretation of the results of measurements of material hardness and its impact toughness for determination of current value of σ_y and σ_t (degradation can reach 10 %) as well as K_{Ic} (to 40 %) can be inapplicable in the case of significant development of scattered damage of pipe material as a result of its hydrogenation. Particularly, this should be expected for sections of the pipelines with high operating time, number of which is high in the Ukrainian GTS.

If the order of calculation of effect of defect corrosion development in GHM transportation is not changed in comparison with the conditions of natural gas pumping, than excessive content of hydrogen in the pipeline metal can significantly change metal tendency to nucleation of stress-corrosion cracks. The peculiarity of main stress-corrosion cracks is their elongation, which is caused by growth mechanism. Nucleation of such type cracks is multi-central with further coalescence of small cracks to the main one. This complicates detection of such type defects by

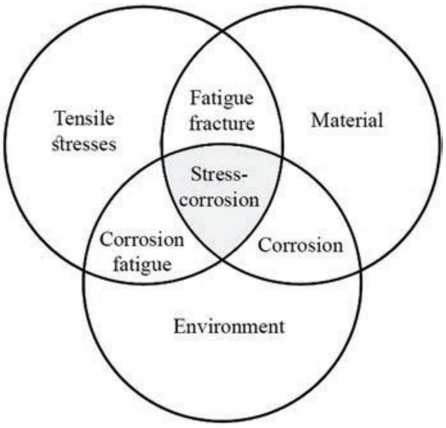

Figure 3. Conditional scheme of effect of interaction of different external factors on fracture mechanism of structural materials

means of express-monitoring, in particular ILI, therefore a prior determination of the pipeline sections having the highest tendency to stress-corrosion is important.

It is known that the necessary condition for nucleation of stress-corrosion cracks is simultaneous fulfilment of three conditions, namely tensile stresses higher that the threshold limit; sensitive metal structure; unfavourable corrosion medium (Figure 3) [28]. Each medium, which stipulates additional flow of hydrogen into metal and corresponding growth of microstresses in the areas of available discontinuities can result in stress-corrosion cracking. Therefore, determination of the possibility of application of the existing GTS for GHM transporting requires performance of the laboratory investigations of susceptibility of pipe metal of different sections to stress-corrosion damage.

If certain MGP section is subjected to effect of cyclic loads then in case of nucleation of fatigue cracks the life time of such sections is determined using crack resistance parameters as well as fatigue crack growth rate *da/dN*. The available results of investigations [29] show that in presence of hydrogen the typical pipe steels are characterized not only with rise of *da/dN,* but also with possibility of change of the failure nature (Figure 4) from intergranular to transgranular. So, in GHM transportation the frequency of technical diagnostics of such pipeline sections should be increase and conservativeness of the analysis of crack-like defects be higher.

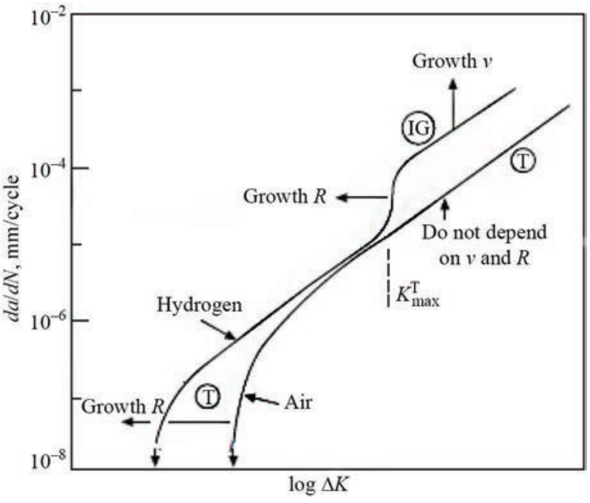

Figure 4. Schematic diagram of effect of hydrogen gas on fatigue crack growth rate in steels: R — coefficient of asymmetry of loading cycle; ν — loading frequency; T — mainly transgranular fracture; IG —mainly intergranular fracture [29]

APPLICABILITY OF REPAIR WELDING METHODS TO ELEMENTS OF MAIN GAS PIPELINES WITH DETECTED OPERATION DEFECTS IN GHM TRANSPORTATION

The methods of repair pressure welding [30] become more and more widespread in restoration of design strength and workability of MGP elements with discontinuity defects, which were determined during diagnostics. This allows increasing bearing capacity of the pipelines without a need of stop of product transportation reducing labour content as well as negative effect on environment. Performance of such repair is regulated by a series of standards, in particular [31]. The latter covers the sequence of evaluation of repair necessity, selection of its type depending on level of damage of specific pipeline section, sequence of selection of welding technological parameters etc. However, in case of GHM transportation and significant pipeline metal hydrogenation it is necessary to take into account specific features of MGP state.

First of all, any repair activity on the operating MGP should be preceded by investigation of possibility of hydrogen leakage that can result in explosion dangerous situation. Another factor, limiting application of repair welding technologies on operating pipelines is possible cold cracking of metal in welding area and occurrence of accident. It is known that formation of cold cracks on the specific sections of structure, being welded, needs simultaneously fulfilment of three conditions, namely presence of metal martensite structure, diffusion hydrogen and tensile stresses [32]. Therefore, in order to prevent appearance of cold cracks it is decided to eliminate additional inleak of hydrogen by means on preparation of place of welding and corresponding selection of filler materials as well as application of preheating in repair area at 100–150 °C level depending on pipe dimension-type, its strength and temperature of environment [31]. However, accelerated degradation of pipe metal properties in GHM transporting increases the susceptibility to cold cracking, therefore the recommendations to preparation of pipeline to repair have to be more rigid. Performance of such type of works at environment temperature lower than 0 °C and intensive cooling of welding area can create unfavourable conditions as for tendency of metal structure to cold cracking. Besides, preheating temperature should be increased (to minimum allowable level 150 °C) and be maintained at each step of multipass repair welding or surfacing.

Presence of additional repair welds, which were made under field conditions, reduces life time of the pipeline in case of intensive hydrogen degradation of WM and HAZ [33]. Thus, in case of usage of the existing GTS for hydrogen transportation at its concentration in GHM more than 20 % the repair pressure welding should be considered, first of all, as temporary with next replacement of a repaired pipe spool in a period of planned shutdown of the pipeline section. A period, for which carried repair-restoration works guarantee corresponding pipeline reliability, are to be determined based on the results of prediction of long-term strength depending on operation conditions, actual state of pipe and repair type.

CONCLUSIONS

1. The paper provides a generalization of typical peculiarities of hydrogen effect on the main pipeline material from point of view of decrease of their design strength and operation life. It is shown that the hydrogen degradation of steel properties depends on their strength and the maximum negative effect is caused to ductility and resistance parameters to various fracture types. At that, the most significant metal degradation is observed in the areas of assembly welds, for which coarser microstructure is typical.

2. The typical problems were considered for providing the reliability of main pipelines in transportation of mixtures of hydrogen and natural gas. Based on the available data of the risk-analysis of MGP accident rate due to hydrogen leakage it is shown that its concentration up to 20 % in gas-hydrogen mixture being transported provokes notable increase of the risks due to leakages in the area of corrosion damages. Therefore, a decision making on possibility of application of the existing GTS should be based on the corresponding evaluation of actual defectiveness and proof of the required residual strength of pipelines with corrosion damage.

3. It is shown the need of overview of the categories of separate sections of MGP in case of transportation by them of GHM. In particular, it relates to aerial crossings through artificial and natural barriers as well as underground crossings through railway rails and roads, as places of increased danger, for which rise for one category is necessary.

4. The peculiarities of evaluation of pipeline technical state at consideration of increased hydrogen concentration in a mixture being transported were discussed. It is shown the necessity of clarification of a period of non-destructive testing taking into account more intensive influence of typical damaging factors in GHM transportation in order to guarantee the required static strength and service life of MGP. Besides, the methods of express-evaluation of actual properties of pipelines recommended by the existing reference documents are limitedly used in case of GHM transportation.

5. The analysis was carried out on applicability of the methods of repair pressure welding of gas pipelines in transportation by them of a mixture of natural gas and hydrogen. It is shown that the main technological task at that is a prevention of cold crack formation in hydrogenized pipe metal. It can be fulfilled by selection of the corresponding preheating temperature of a place of repair welding and more rigid requirements to allowable environmental temperatures. Moreover, presence of additional repair welds reduces general resistance of the pipeline to brittle and fatigue fracture that should be considered at its further operation.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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SUGGESTED CITATION

O.S. Milenin, O.A. Velykoivanenko, G.P. Rozynka, N.I. Pivtorak (2022) Features of analysis of the technical state and support of reliability of the main gas pipelines at transportation of gas-hydrogen mixtures (Review). *The Paton Welding J.*, **6**, 49–56.

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https://pwj.com.ua/en

Received: 07.04.2022
Accepted: 15.08.2022