

ADAPTIVE INTEGRITY MANAGEMENT OF THE UKRAINIAN GAS TRANSMISSION SYSTEM IN THE CONTEXT OF THE INDUSTRY 4.0/5.0 PARADIGM

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ABSTRACT

The paper develops a scientifically substantiated concept of adaptive integrity management for the Ukrainian gas transmission system under the transition to the Industry 4.0/5.0 paradigm and the increasing complexity of operating conditions, including wartime impacts, decarbonization of the energy sector, and the prospective transportation of natural gas-hydrogen mixtures. A system-based approach to the life cycle analysis of gas transmission system facilities is proposed, integrating physics-based modelling, probabilistic reliability assessment methods, and innovative technologies for restoring the technical condition. A multilevel management architecture is considered, encompassing the system level of operational optimization, individualized analysis of defective sections based on finite element modelling, Weibull and Monte Carlo methods, as well as degradation process prediction as an essential component of predictive maintenance. Particular attention is paid to adapting repair technologies to the current technical condition of structures, taking into account corrosion-hydrogen fracture mechanisms and local stress-strain states.

KEYWORDS: gas transmission system, adaptive integrity management, Industry 4.0, Industry 5.0, predictive maintenance, finite element modelling, hydrogen degradation, corrosion cracking, repair.

INTRODUCTION

The Ukrainian gas transmission system (GTS) is one of the largest infrastructure complexes in Europe and performs a strategic role in ensuring the country energy security, maintaining the stability of energy markets, and fostering cross-border energy integration. At the same time, the current operating conditions of the gas transmission infrastructure differ significantly from those for which the vast majority of trunk pipelines (TPs) and other infrastructure facilities were originally designed. Changes in natural gas transportation modes, the use of reverse flows, the increasing role of underground gas storage facilities as balancing elements of energy systems, the need to ensure resilience against technogenic and wartime impacts (Figure 1), as well as the prospects for transporting natural gas-hydrogen mixtures, create new requirements for the reliability, durability, and operational safety of GTS facilities.

Traditionally, ensuring the operability of both TPs and the GTS as a whole has been based on a regulatory integrity management paradigm founded on

deterministic design assumptions, standardized safety factors, prescribed maintenance intervals, and unified criteria for technical decision-making. However, its fundamental characteristic is its orientation toward describing the most adverse operating scenarios and employing conservative assumptions to compensate for uncertainties regarding the actual technical condition. In recent years, it has become increasingly evident that the capabilities of the traditional regulatory paradigm are gradually reaching their limits. Infrastructure ageing, increasing heterogeneity of operating conditions, growing requirements for economic efficiency and environmental responsibility, as well as the need to adapt the GTS to new operational demands, call into question the appropriateness of relying exclusively on standardized approaches to technical condition assessment and reliability maintenance technologies. Under these circumstances, the principal limitation is no longer the absence of a regulatory framework but rather the insufficient capability of existing methods to account for the individual degradation characteristics of specific facilities and the actual level of risk associated with their continued operation.



Figure 1. Pipelines damaged as a result of military operations

Simultaneously, fundamental research in materials science, fracture mechanics, diagnostic technologies, and repair methods has advanced considerably. Contemporary scientific findings demonstrate that the degradation of pipeline steels is governed by the complex interaction of structural, mechanical, corrosion-related, and hydrogen-induced factors evolving across multiple length scales, from microstructural material evolution to the formation of macroscopic defects and changes in the operability of the pipeline system as a whole. Consequently, integrity management increasingly requires the integration of multiscale concepts of material degradation with engineering decision-making processes and life cycle management of critical infrastructure facilities.

This issue becomes even more significant in the context of the energy transition and the prospective use of existing GTS infrastructure for transporting natural gas-hydrogen mixtures. Unlike conventional operating conditions, hydrogen can substantially affect the deformation and fracture mechanisms of pipeline steels, alter fracture toughness characteristics, accelerate damage evolution, and generate new sources of operational risk. Under these conditions, the traditional technical condition assessment criteria, developed primarily for natural gas transportation, require reconsideration based on current knowledge of the physical mechanisms of hydrogen-induced material degradation.

These trends coincide with the global transformation of industrial systems within the Industry 4.0 and Industry 5.0 paradigms. In the context of gas transmission infrastructure, the significance of Industry 4.0 lies not only in the implementation of digital

technologies but, above all, in creating opportunities to transition from periodic inspection to continuous condition monitoring, predictive analytics, and risk-based decision-making approaches. At the same time, Industry 5.0 extends this concept by integrating the principles of human-centricity, resilience, and sustainable development. For the GTS, this means transitioning from the management of individual components to life cycle management of infrastructure facilities, from preventive maintenance to adaptive condition-based maintenance, from capital-intensive component replacement to scientifically substantiated life extension for safe operation, innovative restoration of operability, as well as from process automation to scientifically grounded engineering decision support.

At present, the integration of the Industry 4.0 and Industry 5.0 paradigms into oil and gas production systems remains unsystematic and fragmented. The scientific literature demonstrates that the implementation of Industry 4.0 technologies in gas transmission significantly improves operational efficiency and safety while simultaneously establishing the foundation for more sustainable asset management through real-time monitoring, predictive analytics, digital twins, and blockchain-based transparency approaches [1–4]. At the same time, a number of review studies emphasize that the transition to Industry 5.0 is still at an early stage of development, and practical implementation lags considerably behind conceptual and theoretical advances [5], particularly in the context of comprehensive human-centric models and circular economy frameworks. Key systemic barriers remain unresolved, including high implementation costs (es-

pecially for operators outside global corporations), limited compatibility with ageing infrastructure, insufficient digital competencies of personnel, increasing cybersecurity risks associated with the expansion of the IoT ecosystem, and fragmented management practices that result in isolated pilot projects rather than comprehensive transformational strategies [6–7]. Meanwhile, contemporary research increasingly highlights that the effectiveness of digital transformation is determined not only by technological factors but also by the alignment of digital initiatives with long-term business objectives and sustainable development goals [8–9]. Thus, the transition from a purely technology-oriented paradigm to a balanced approach that combines productivity with societal and environmental priorities remains a key, yet still insufficiently implemented, component of the Industry 5.0 concept.

Accordingly, current challenges necessitate the development of a new GTS integrity management paradigm that integrates advances in fundamental materials science, multiscale modelling of degradation processes, risk-based methods for assessing structural integrity, Industry 4.0 digital technologies, and the Industry 5.0 principles of human-centricity, resilience, and sustainable development. Unlike the traditional regulatory-oriented model, this paradigm envisages scientifically substantiated and adaptive integrity management, in which each infrastructure asset is considered as a unique system with its own individual history of degradation, operation, and residual service life. In the context of Ukraine post-war recovery, the development of new scientifically substantiated paradigms for critical infrastructure management becomes particularly important, focusing not on merely restoring the pre-war state but on fundamentally transforming the principles of infrastructure design, operation, and maintenance. Under these conditions, the restoration of the GTS should be regarded as an opportunity to transition to a fundamentally new level of technological maturity based on the integration of digital technologies, risk-based integrity management, and modern fundamental materials science. This approach requires abandoning the principle of restoring the infrastructure “as it was” in favour of creating an adaptive, resilient, and intelligently managed system capable of operating under conditions of increased uncertainty, variable loading regimes, and emerging energy scenarios, including the transportation of hydrogen-containing gas mixtures. Within this framework, post-war reconstruction becomes a process of long-term scientific and technological modernization, where the key performance criterion is not only the restoration of transmission capacity but also the enhancement of infrastructure safety, service life,

and environmental sustainability based on the principles of Industry 4.0 and Industry 5.0.

THE AIM

of this study is to summarize the contributions of the authors’ research team and to further develop a scientifically substantiated concept of adaptive integrity management for the Ukrainian GTS under the transition to the Industry 4.0/5.0 paradigm, which encompasses the changing operational conditions and extreme impacts (including those associated with military activities), energy sector decarbonization processes, and the prospective transportation of natural gas-hydrogen mixtures, through the integration of physics-based modelling, probabilistic analysis methods, and innovative repair technologies.

SYSTEM-LEVEL MANAGEMENT OF THE GTS AS THE BASIS FOR SCIENTIFICALLY SUBSTANTIATED DECISION-MAKING AND ENHANCED ADAPTABILITY

One of the fundamental principles of the Industry 4.0/5.0 paradigm is the adaptability of complex engineering systems, which implies their ability to continuously adjust operating modes in response to the current technical condition, external influences, and projected development scenarios. For critical energy infrastructure, this means transitioning from rigidly regulated operating modes to scientifically substantiated management based on the integration of physics-based modelling, digital technologies, technical condition prediction, and risk-based analysis. Under wartime conditions, adaptability becomes the defining characteristic of the Ukrainian GTS, ensuring its ability to maintain operability despite significant changes in gas flow patterns, damage to individual infrastructure components, and changes in operating conditions.

Thus, intensive military operations have become a catalyst for a fundamental transformation of the operating principles of the Ukrainian GTS. The cessation of natural gas transit to the European Union countries, the transition to reverse-flow transportation, the uneven loading of TPs, changes in compressor station operating modes, and the substantially increased role of underground gas storage facilities have created new requirements for system management. Under these conditions, the traditional approach, in which individual pipelines, compressor stations, or underground gas storage facilities are considered independent facilities, no longer provides the required level of efficiency and resilience. The GTS should instead be regarded as a unified multilevel engineering system that integrates TPs, compressor stations, underground

gas storage facilities, wells, automation systems, and technical diagnostic systems into a single network of interconnected components. Any change in the operating mode of one component inevitably affects gas flow distribution, pressure levels, equipment loading cycles, the stress-strain state (SSS) of structures, and the rate of operational damage accumulation. Therefore, the optimization objective should not be individual facilities but the GTS as a whole.

Scientifically substantiated system-level management becomes particularly important under conditions involving potential damage to individual infrastructure components. The loss of individual compressor stations, changes in the operating modes of underground gas storage facilities, or local damage to TPs should not be treated as isolated emergency situations but rather as one of the possible system operating scenarios. This requires the application of adaptive control algorithms capable of predicting, in real time, the consequences of changes in network configuration, determining optimal gas transportation modes, and minimizing technical and operational risks.

The transmission capacity of the GTS is a key indicator of its operational performance and it is determined by the interaction between pipeline sections and compressor stations within a unified network of serially and parallel-connected components. It depends on the parameters of each section and the transportation operating conditions. Even for a simple single-line gas pipeline, its determination represents an iterative problem because hydraulic resistance, temperature, and gas compressibility depend on the flow rate. For complex multicomponent systems, the problem becomes significantly more complicated due to the need to coordinate the characteristics of all system components and determine a common operating point. Within the system approach, this is achieved by matching the performance characteristics of the pipeline section and compressor stations, followed by further refinement of the parameters taking actual operating conditions into account. To simplify calculations, multi-line systems are often reduced to an equivalent single-line gas pipeline using the equivalent diameter method, followed by iterative refinement of the characteristics of a GTS with an arbitrary configuration. The transmission capacity of the equivalent pipeline is determined based on the fundamental gas pipeline equation formulated for the fully rough pipe zone of the turbulent flow [10]:

$$Q = 1.64 \cdot 10^{-6} d_{in}^{2.6} \sqrt{\frac{P_{in}^2 - P_{out}^2}{\Delta z T_{av} L}}, \quad (1)$$

where P_{in} and P_{out} are the pressures at the inlet and outlet of a pipeline section of length L ; T_{av} and z the average temperature and the gas compressibility factor, respectively; d_{in} is the internal diameter of the gas pipeline.

Subsequently, the gas flow rate is distributed among the parallel pipeline branches of the system, taking into account their diameters and hydraulic resistance coefficients, which depend on the flow rate for each branch. The iterative procedure is based on the general gas pipeline flow equation and the classical relationships for the governing parameters:

$$\begin{aligned} Q &= 0.326 \cdot 10^{-6} d_i^{2.5} \sqrt{\frac{P_{in}^2 - P_{out}^2}{\lambda_i \Delta z T_{av} L}}, \\ \lambda_i &= 0.067 \left(\frac{158}{Re_i} + \frac{2K_i}{d_i} \right)^{0.2}; \\ Re_i &= 1.81 \cdot 10^3 \frac{Q_{\Delta}}{d_i \eta}, \end{aligned} \quad (2)$$

where λ_i is the hydraulic resistance coefficient of the i -th gas pipeline; Re is the Reynolds number; η is the dynamic viscosity coefficient.

As a result, the performance characteristic of a pipeline section of a complex GTS based on Eq. (2) can be represented by the following equation:

$$P_{H_j} - P_{K_j} = c_j Q^2, \quad (3)$$

where $c_j = \frac{\lambda_j \Delta z T_j L_j}{(0.326 \cdot 10^{-6} d_j^{2.5})^2}$; j is the section number.

Based on the performance characteristics of compressor stations and pipeline sections of a complex GTS, a mathematical model of the quasi-steady-state operating mode has been developed, enabling the determination of the system transmission capacity and its operating parameters. It has been shown that GTS capacity can be regulated by taking individual compressor stations out of operation, and the quantitative influence of their parameters on the overall operating mode of the system has been established. The proposed model can be used to predict the operation of the GTS in conjunction with underground gas storage facilities.

Under conditions of partial utilization of the GTS, its actual throughput may be significantly lower than its transmission capacity, giving rise to the problem of optimal operating mode control based on the criterion of minimizing energy consumption. One mechanism for such control is the sequential shutdown of individual compressor stations. When compressor station CS- j is taken out of operation under steady-state conditions, the inlet and outlet pressures of the station become equal. This makes it possible to determine the transmission capacity of the system for different

operating configurations. At the same time, shutting down CS-1 actually results in the shutdown of the entire system due to an unacceptable pressure drop at the inlet of CS-2 [11].

As an example, calculations were performed for the Soyuz gas pipeline section within the territory of Ukraine, assuming that the pipeline crossovers with the Trans-Ukrainian GTS were closed. It was established that its transmission capacity, under conditions of maximum hydraulic efficiency and the rated performance characteristics of the gas pumping units (GPUs) along the Novopskov-Khust section, is 92.219 mln m³/day. Further analysis of the shutdown of compressor stations (from CS-12 Borova to CS-22 Khust) revealed a nonuniform effect on the reduction in transmission capacity: shutting down Borova CS (No. 2) decreases the transmission capacity by 14.2 %, Pershotravneva CS (No. 3) by 9.7 %, and Makivka CS (No. 4) by 7.2 %, whereas for Bar CS (No. 10), Husiatyn, Bohorodchany, and Khust, the reduction ranges from 2.5 to 2.2 % (Figure 2). These results indicate that the effect of compressor station shutdown decreases with increasing station sequence number within the system, confirming the feasibility of controlled regulation of GTS operating modes through the selective decommissioning of compressor stations [11].

In addition, the influence of changes in the rotational speed of compressor rotors at CS-1 Novopskov, CS-2 Borova, and CS-3 Pershotravneva was investigated. It was found that reducing the relative rotational speed from 1.0 to 0.8 results in a decrease in the system transmission capacity by 7.2, 6.4, and 5.6 %, respectively (Figure 3). The obtained results demonstrate that the effectiveness of this control method is higher for compressor stations located closer to the beginning of the system [11].

Reducing the energy consumption associated with natural gas transportation can be achieved through the efficient utilization of underground gas storage (UGS) facilities, which serve as both intermediate gas sources and consumers within the GTS.

Optimization of TP operating modes includes determining the transmission capacity, calculating optimal operating conditions for a specified throughput, and developing system expansion strategies. It is based on the integration of design data, operational statistics, and predictive assessments and is implemented using hybrid mathematical models that combine dynamic programming methods with reliability theory. This approach makes it possible to determine the optimal operating modes of compressor stations, the configuration of gas pumping units (GPUs), and the load distribution while minimizing gas transmission costs.

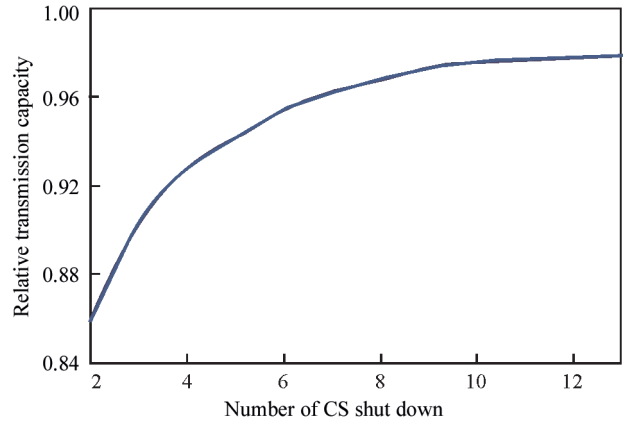


Figure 2. Effect of compressor station shutdown on the system transmission capacity

The mathematical description of gas transportation processes is based on steady-state and transient models. Steady-state models establish relationships between the parameters of system components, whereas transient models, based on partial differential equations, describe the time-dependent evolution of pressure and flow rate. Their formulation is based on the conservation equations of mass, energy, and momentum, followed by parameter identification using experimental data.

The complete mathematical model includes relationships for compressor stations and pipeline sections:

- for compressor stations

$$F_1(P_{B_i}, P_{H_i}, Q_i, R_i, n_i, N_i) = 0;$$

- for pipeline sections

$$F_2(P_{H_i}, P_{B_{i+1}}, Q_i) = 0,$$

where P_{B_i} and P_{H_i} are the inlet and outlet pressures of the i -th compressor station; Q_i is its throughput; R_i is the number of GPUs at the i -th compressor station of the total power N_i operating with rotor rotational speed n_i .

The optimality criterion is the minimization of energy consumption while ensuring a specified level of

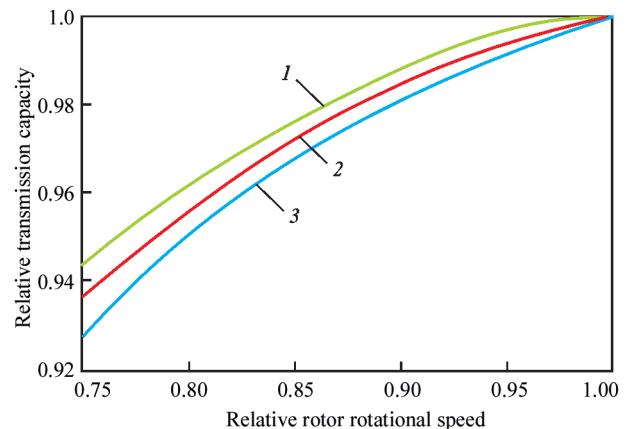


Figure 3. Regulation of the system throughput by varying the compressor rotor rotational speed: 1 — CS-3; 2 — CS-2; 3 — CS-1

gas supply reliability. The optimal control problem is formulated as a discrete dynamic programming problem in which the daily operating cycle is divided into time intervals, and the optimal configuration of GPU operation is determined for each interval. The minimization of the total cost is performed according to the Bellman principle, taking into account the costs associated with transitions between system states. The developed model integrates energy consumption and losses caused by gas supply unreliability, while its accuracy depends on the quality of the statistical data. A comparison between the calculated and actual operating modes of the mobile gas pumping units demonstrates satisfactory agreement, confirming the practical applicability of the proposed approach for predicting and optimizing GTS operating modes [12].

INDIVIDUALIZED ASSESSMENT OF THE TECHNICAL CONDITION OF GAS TRANSMISSION SYSTEM COMPONENTS BASED ON FINITE ELEMENT AND PROBABILISTIC APPROACHES

The transition from system-level GTS management to the implementation of adaptive operating strategies inevitably requires a shift toward an individualized assessment of the technical condition of its components. In this context, it is important to emphasize that individualized decision-making constitutes an integral part of the Industry 5.0 paradigm, complementing the principles of Industry 4.0 by moving beyond purely digital and automated optimization toward human-centric, context-dependent, and physics-based management of complex engineering systems. For critical infrastructure, this implies the need to consider the unique operating conditions of each system component, its actual technical condition, loading history, and degradation processes when making management decisions. At the GTS level, this leads to a fundamental conclusion: the global adaptability and resilience

of the GTS are determined by the combination of the local conditions of its structural components. It is precisely in regions of geometric anomalies, welded joints, corrosion damage, and operational degradation that the conditions governing the limiting state of pipelines are formed. Therefore, effective integrity management of the system is possible only through an individualized assessment of each critical component, taking into account its actual operating conditions.

Under real engineering conditions, defects exhibit complex three-dimensional geometries, and their influence on the load-bearing capacity of structures is highly nonlinear and localized. Additional complexity arises from the stochastic nature of the mechanical properties of materials, resulting from microstructural heterogeneity, manufacturing history (particularly field welding), and service-induced degradation, including corrosion-hydrogen degradation processes. This makes an adequate assessment of limit states impossible within the framework of purely deterministic or code-based averaged models. Consequently, an integrated approach is required in which finite element modelling (FEM) serves as the basic tool for reproducing the local SSS and damage state in regions containing geometrically complex defects, including the vicinity of field or repair welded joints. FEM makes it possible to account for actual loading conditions, three-dimensional stress concentrations, and the interaction between structural components, which is critical for the accurate description of fracture mechanics in pipelines during service.

The first stage of numerical assessment of the technical condition of a pipeline component (PC) is the prediction of the temperature field evolution during welding heating. The spatial and temporal temperature distribution is governed by conductive heat transfer processes, for which the relationship between time τ and the temperature field $T = T(r, \beta, z)$ (Figure 4) is described by the three-dimensional heat conduction equation. In the present case, the heat source is the welding arc (or another concentrated heat source) with a power of q_i . The energy distribution within the heating zone for typical welding processes can be described by a normal distribution function. Heat dissipation from the surface of the structure occurs through radiant heat transfer, heat dissipation to the ambient atmosphere, and the tooling. Accordingly, the heat flux from the surface of the component due to radiation and convection depends on both the surface and ambient and temperatures is quantitatively described by the Stefan–Boltzmann and Newton–Richmann laws, respectively [13].

Subcritical failure of pipelines and pressure vessels manufactured from typical structural steels and alloys is associated with plastic deformation of the structure metal; therefore, strain-based approaches are appropri-

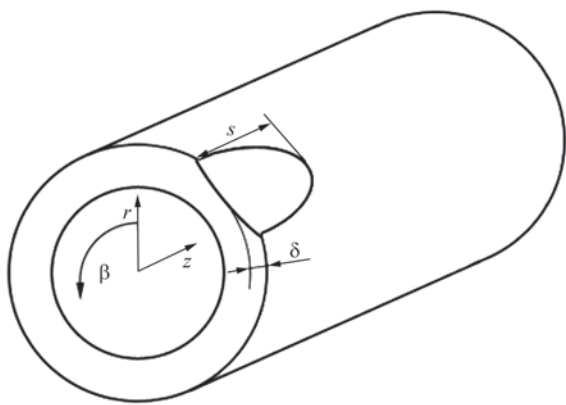


Figure 4. Schematic representation of a PC with a local external metal loss defect

ate as fracture initiation criteria. In the absence of sharp geometric stress raisers (in particular, for a defect-free PC or in the presence of local metal loss defects), the dominant failure mechanism is ductile fracture, which is characterized by the nucleation of uniformly distributed pores. To pore nucleation during plastic flow of the material under non-isothermal conditions, a modified Johnson–Cook criterion is proposed. According to this criterion, initial porosity with a volume fraction of f_0 develops within a given volume of the material when the cumulative equivalent plastic strain exceeds a specified critical value [14].

The mathematical formulation of the coupled problem involving the kinetics of the temperature field, the development of the SSS, and micropore formation is based on the finite element formulation. The increment of the strain tensor (taking into account the presence and uniform distribution of micropores) can be represented as follows [15]:

$$d\epsilon_{ij} = d\epsilon_{ij}^e + d\epsilon_{ij}^p + \delta_{ij}(d\epsilon_T + df/3), \quad (4)$$

where $d\epsilon_{ij}^e$, $d\epsilon_{ij}^p$, $\delta_{ij}d\epsilon_T$, and $\delta_{ij}df/3$ are the components of the strain tensor increment associated with elastic deformation, instantaneous plastic deformation, the kinetics of the nonuniform temperature field, and porosity, respectively.

The tensors of mechanical stresses σ_{ij} and elastic strains $d\epsilon_{ij}^e$ are related through the generalized Hooke's law, i.e.,

$$\epsilon_{ij}^e = \frac{\sigma_{ij} - \delta_{ij}\sigma}{2G} + \delta_{ij}(K\sigma + \varphi), \quad (5)$$

where σ is the mean value of the normal components of the stress tensor σ_{ij} , i.e., $\sigma = (\sigma_{\beta\beta} + \sigma_{zz} + \sigma_{rr})/3$, $K = (1-2\nu)/E$ is the bulk modulus.

The increment of the instantaneous plastic strain $d\epsilon_{ij}^p$, resulting from the stress state within a particular finite element (FE), can be calculated using the linear relationship between the scalar function Λ and the deviatoric component of the stress tensor, namely:

$$d\epsilon_{ij}^p = d\Lambda(\sigma_{ij} - \delta_{ij}\sigma). \quad (6)$$

The specific value of the function Λ depends on the stress state in the considered region of the structure, as well as on the shape of the material yield surface Φ , which is characterized by the yield stress σ_s :

$$\begin{aligned} d\Lambda &= 0 \text{ if } \sigma_i < \sigma_s; \\ d\Lambda &= 0 \text{ if } \sigma_i = \sigma_s; \\ \text{state } \sigma_i > \sigma_s &\text{ is inadmissible.} \end{aligned} \quad (7)$$

Based on the above, the strain tensor increments can be represented as the superposition of the increments of the corresponding components:

$$\begin{aligned} \Delta\epsilon_{ij} &= \Psi(\sigma_{ij} - \delta_{ij}\sigma) + \delta_{ij}(K\sigma + \Delta\epsilon_T + \Delta f/3) - \\ &\quad - \frac{1}{2G}(\sigma_{ij} - \delta_{ij}\sigma)^* - (K\sigma)^*, \end{aligned} \quad (8)$$

where the superscript “*” denotes the corresponding quantity from the previous load increment, and Ψ is the material state function defining the condition of plastic flow according to the von Mises criterion, with additional consideration of the reduction in the effective net cross-sectional area of the finite element due to the formation of discontinuities within the framework of the TN model [16].

$$\begin{aligned} \Psi &= \frac{1}{2G}, \\ \text{if } \sigma_i < \sigma_s &= \sigma_y \sqrt{1 + (q_3 f')^2 - 2q_1 f' \cosh\left(q_2 \frac{3\sigma}{2\sigma_y}\right)}, \\ \Psi &> \frac{1}{2G}, \text{ if } \sigma_i = \sigma_s, \\ \text{state } \sigma_i > \sigma_s &\text{ is inadmissible.} \end{aligned} \quad (9)$$

The criterion for the initiation of macroscopic damage in the PC is the onset of plastic instability of the porous material, taking into account its limited ductility in accordance with the McClintock criterion, which can be expressed mathematically as follows [17]:

$$\Psi > \frac{1}{2G} + \frac{\epsilon_f - \epsilon^p}{1.5\sigma_i(T, \epsilon^p)(1 - 2f/3)}, \quad (10)$$

where ϵ_f is the ultimate strain of the material, which, in the general case, depends on the severity of the stress state.

In addition, substantial porosity development in the material through a ductile mechanism causes a significant increase in the true stresses in the structure metal and, consequently, its failure. Therefore, to formulate a correct and numerically stable failure criterion for the structure, the following condition may be added to Eq. (9):

$$\sigma_s \rightarrow 0. \quad (11)$$

Using Eq. (9), the critical volumetric porosity concentration, which is equivalent to the boundary transition defined by Eq. (11) and constrains the applicability of the proposed models through the condition of unacceptable defectiveness, can be estimated as follows:

$$\begin{aligned} f' &\rightarrow f'_d = \\ &= \frac{q_1 \cosh\left(\frac{3q_2\sigma}{2\sigma_y}\right) - \sqrt{q_1^2 \cosh^2\left(\frac{3q_2\sigma}{2\sigma_y}\right) - q_3^2}}{q_3^2}. \end{aligned} \quad (12)$$

In the case of a low level of stress triaxiality, the increase in local stresses may not be accompanied by

significant plastic flow, and the initiation of macroscopic failure occurs through a brittle micro-cleavage mechanism. Therefore, an additional failure criterion for the porous material is that the true stress intensity exceeds the micro-cleavage stress, S_K :

$$\frac{\sigma_1}{1 - 2f/3} \geq S_K. \quad (13)$$

Thus, conditions (10), (12), and (13) constitute a comprehensive criterion for ductile-brittle fracture of the material, taking into account the evolution of its yield surface during plastic deformation and precritical damage accumulation.

At the same time, a deterministic result of FEM analysis alone is insufficient for assessing the actual reliability of a structure, since the fracture process is inherently probabilistic. Therefore, the next level of modelling involves the application of statistical models, in particular the Weibull distribution, which makes it possible to describe the scatter in strength characteristics, critical strains, and fracture initiation parameters. This provides a physically substantiated means of accounting for the microstructural uncertainty of the material and the statistical nature of damage initiation. A rational approach is to characterize the structure condition through a statistical interpretation of the SSS obtained by the finite element method. For pipelines and pressure vessels without sharp stress raisers, the probability of failure can be determined by integrating the principal stress field over the characteristic area of the weakest cross-sections, thus allowing the evaluation of the overall probability of structure failure [18]:

$$p = 1 - \exp \left[- \int_S \left(\frac{\sigma_1 - A_\sigma}{B_\sigma} \right)^{n_\sigma} \frac{dS}{S_0} \right], (\sigma_1 > A_\sigma), \quad (14)$$

where S_0 is the material constant characterizing the spatial scale of the transition from microdamage to a macrodefect.

The accuracy of the probabilistic assessment according to Eq. (14) is determined by the adequacy of the Weibull distribution parameters for the specific problem under consideration. To simplify the analysis, it is assumed that the probabilistic nature of fracture is manifested at stresses exceeding the plastic flow stress, σ_{flow} , which is defined as $\sigma_{\text{flow}} = (\sigma_t + \sigma_y)/2$. For structural materials, parameter n_σ is generally taken within the range of 3–4. It has been shown that the influence of the geometry of isolated defects on the model coefficients is insignificant over a wide range of geometric variations and is governed predominantly by the characteristics of the finite element discretization. Consequently, the coefficient B_σ may be regarded as a material prop-

erty for a given stress state and the characteristic scale of the problem.

An alternative approach to evaluating the probability of failure of welded components and pressure vessels without sharp stress raisers under conditions of intensive plastic deformation is based on integration of the equivalent plastic strain field, i.e. [18]:

$$= 1 - \exp \left[- \int \left(\frac{\varepsilon - B_\varepsilon}{B_\varepsilon} \right)^{n_\varepsilon} \frac{dS}{S} \right], \quad (15)$$

where A_ε , B_ε , and n_ε are the Weibull parameters.

It is assumed that, for structural materials, a non-zero probability of failure arises at the onset of macroscopic plastic deformation, i.e., $A_\varepsilon \approx 0.887\sigma_y/E$, which is negligible compared with the equivalent plastic strain at the limit state. Parameter n_σ , characterizing the material susceptibility to fracture, is typically taken within the range of 3–4, which corresponds to $n_\varepsilon \approx 5$. Accordingly, the principal objective of the strain field analysis for a defective pipe under the limit internal pressure is to determine the Weibull distribution parameters B_ε in Eq. (15), taking the material properties into account.

Of practical interest is the comparison of numerical simulation results with code-based approaches for assessing the limit state of corroded pipelines. In particular, the DNV-RP-F101 (1999) standard establishes failure the criterial dependencies relating the geometry of corrosion-erosion defects to the limit pressure, whereas in Ukraine the standard DSTU-N B V.2.3-21:2008 is applied, which is based on the assessment of the residual safety factor using both design specifications and operational data.

A comparative analysis performed for a pipeline ($D \times t = 1420 \times 20$ mm, X65 steel) containing a local corrosion defect ($2s \times 2u = 100 \times 50$ mm) shows that the $P_{0.002}$ curve (corresponding to a probability of failure $p = P_{0.002}$) agrees well with the limit relationships specified in DNV-RP-F101, whereas the P_{max} curve exhibits a substantially different shape and pressure levels (Figure 5). At the same time, according to DSTU-N B V.2.3-21:2008, the $P_{0.002}$ curve adequately describes the condition of a pipeline containing shallow wall-thinning defects. For defects of intermediate and critical severity, the corresponding states fall between the $P_{0.002}$ and P_{max} curves, which effectively corresponds to different probabilities of failure and different levels of conservatism of the code requirements. Significant discrepancies between the numerical methodology and DSTU-N B V.2.3-21:2008 were identified for defect depths exceeding 0.5 of the pipeline wall thickness. This is explained by the fact that the code-based approaches account for the transition from ductile to brittle fracture through

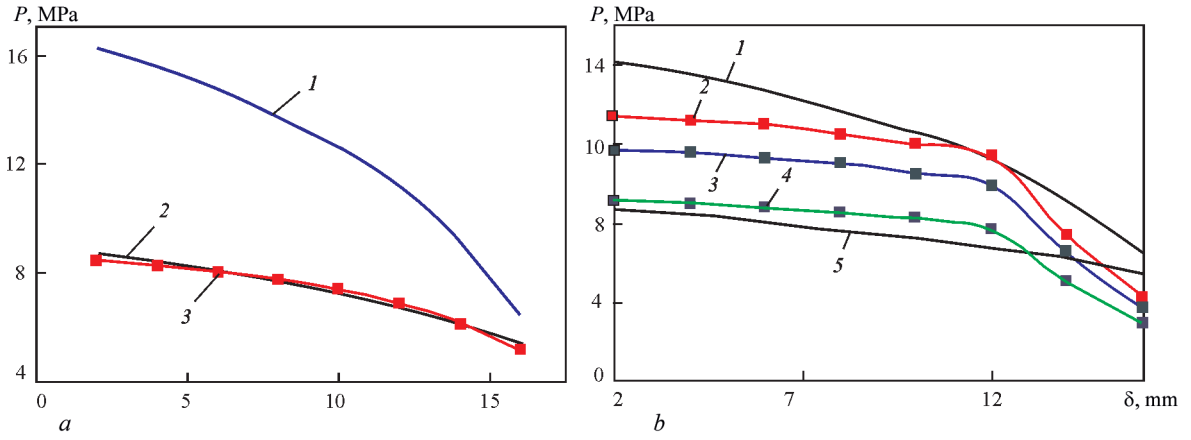


Figure 5. Comparison of the results of probabilistic analysis of the condition of a TP element ($D \times t = 1420 \times 20$ mm, X65 steel) containing an isolated corrosion metal loss defect of varying depth a ($2s \times 2u = 100 \times 50$ mm) with the requirements of current standards: a — DNV-RP-F101, 1 — $P_{\max}$, 2 — $P_{0.002}$, 3 — P_{DNV} ; b — DSTU-N B V.2.3-21:2008, 1 — $P_{\max}$, 2 — critical, 3 — significant, 4 — moderate, 5 — $P_{0.002}$

stress intensity criteria, resulting in more conservative assessments. Comparison with DNV-RP-F101 indicates that, in some cases, the influence of the brittle fracture mechanism may be overestimated even under conditions of high stress concentration. Therefore, the applicability of the proposed numerical methodology should be limited to defects with a depth not exceeding 0.5 of the wall thickness and a length at least five times greater than the defect depth. Based on this approach, equiprobability diagrams relating the limit pressure to the geometry of corrosion-erosion defects can be constructed, as well as generalized surface diagrams correlating defect length, defect depth, and allowable pressure for a specified probability of failure (Figure 6).

Further generalization is achieved through the Monte Carlo method, which enables the generation of multiple realizations of material properties, defect geometries, and loading conditions. As a result, the complete probability distribution of failure is obtained, rather than a single limit-state value, providing the basis for risk-based and individualized decision-making. The probability of failure, p , is determined as the

frequency with which the limit state is reached within a representative sample of realizations. A widely used approach for accounting for the stochastic nature of material properties and loading conditions is the application of the Weibull distribution. At each step of the numerical simulation, the value of the random variable X for a finite element is generated according to the prescribed probability distribution (Weibull), ensuring statistically consistent realizations of the system parameters within the Monte Carlo framework:

$$X_{ijk} = \left[-\ln(1 - RND) \right]^{\frac{1}{\eta_X}} (B_X - A_X) + A_X, \quad (16)$$

where A_X , B_X and η_X are the Weibull parameters for characteristic X ; RND is a random number uniformly distributed over the interval $[0; 1]$.

As an example of application of the developed numerical approach, a steel PC ($D = 1420$ mm, $t = 20$ mm) containing an isolated semi-elliptical local wall-thinning defect on the external surface of the pipe ($2s = 20$ mm, $2c = 20$ mm, $a = 20$ mm) was considered. The material was 17G1S-U steel ($E = 206$ GPa,

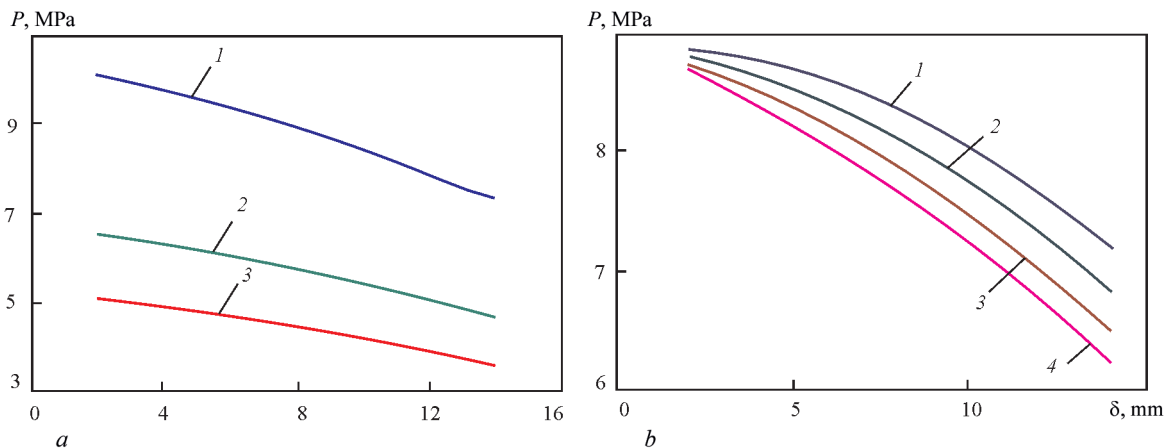


Figure 6. Equiprobability acceptability curves for a local wall-thinning defect in a PC $D \times t = 1420 \times 20$ mm, 17G1S-U steel): a — as a function of the critical probability of failure ($2s \times 2u = 100 \times 50$ mm), 1 — $p = 0.03$, 2 — $p = 0.01$, 3 — $p = 0.005$; b — as a function of the wall-thinning defect length ($p = 0.01$, $2u = 50$ mm), 1 — $2s = 25$ mm, 2 — $2s = 50$ mm, 3 — $2s = 75$ mm, 4 — $2s = 100$ mm

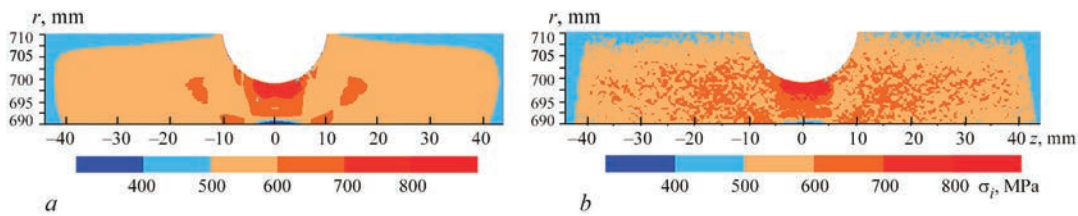


Figure 7. Examples of equivalent stress distributions in a pipeline ($D \times t = 1420 \times 20$ mm, 17G1S-U steel) containing an external corrosion defect ($2s \times 2c \times a = 20 \times 20 \times 10$ mm) under the limiting internal pressure of 14.0 MPa: *a* — finite element analysis; *b* — calculation using the Monte Carlo algorithm

$\nu = 0,3$, $\sigma_y = 365\text{--}490$ MPa, $S_K = 800\text{--}1000$ MPa). The criterion for ductile pore nucleation uses a strain-based approach, according to which damage initiation occurs when the accumulated equivalent plastic strain exceeds the critical value ε_c , corresponding to the formation of uniformly distributed discontinuities with an initial pore volume fraction of $f_0 = 0.001\text{--}0.010$. Within the adopted parameter ranges, the input material properties are described by the Weibull distribution: for σ_y ($A_\sigma = 365$, $B_\sigma = 450$, $\eta_\sigma = 4$), for f_0 ($A_f = 0.001$, $B_f = 0.0052$, $\eta_f = 2$), and for S_K ($A_s = 800$, $B_s = 937$, $\eta_s = 4$).

Comparison of the deterministic and stochastic approaches to SSS assessment shows that the maximum stress values within the defect are similar; however, the stochastic model (Monte Carlo) produces substantially higher local stress gradients owing to the spatial variation of mechanical properties, primarily the yield strength (Figure 7). Since ductile fracture is a localized process, accounting for spatial uncertainty has a significant influence on the evaluation of the limit pressure P_r , reducing the discrepancy between the predicted and the actual structure condition. Thus, the combination of FEM, Weibull statistics, and the Monte Carlo method enables the transition from code-based averaged approaches to an individualized, physics-based, and risk-oriented analysis of GTS components. Within the Industry 5.0 paradigm, such individualized decision-making becomes a key principle for the management of critical infrastructure.

TEMPORAL DIMENSION OF INTEGRITY MANAGEMENT: PREDICTIVE MAINTENANCE AND CONDITION FORECASTING OF THE GTS

Within the Industry 4.0/5.0 paradigm, where adaptability, real-time data, and intelligent decision support are regarded as the fundamental system-forming principles, the temporal dimension of GTS integrity management becomes of paramount importance. Whereas the previous sections focused on the spatial heterogeneity of infrastructure facilities and the need for individualized assessment of their performance, this section logically extends the concept toward forecasting the evolution of the technical condition over time. Consequently, GTS

integrity management evolves from a static assessment to a dynamic one, in which not only the current condition but also its evolution path under the influence of operational, corrosion-hydrogen, and external factors becomes the key consideration.

Modern approaches to predictive maintenance are based on the integration of physics-based material degradation models, non-destructive testing (NDT) results, and operational monitoring data. In the context of TPs, this implies a transition to a model of continuous updating of residual life assessments, in which each new measurement refines the predicted evolution of damage. At the same time, within the Industry 5.0 framework, predictive maintenance acquires an additional dimension, namely the individualization of decision-making. This means that forecasting the condition of GTS components is no longer based on averaged models but instead accounts for the unique characteristics of each asset, including its operating history, local loading conditions, spatial heterogeneity of material properties, diagnostic results for specific defects, and the criticality of the component within the overall system. Consequently, the concept of a personalized engineering asset is established, in which the maintenance strategy is determined not by generalized regulations but by the individual degradation trajectory of the asset, for which appropriate analytical and instrumental approaches have been developed.

It is well known that, during the long-term operation of underground TPs, various forms of environmental degradation may develop, including coating delamination and the formation of wall defects, particularly corrosion defects. The most hazardous phenomenon, which is difficult both to predict and to prevent, is stress corrosion cracking (SCC). According to statistical analyses reported by various researchers, the proportion of trunk TP failures, caused by SCC ranges from 24 to 36 %. Given both the severity and the widespread occurrence of SCC, this problem remains highly relevant, while investigating the mechanisms governing its development is of considerable scientific and practical importance. The need for a more comprehensive understanding of SCC in TPs determines the importance of conducting fundamental

research and developing new approaches for assessing the probability of its initiation and propagation.

To investigate the mechanisms governing SCC in TPs, a unique scientific approach has been developed and applied based on laboratory simulation of SCC factors under conditions equivalent to actual service environments. This approach is founded on a novel methodology for assessing the susceptibility of pipeline steels to SCC by simulating the combined effects of external and internal factors. For this purpose, the coefficient K_s is proposed, which accounts for changes in the plastic properties of the metal in a corrosive environment relative to its properties in air [19]:

$$K_s = \frac{\psi_{air}}{\psi_p} = \left(\frac{s_0 - s_1^{air}}{s_0} \right) / \left(\frac{s_0 - s_1^{sol}}{s_0} \right), \quad (17)$$

where ψ_{air} and ψ_{sol} are the reduction in area of the specimens tested in air and in the corrosive solution, respectively; s_0 is the initial cross-sectional area of the specimens before testing, mm²; s_1^{air} and s_1^{sol} are the cross-sectional areas of the specimens at the fracture location after testing in air and in the corrosive solution, respectively, mm².

Changes in the mechanical properties under the combined influence of SCC factors can be evaluated using the property degradation coefficients F_x (for elongation at fracture F_δ , ultimate tensile strength F_{σ_t} , and yield strength F_{σ_y}) relative to the corresponding values measured in air:

$$F_x = \frac{F_x^{air} - F_x^{sol}}{F_x^{air}} 100 \%, \quad (18)$$

where F_x^{air} and F_x^{sol} are the average values of the corresponding properties measured in the corrosive solution and in air, respectively.

To quantitatively assess the SCC susceptibility of pipeline steels, a series of laboratory investigations was conducted in which physical simulation of SCC factors which can be present in the TP section (corrosive environment is model soil electrolyte, NS4 solution was performed, namely cathodic protective potential, accumulated stress cycles, stress raisers, periodic wetting with the solution, and the presence of different types of polymeric coatings) [20]. Slow strain rate testing (SSRT) of X70 steel specimens demonstrated that shifting the potential toward the cathodic region ($E_{corr} \rightarrow -1.0 \text{ V} \rightarrow -2.0 \text{ V}$) increased the post-fracture cross-sectional area of the specimens compared with those tested in air (specimens 1, 2, and 12), indicating an increased susceptibility of the steel to brittle fracture.

At the same time, at a potential of -1.0 V , differences in the SCC susceptibility of X70 steels having different structural characteristics may become evident. In particular, fracture of the specimen taken from pipe B was accompanied by plastic deformation (Figure 8, *a*, curve 3), and its post-fracture cross-sectional area (Figure 8, *b*, photo 3) was smaller than that of the specimen taken from pipe A (4.35 mm² versus 6.07 mm², respectively). The corresponding values of coefficient K_s were 1.31 and 1.70. Thus, metal containing a lower level of nonmetallic inclusions and a finer pearlitic constituent exhibits lower susceptibility to SCC under otherwise identical conditions.

According to DSTU 4219:2003, the specified range of the protective polarization potential is -0.85 to -1.15 V (relative to the copper/copper sulfate reference electrode, CSE), corresponding to -0.75 to -1.05 V . The corrosion-mechanical properties of X70 steel were investigated at a potential close to the maximum protective value (-1.00 V) under different combinations of SCC-promoting factors. Fracture of the specimens at -1.00 V potential (Figure 8, *a*) during complete immersion in the NS4 solution (curve 2), under periodic wetting with the solution (curve 6), after cyclic loading followed by periodic wetting (curve 7), in the presence of a polymer primer layer with periodic wetting (curve 9), and after cyclic loading in the presence of a polymer primer layer with periodic wetting (curve 10) occurred with virtually no plastic deformation. For all specimens, the cross-sectional area increased by 52–66 % compared with specimens tested in air. The corresponding values of coefficient K_s were 1.70 (specimen 2), 2.15 (specimens 6 and 7), 2.07 (specimen 8), 1.75 (specimen 10), and 1.7 (specimen 9).

The fracture curves of specimens tested in the solution after prior cyclic loading (curve 4) exhibit a short region of ductile fracture. The cross-sectional area of these specimens is approximately 65 % larger than that of the specimens tested in air, with a corresponding coefficient of $K_s = 1.65$. The fracture curves of specimens containing stress raisers differ from those discussed above by exhibiting significantly lower elongation (Figure 8, *a*, curves 5 and 8). The post-fracture cross-sectional area of these specimens (specimens 5 and 8) is larger than that of specimens 2, 6, 7, 9, and 10, reaching 40 mm², while the corresponding SCC susceptibility coefficients K_s are 1.87 and 2.07, respectively. It should be emphasized that, at a potential of -1.0 V , the fracture surfaces of all specimens except specimen 3, tested under different combinations of SCC-promoting factors, contain a brittle fracture component (Figure 8, *b*, photos 2, 4–10), the fraction of which is greater than that observed at the corrosion potential. The values of coef-

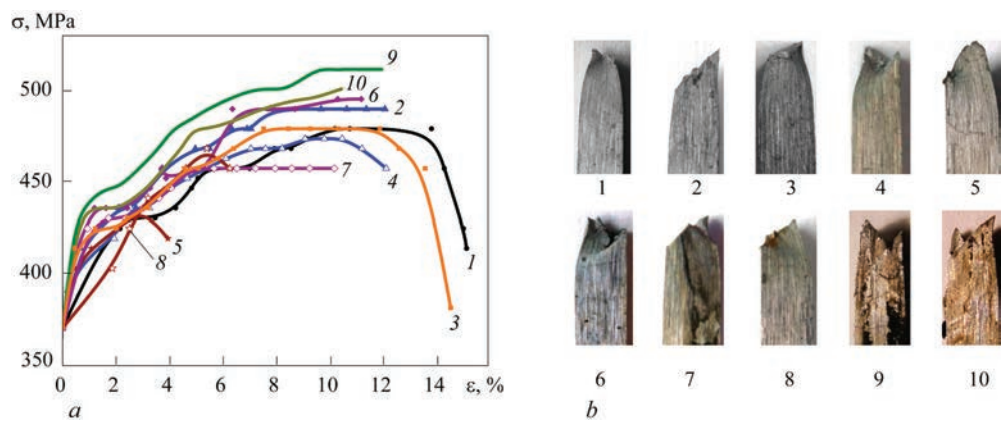


Figure 8. Fracture diagrams of X70 pipeline steel specimens tested in air and in the NS4 solution at a potential of -1.0 V under the influence of SCC-promoting factors (a); photographs of the corresponding fracture surfaces (b). Strain rate: 10^{-6} s $^{-1}$

ficient K_s vary from 1.65 to 2.15. The factors exerting the strongest influence on SCC susceptibility at this potential are the presence of stress raisers and periodic wetting with NS4 solution.

Specimens 2–7 underwent plastic deformation during testing, resulting in the characteristic necking in the fracture region. Their fracture surfaces exhibited a ductile fracture mode, while the values of coefficient K_s ranged from approximately 1.04 to 1.56. The fracture surfaces of specimens 8–15 differed from those described above: visually, they exhibited a smaller degree of plastic deformation and, consequently, higher values of coefficient K_s , ranging from approximately 1.6 to 3.5. During the investigation of the causes of failure of a 1420×15.7 mm TP, the remaining wall thickness in the failure region adjacent to the corrosion crack was approximately 35–40 % of the nominal wall thickness, and the fracture surface (Figure 9) exhibited many features similar to those observed under laboratory conditions. This corresponds to a coefficient value of $K_s = 1.6$.

The corrosion rate of X70 steel in the solution after exposure of the coating to the solution at 20 °C for 1 month increased by nearly 13 %, from 0.089 mm/

year in the original solution to 0.101 mm/year in the solution that had been in contact with the coating. In contrast, after 2.5 months of contact with the coating, the corrosion rate decreased by 76 %, reaching 0.021 mm/year (Figure 10). At 60 °C, the variation in the corrosion rate of X70 steel followed a similar trend, increasing to 0.09 mm/year after 1 month and subsequently decreasing to 0.012 mm/year after 2.5 months.

To determine the effect of cathodic polarization on the properties of the protective coating, cathodic delamination tests were carried out using a delamination laboratory test stand (Figure 11). At a potential of -1.45 V, the degradation process proceeds more intensively than at the corrosion potential, as confirmed by the increase in the coating radius of delamination from the substrate (11.0 mm at E_{corr} to 17.0 mm at -1.45 V). During coating delamination under cathodic polarization, the pH of the solution increased by approximately 15 % (from 9.6 at E_{corr} to 11.0 at -1.45 V), its electrical conductivity increased three-fold (from 2.2×10^{-3} to 6.6×10^{-3} S/cm, respectively), and its corrosivity toward X70 steel increased, with the corrosion rate rising from 0.167 to 0.234 mm/year.

Based on the comprehensive set of investigations performed, a novel concept has been developed according to which the initiation and propagation of SCC in TPs require the simultaneous presence of three principal factors of sufficient intensity within the investigated pipeline section. These principal factors are conventionally designated as “corrosion” (C_i), “corrosion protection” (Z_i), and “mechanical stresses” (N_i). Each principal factor is influenced by a number of additional factors. Since the intensity of both the principal and additional factors varies along TP section, the recommended numerical values have been assigned to each factor based on the susceptibility of pipeline steel to SCC under the influence of the factors investigated in the present study. The objective of the assessment is to identify the factors present within the investigated TP section and to de-



Figure 9. Fracture surface of an X70 steel pipeline in the vicinity of a corrosion crack formed during service of a 1420×15.7 mm TP

termine their respective intensity levels. According to the proposed methodology, the identification of potentially SCC-prone sections of a TP involves the following steps: analysis of design, construction, and operational documentation; identification of external and internal factors based on above-ground technical diagnostics and laboratory investigations; analysis of the obtained results and assessment of the probability of SCC occurrence within the TP section; ranking of potentially SCC-prone TP sections according to their susceptibility to SCC; in-ditch technical inspection of the TP; and development of recommendations for repairing the TP section containing crack-like defects. During inspection of the TP, a comprehensive set of investigations is carried out to identify the conditions and factors promoting SCC in accordance with the algorithms described above.

It is proposed that the probability of SCC for the i -th section of a TP be calculated by taking into account the numerical values of the principal and additional factors according to the following expression:

$$R_i = r_{C_i} r_{Z_i} r_{N_i} = \prod_{j=1}^n r_{ji} \left(1 - \sum_{k=1}^m G_{ki} \right), \quad (19)$$

where R_i is the probability of SCC at the i -th section of the TP; r_{C_i} , r_{Z_i} and r_{N_i} are the numerical values of the principal independent factors; r_{ji} is the numerical value of the j -th principal independent factor; j is the index of a principal independent factor; n is the total number of principal independent factors; G_{ki} denotes the numerical values of the k -th additional factors affecting the corresponding principal factors at the i -th pipeline section; k is the index of the additional factor; m is the total number of additional factors influencing the corresponding principal factor.

SCIENTIFICALLY GROUNDED SELECTION OF TP REPAIR AND REHABILITATION TECHNOLOGIES

Within the Industry 4.0/5.0 paradigm, maintenance is regarded as a system of individualized decision-making that simultaneously ensures achievement of safety, reliability, economic efficiency, and environmental sustainability criteria. Of particular importance are in-service repair technologies, which do not require eliminating gas transportation, eliminate the need for natural gas release into the atmosphere, reduce material consumption and repair duration, decrease the scope of repair operations, and minimize risks to personnel. Consequently, repair under internal pressure fully complies with the principles of sustainable development and the human-centric concept of Industry 5.0. The effectiveness of such technologies is determined not only

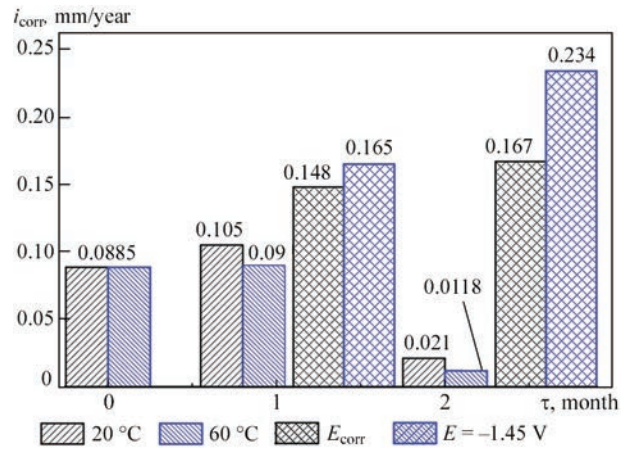


Figure 10. Corrosion rate of X70 steel in the NS4 solution after exposure of a tape coating in the solution at 20 and 60°C, and after cathodic delamination testing at the corrosion potential and at a polarization potential of -1.45 V

by their design features but also by their scientifically justified selection for a specific defect. Decision-making should therefore be based on a comprehensive analysis of the SSS, fracture mechanisms, material degradation, residual life, and operating conditions. Under these circumstances, FEM becomes a tool not only for assessing structural integrity but also for optimizing repair technology, making it possible to evaluate the effectiveness of different repair methods, determine the geometric parameters of reinforcing structures, optimize multipass surfacing procedures, and establish permissible conditions for performing repairs without shutting down the pipeline.

In particular, multipass surfacing provides compensation for corrosion-induced metal loss without removing the TP from service. Following preheating, the risk of cold cracking is virtually eliminated, while the plastic instability of the locally overheated metal under the action of internal pressure becomes the governing factor of technological integrity. At the same time, localized heating may induce residual plastic deformations and bulging, thus reducing

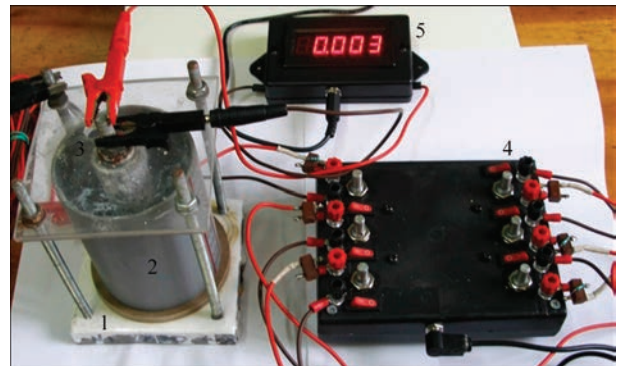


Figure 11. Laboratory test stand for investigating cathodic delamination of protective coatings: 1 — coated steel plate; 2 — electrochemical cell; 3 — anode; 4 — potentiostatic unit; 5 — microammeter

the load-bearing capacity of the structure. Therefore, optimization of the repair surfacing procedure should simultaneously satisfy the criteria of technological integrity during repair and the admissibility of residual deformations in the restored structure.

The characteristics of a TP section containing an externally detected local corrosion wall-thinning defect during repair surfacing were investigated using a representative example of a pipeline with a diameter of $D = 1420$ mm and a wall thickness of $t = 20$ mm manufactured from X65 steel ($\sigma_y = 490$ MPa, $\sigma_t = 590$ MPa), operating at a maximum internal pressure of $P = 7.4$ MPa. A metal loss defect ($2s \times u \times \delta = 70 \times 70 \times 10$ mm) located on the external pipe surface was considered. Taking into account the controlled grinding stage, the defect geometry was assumed to be semi-elliptical. Elimination of this defect requires two deposited weld layers (excluding the contour pass); the corresponding weld bead arrangement is shown in Figure 12. It was assumed that the repair area was preheated to a temperature of $T_{pre} = 100$ °C in order to prevent cold cracking. The technological parameters of arc surfacing were selected in accordance with the recommendations of the applicable standards as follows: welding current $I_w = 80$ A, welding speed $v_w = 2$ mm/s, and pipeline pressure during repair $P_r = 4$ MPa. Accordingly, the governing repair parameters are the welding current I_w , the internal pipeline pressure during surfacing P_r , and the time interval between the deposition of successive weld beads, which must ensure that the maximum metal temperature does not fall below the required minimum value, i.e., $T_{min} \geq T_{pre}$.

The analysis of the residual SSS after surfacing revealed a strongly nonlinear distribution of residual stresses. This behavior is attributed to the gradual change in the structure geometry during successive weld bead deposition within the defect region, as well as to the complex thermal cycles in the metal associated with repeated heating and cooling. During repair welding of a defect on a pressurized pipeline, the combined action of external loading and localized nonuniform thermal deformation (accompanied by intensive plastic flow of the metal) results in the formation of a localized damage field. It should be

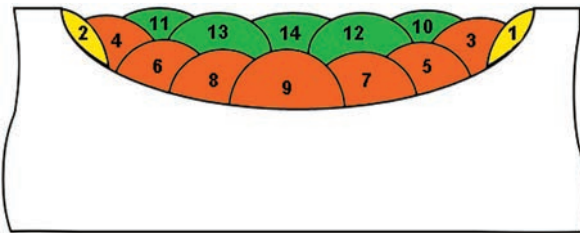


Figure 12. Schematic of surfacing for repairing a wall-thinning defect on the external surface of the pipeline

emphasized that, in the case considered, the growth rate of the nucleated ductile fracture micropores is relatively low owing to the low stress triaxiality in the locally heated region. Consequently, according to the Rice–Tracey law, the growth rate of the nucleated pores remains low. At the same time, an increase in the internal repair pressure P_r (or in the heat input during surfacing) predictably leads to an increase in the accumulation of plastic strain, corresponding growth of ductile fracture pores, and an increased susceptibility of the structure to macroscopic failure. The developed methodology for evaluating the susceptibility of welded pipeline metal to ductile fracture makes it possible to investigate the influence of various repair parameters on both the technological strength and the serviceability of the pipeline. As a representative example, the deposition of a single weld bead at the center of the wall-thinning defect was analyzed for the above-mentioned pipeline with a diameter of $D = 1420$ mm and a wall thickness of $t = 20$ mm. The evolution of the SSS during multipass surfacing is complex and is governed by the relative positions of the individual weld beads with respect to the wall-thinning defect, as well as by the progressive change in the profile of the damaged pipeline section as the deposited metal solidifies. This, in turn, results in strongly nonlinear relationships between the surfacing parameters that ensure repair safety and the structural integrity of the pipeline after repair of the wall-thinning defect. Depending on the degree of PC preheating during repair and the magnitude of the internal pressure in the repaired region, a shape defect of different sizes is formed. The acceptability of such defects determines the possibility of further operation of the repaired TP section of the. These results can be presented in the form of two-dimensional diagrams, for example in the repair pressure–welding current coordinates. An example for the considered case (pipeline geometry and material properties, as well as the type and severity of damage) is shown in Figure 13.

From these results, it can be concluded that, at a high heat input, the dominant factor limiting the applicability of surfacing is the risk of plastic instability, whereas at relatively low local heating power and high internal pressure, the principal concern is excessive residual deformation of the structure. The curves in the presented diagrams represent the boundary separating the permissible and impermissible states of the pipeline during multipass repair surfacing and subsequent operation. The region below curve 1 corresponds to conditions satisfying the acceptance criteria for the shape defect within the repaired area, whereas the region below curve 2 corresponds to the parameters that satisfy the criteria of the material resistance

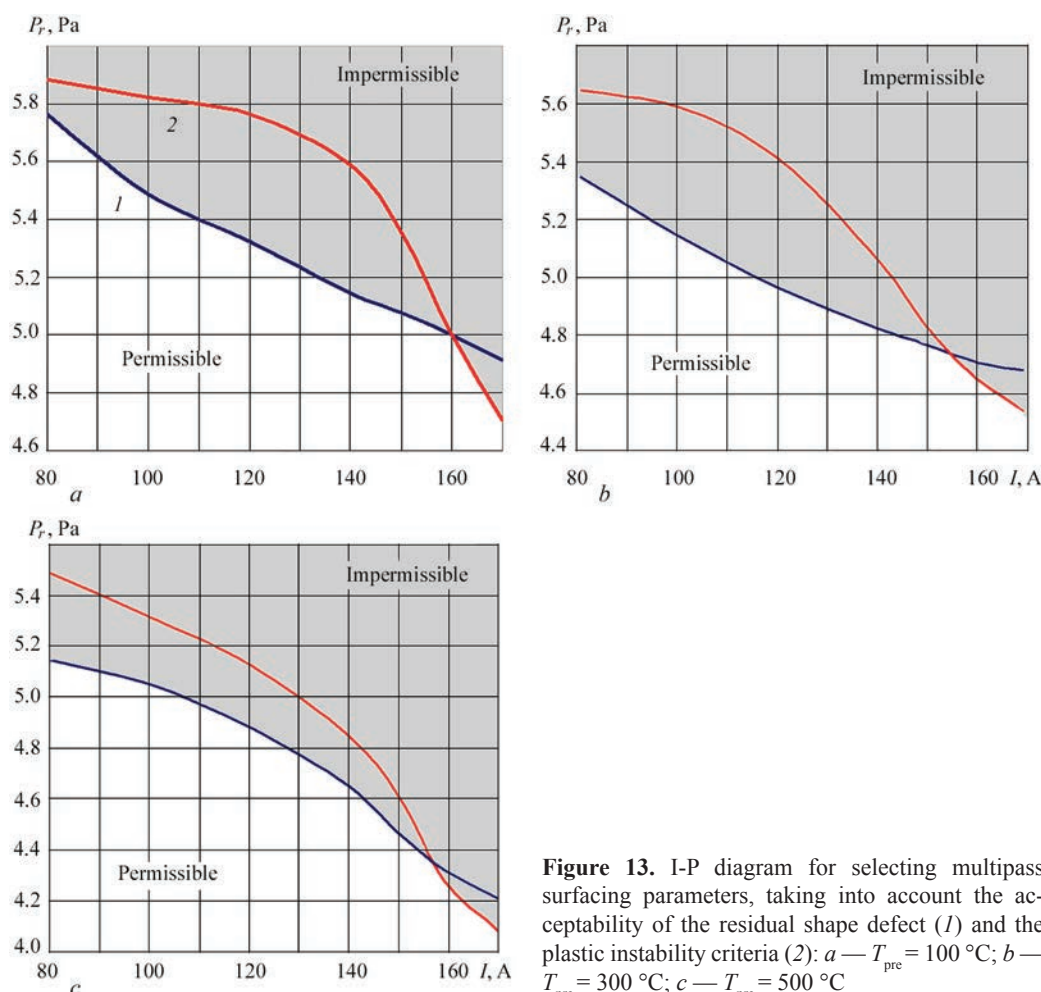


Figure 13. I-P diagram for selecting multipass surfacing parameters, taking into account the acceptability of the residual shape defect (1) and the plastic instability criteria (2): *a* — $T_{\text{pre}} = 100\text{ °C}$; *b* — $T_{\text{pre}} = 300\text{ °C}$; *c* — $T_{\text{pre}} = 500\text{ °C}$

against ductile fracture according to the results of the comprehensive numerical calculation package of the evolution of the TP state during surfacing [21].

In addition to repair welding, increasing attention is being given to the application of various types of reinforcing structures, composite repair sleeves, metallic sleeves, and hybrid repair systems (Figure 14) [22]. Their effectiveness is determined not only by the strength of the reinforcing components proper but also by the manner in which the load is transferred between the damaged structure and the repair system. Therefore, optimization of the reinforcement geometry, material properties, and installation parameters also requires numerical modelling and multi-criteria analysis. In addition, adequate reliability of the welded joints must be ensured, as they often represent the weakest elements of the pipeline-reinforcement system, thereby guaranteeing both the serviceability of the repaired structure and the safety of maintenance personnel.

Based on the conducted investigations and experimental testing, the use of 1.2 mm gas-shielded flux-cored wires and 1.6–2.0 mm self-shielded flux-cored wires is recommended for mechanized gas metal arc welding (GMAW). The welding consumables shall provide welded joints with mechanical properties

meeting the requirements specified for the pipe base metal: the ultimate tensile strength shall not be lower than the specified value for the pipe material; the impact toughness of the weld metal at -20 °C shall be at least 34 J/cm^2 ; the static bend angle shall be not less than 120° ; and the hardness of both the weld metal and the HAZ shall not exceed 300 HV_{10} for pipes up to and including strength class K55, and 325 HV_{10} for pipes of strength classes above K55 up to and including K60.

Examples of butt joints produced during the optimization of welding procedures in different welding positions using mock-up specimens measuring $350 \times 100 \times 16\text{ mm}$ and $250 \times 151 \times 2\text{ mm}$ are shown in Figures 15 and 16. During the development of the mechanized gas metal arc welding technology for reinforcing structural components, particular attention was paid to establishing welding techniques for butt joints and lap-butt joints in various welding positions. At the same time, the objective was to determine welding parameters that, on the one hand, ensured high-quality formation of multilayer welds and on the other hand, minimized the need for substantial adjustment when changing the welding position.

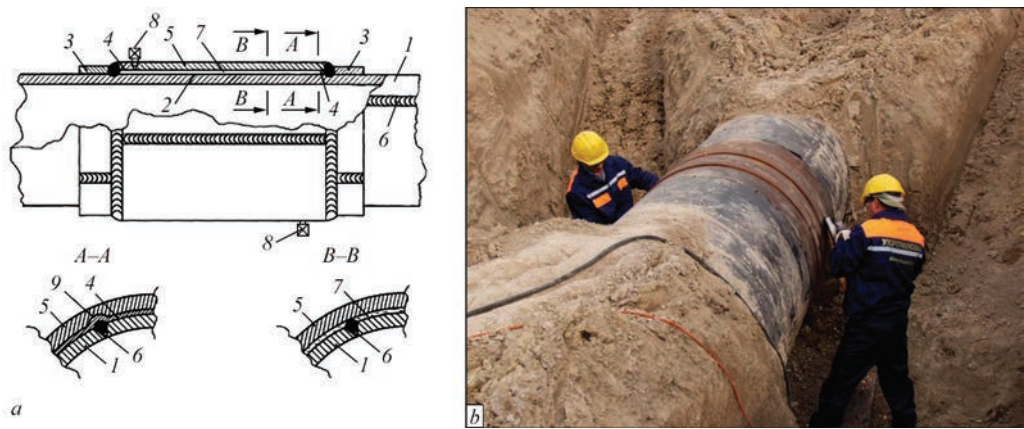


Figure 14. Schematic of a composite repair sleeve for reinforcing defective sections of a TP (a) and an example of its installation (b)

The technology for producing multilayer circumferential lap-butt joints envisages performing the welding process sector by sector in the upward direction. When the groove width is $l \geq 15$ mm, all weld layers should be deposited using the one layer-two passes technique. This promotes grain refinement of the weld metal and additionally improves its impact toughness. When the groove width is $l < 15$ mm, the first layer is deposited using the one layer-one pass technique, and all subsequent layers are deposited using the one layer-two passes technique. The final capping layer of the lap-butt joint should be deposited either by the one layer-one pass or one layer-two passes technique, depending on the value of l . The total number of weld layers in lap-butt joints is determined by the wall thickness of the reinforcing structural elements. To ensure complete fusion between the reinforcement and the pipeline, overhead welding should be performed with the electrode positioned using the backhand technique. The recommended welding parameters are presented in the Table 1.

Particular attention should be paid to the strength of the welded joints of compound-filled repair sleeves. The principle of application of this type of

repair system is based on filling the uniform annular gap between the sleeve and the pipeline with a liquid compound, thereby providing the required level of hydrostatic pressure and reducing the stress level in the wall of the defective pipe. However, TPs using compound-filled sleeves has certain limitations associated with the features of installation of the reinforcing structure on the pipe, specifically with the geometry of the welded joint. The presence of a technological spacer ring, which ensures the required gap between the walls, results in the formation of a crack-like slit in the weld area. Consequently, such a welded joint belongs to the class of slotted joints, whose design is based on the principles of linear elastic fracture mechanics (LEFM) for cracked bodies. The limit state of this type of welded joint is formulated from the condition that the adjacent sharp cavity is located in the stress field, capable of causing its spontaneous propagation. The well-established R6 assessment procedure, based on the two-parameter criterion for ductile-brittle fracture, can be used to evaluate the limit state. This method relates the parameter characterizing a purely brittle fracture at the crack tip $K_r = K_I/K_{IC}$ to the parameter characterizing a purely ductile failure for the

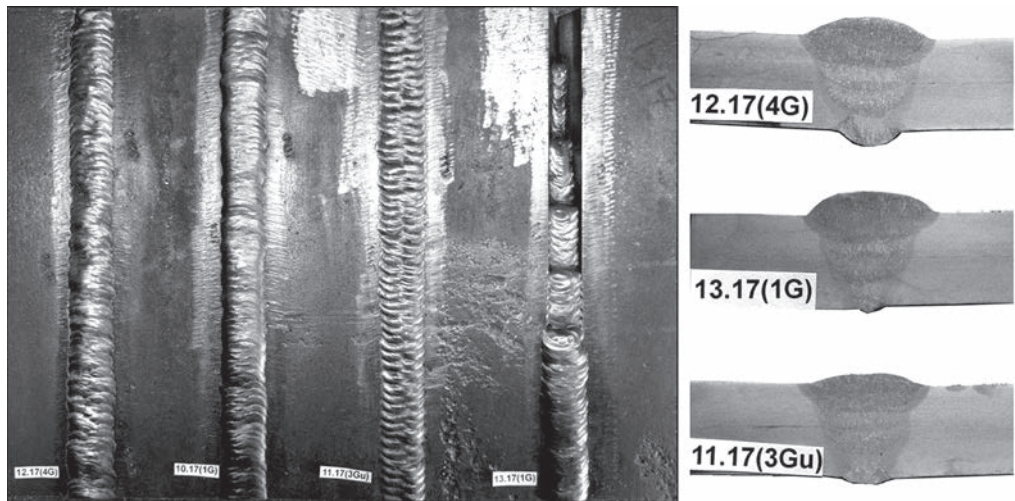


Figure 15. Butt joint specimens welded in the overhead (4G), flat (1G), and vertical-up (3G-up) welding positions using solid wire

same crack $L_r = \sigma_{ref}/\sigma_y$. The calculation of the stress intensity factor K_I and the reference stress σ_{ref} located in the stress field for slotted welded joints is conveniently performed by first determining the bending moment M_L and the shear force Q_r acting in the welded joint per a unit of its circumferential length using the following relationships [23]:

$$K_I = \frac{0.5369}{\sqrt{h}} \left(Q_r \cos \varphi + \frac{8M_L}{h} \right); \quad (20)$$

$$\sigma_{ref} = \sqrt{\left(\frac{4M}{h^2} + \frac{Q_r \cos \varphi}{h} \right)^2 + 3 \left(\frac{Q_r \sin \varphi}{h} \right)^2},$$

where h is the minimum distance from the tip of the sharp cavity in the weld to the free surface (Figure 17). In the case considered, there are two such distances, h_1 and h_2 . The more conservative value is h_1 :

$$h_1 = t_M \cos \varphi = t_M (1 + \beta^2)^{-0.5};$$

$$\beta = \frac{t_M + \Delta - \delta_{mk}}{a_M}. \quad (21)$$

It follows from the foregoing that the ductile-brittle fracture limit state (i.e., spontaneous propagation of the crack, represented by the sharp cavity associated with the circumferential weld) is governed by the bending moment M_L and the shear force Q_r , which are determined by the internal pressure in the pipe P , the pressure in the filler material P_{fill} , the cross-sectional geometric parameters, namely D , t , δ_{mk} , c_M , a_M , b_M , Δ and t_M values, as well as by the corresponding material properties of the welded joint, namely fracture toughness K_{IC} , yield strength σ_y , and ultimate tensile strength σ_v evaluated in sections h_1 and h_2 .

To obtain the corresponding quantitative results, the numerical procedure for SSS prediction by FEM described previously was employed. The bending moment M_L and the shear force Q_r at the tip of the sharp cavity were calculated from the normal stresses σ_{zz} in the cross-section corresponding to the sharp cavity tip for its propagation along either h_1 or h_2 . The bending moment M_L is expressed as the difference $M_L = M_1 - M_2$ where:

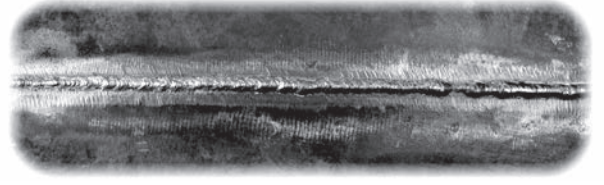


Figure 16. Root weld on the reverse side of a butt welded joint produced in the vertical position

- for the case of crack propagation along ray h_1 :

$$M_1 = \int_{-t_M/2}^{t_M/2} \sigma_{zz} \xi d\xi, M_2 = \int_{\frac{t+\Delta}{2}}^{\frac{t+\Delta}{2}} \sigma_{zz} \xi d\xi; \quad (22)$$

- for the case of crack propagation along ray h_2 :

$$M_1 = \int_{\frac{t_M+\Delta}{2}}^{\frac{t_M+\Delta}{2}} \sigma_{zz} \xi d\xi, M_2 = \int_{-t/2}^{t/2} \sigma_{zz} \xi d\xi. \quad (23)$$

The corresponding calculation results for an X70 steel pipeline with $D = 1420$ mm, $t = 20$ mm, and an operating pressure of $P = 7.5$ MPa are presented below for a repair sleeve with a length of 1400 mm, a wall thickness of $t_M = 14$ mm and $\delta = 20$ mm at a repair pressure of $P_r = 7.5$ MPa, as well as for $t_M = 14$ mm at $P_r = 0.7P = 5.25$ MPa. The dimensions of the spacer rings, $\delta_{sp,r}$ and c_M were assumed as follows: $\delta_{sp,r} = t_M$, $c_M = 140$ mm. The gap size Δ was adjusted using additional spacer rings having a width of $b_M = 30$ mm.

Based on the calculated values of M_L and Q_r , the stress intensity factor K_I and the reference stress σ_{ref} were determined. Subsequently, assuming $K_{IC} = 1500$ MPa·mm^{1/2} and yield strengths of $\sigma_y = 440$ MPa and 360 MPa, the safety factor, n , was evaluated. The presented results indicate that reducing the yield strength from 440 to 360 MPa (corresponding to X70 and X60 steels) at $P_r = P = 7.5$ MPa and $P_r = 0.7P$ has only a negligible effect on the allowable filler pressure, $[P_{fill}]$, for a safety factor of approximately $n \approx 2.0$. The slit width Δ has a pronounced influence: increasing Δ from 3 to 12 mm reduces $[P_{fill}]$

Table 1. Recommended welding parameters for a lap-butt joint welded using DW-A55 and Sv-08G2S wires (shielding gas: 82 % Ar + 18 % CO₂)

Parameter	Passage when filling the groove	
	Filling pass	Capping pass
Wire feed rate, m/min	(8.0–9.1)/(4.0–4.1)	(7.4–8.0)/(3.7–3.8)
Welding current, A	(190–220)/(135–140)	(180–200)/(125–130)
Arc voltage, V	(26.5–27.0)/(19.5–20.5)	(26.0–26.5)/(18.0–18.5)
Wire stick-out, mm	(12–23)/(12–23)	(10–16)/(10–16)

Note. The numerator corresponds to DW-A55 wire, while the denominator corresponds to Sv-08G2S wire.

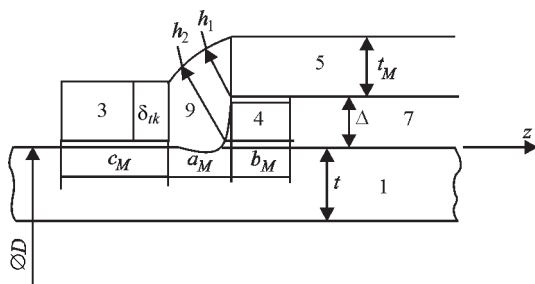


Figure 17. Cross-sectional schematic of the circumferential welded joint of the attachment assembly for mounting a compound-filled sealing sleeve on a pipeline

from 4.3 MPa to 2.3 MPa at $P_r = P$, and from 3.5 to 1.7 MPa at $P_r = 5.25$ MPa. Increasing the filler pressure a pfile bove the allowable value $[P_{\text{fill}}]$ is undesirable because it leads to a significant reduction in the safety factor (Figure 18).

For the case of crack propagation along ray h_2 , the calculated results confirm the previous assumption that crack propagation along h_1 represents the more conservative failure scenario (Figure 19). For the considered input parameters variant, the obtained results of numerical analysis show that, for the standard dimensions of the sealing sleeve and the specified conditions for filling the annular gap, the recommended filler pressure ensuring the integrity of the circumferential welds is $[P_{\text{fill}}] = 4.3\text{--}4.5$ MPa at $P_r = 5.25\text{--}7.5$ MPa with $\Delta = 3$ mm. Increasing Δ to 12 mm sharply decreases the allowable filler pressure to 1.7–2.3 MPa. Since in many practical applications, the gap size Δ is approximately 3 mm and the generated filler pressure $[P_{\text{fill}}]$ does not exceed 4 MPa, the proposed repair sleeve design for TP elements of $D \times t = 1420 \times 20$ mm manufactured from X60–X70 steels can provide sufficient unloading of the defective region in the pipeline wall, provided that the specified pressure of the liquid filler is maintained, at least partially, also after polymerization.

Thus, repair technologies in modern GTS should be regarded as an integral component of adaptive integrity management, integrating the results of diagnostics, numerical modelling, degradation prediction, and risk-based assessment. The transition from the normative selection of repair solutions to their digitally enabled, physically justified, and individualized optimization represents one of the key manifestations of the Industry 4.0/5.0 paradigm and provides the methodological foundation for ensuring the long-term reliability of the Ukrainian GTS.

INTEGRITY MANAGEMENT OF TRUNK PIPELINES UNDER GREEN HYDROGEN TRANSPORTATION CONDITIONS

The decarbonization of the energy sector and the emergence of a new architecture of the European energy markets are driving the gradual transition toward the transportation of natural gas-green hydrogen mixtures. Within the framework of the Industry 4.0/5.0 paradigm formulated in the previous sections, this transition should not be regarded merely as a change in the GTS working medium, but rather as a fundamental transformation of its operating conditions, directly affecting all levels of integrity management, from materials science to system-level decision-making. In this context, two interrelated scientific and technological aspects become particularly important. The first concerns the need for a fundamental understanding of the mechanisms of hydrogen-induced degradation in structural steels, which differ substantially from the classical corrosion-mechanical processes characteristic of natural gas transportation. Hydrogen acts not only as a diffusion-active element but also as a catalyst for the localization of plastic deformation, decohesion-induced weakening of interphase and intergranular bonds, and accelerated initiation and propagation of micro- and macrocracks.

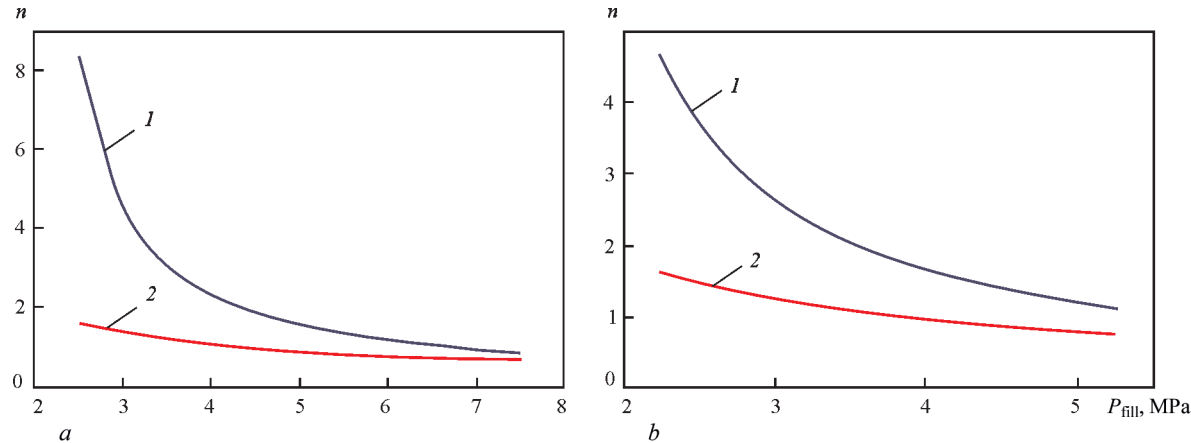


Figure 18. Dependence of the safety factor, n , of the welded joint between the sealing sleeve and the pipeline element ($D \times t = 1420 \times 20$ mm, $\sigma_y = 440$ MPa) for crack propagation along h_1 as a function of the liquid filler pressure, P_{fill} : a — internal pipeline pressure $P = 7.5$ MPa; b — $P = 5.25$ MPa; 1 — $\Delta = 3$ mm; 2 — $\Delta = 12$ mm

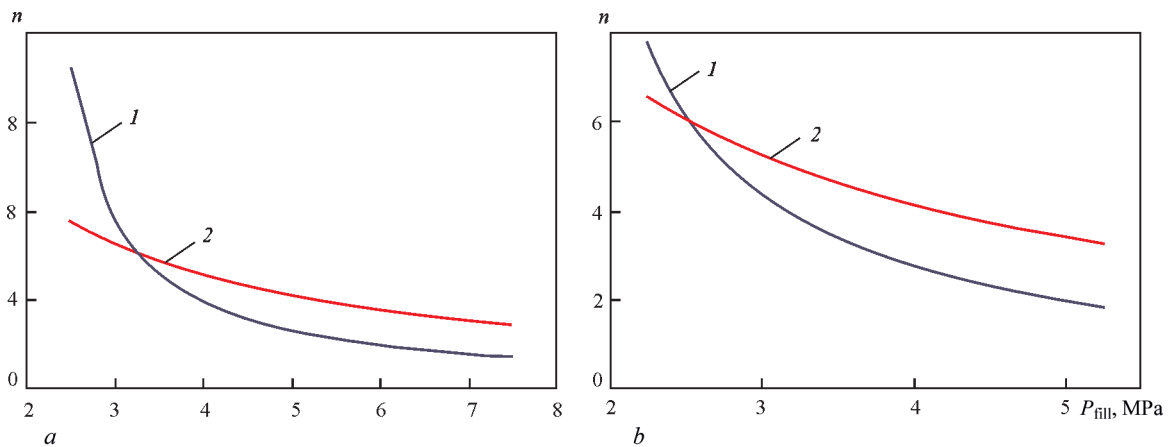


Figure 19. Dependence of the safety factor, n , of the welded joint between the sealing sleeve and the pipeline element ($D \times t = 1420 \times 20$ mm, $\sigma_y = 440$ MPa) for crack propagation along h_2 as a function of the liquid filler pressure, P_{fill} : *a* — internal pipeline pressure $P = 7.5$ MPa; *b* — $P = 5.25$ MPa; 1 — $\Delta = 3$ mm; 2 — $\Delta = 12$ mm

The second aspect is directly related to the practice of individualized integrity assessment and repair restoration operations, which was established in the previous sections as an essential component of adaptive integrity management.

The results of a series of scientific investigations have demonstrated that the key factor governing corrosion-hydrogen degradation is absorbed hydrogen, which is generated as a result of electrochemical corrosion occurring on both the internal and external pipe surfaces [24]. Its accumulation intensifies the diffusion processes, promotes the formation of vacancies and micropores, and accelerates the development of distributed damage, thereby reducing the strength and increasing susceptibility to corrosion-hydrogen cracking [25]. In addition, a correlation has been established between the reduction in impact toughness and the hydrogen content in service-exposed metal. The most pronounced degradation occurs in pipe sections exposed to aqueous condensate, confirming the decisive role of hydrogenation charging in the processes of pipeline performance loss [26].

Regardless of its source, hydrogen accelerates crack development at both the micro- and macroscopic levels by promoting both defect initiation and growth. To quantitatively evaluate its influence on macrocrack propagation, a scientifically substantiated method for determining resistance to hydrogen embrittlement has been developed [27]. The method is based on electrolytic hydrogen charging of part of the specimen followed by hydrogen diffusion toward the crack tip. In addition, a technological approach for retarding the fatigue crack growth through the use of a specially designed environment has been proposed [28].

From the perspective of the future utilization of the Ukrainian GTS for hydrogen energy applications, an experimentally confirmed finding is that the service-exposed pipeline steels become susceptible to

both corrosion cracking and hydrogen-assisted cracking [29], whereas such susceptibility is absent in the initial material condition. In particular, smooth API X52 steel specimens exhibit no susceptibility to corrosion cracking in a model environment simulating pipeline aqueous condensate (Figure 20, *a*). In contrast, precracked specimens demonstrate pronounced susceptibility (Figure 20, *b*), while the application of cathodic polarization further reduces the threshold value of J_{sc} relative to the value of J_i measured in air.

To this end, an accelerated hydrogen-induced degradation method was developed, simulating long-term degradation processes through intensified microdamage accumulation and enabling prediction of changes in mechanical properties over timescales of several decades within only a few days [26]. It has been demonstrated that long-term service alters the fracture mechanisms of pipeline steels and increases their susceptibility to SCC [25]. Of particular importance for the fundamental understanding of TPs long-term reliability is the finding that degradation of pipe steels proceeds through two interrelated mechanisms: microstructural evolution and development of distributed damage. Microstructural changes facilitate damage accumulation, which manifests itself at the macroscopic level as a reduction in resistance to brittle fracture, including impact toughness, crack initiation energy, fracture toughness, etc. In ferrite-pearlite pipeline steels, service-induced embrittlement is associated with the enrichment of grain boundaries and intragranular defects by carbon-containing compounds, as confirmed by electrochemical characterization of transgranular cleavage facets [30].

The development of distributed damage is governed by the characteristics of the microstructure, primarily by nonmetallic inclusions elongated along the rolling direction. Nanometer-sized pores form at the inclusion-matrix interface and act as highly effective

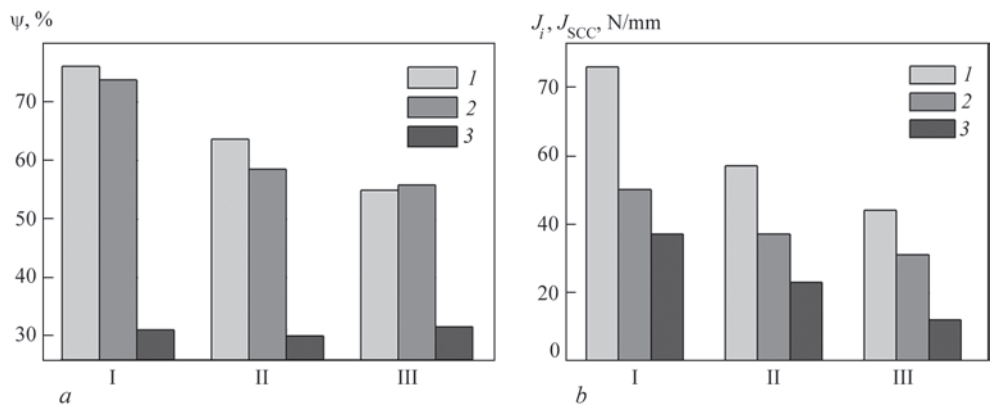


Figure 20. Reduction in area (a) and fracture toughness (b) of X52 steel in the as-received condition (I) and after 30 years of service: X52-12 (II) and X52-10 (III), tested in air (1), in a model aqueous condensate environment at the corrosion potential (2), and under cathodic polarization of 0.1 A/m² (3)

hydrogen traps. The accumulation of recombined hydrogen within these defects reduces the adhesion between the inclusions and the matrix, leading to delamination and plastic deformation of the metal under the action of internal pressure. Consequently, the evolution of microdamage proceeds through the combined action of deformation and decohesion mechanisms, as a result of which even low-strength steels containing a high level of accumulated damage exhibit poor resistance to brittle fracture [31].

It is well established that low-strength steels, which exhibit only limited susceptibility to hydrogen embrittlement in the as-supplied condition, become susceptible during long-term service, thereby increasing the risk of TP integrity loss during transportation of natural gas-hydrogen mixtures. The enhanced development of distributed damage in low-strength steels through deformation caused by the high pressure of hydrogen recombined within defects [31] is influenced by the microstructural constituents, particularly nonmetallic inclusions oriented along the rolling direction. Nanometer-scale pores are formed at the inclusion-matrix interfaces, serving as efficient hydrogen traps. Hydrogen reduces the adhesion strength between the inclusions and the surrounding matrix (Figure 21, a) and accumulates within these pores and other defects. As a consequence, delamination develops between the microstructural constituents, while the metal undergoes deformation under the pressure of recombined hydrogen, resulting in defect growth (Figure 21, b). The cavity volume between the defect contour and the inclusion is extremely small (Figure 21, c), facilitating the generation of high hydrogen pressure within the cavity. Therefore, hydrogen-assisted microdamage evolution in low-strength steels proceeds through a combination of deformation and decohesion mechanisms. Consequently, even low-strength steels with a high degree of accumulated microdamage exhibit poor resistance to brittle fracture.

The damage mechanisms manifested in pipe steels under hydrogen exposure depend on the material strength. In low-strength steels, the accumulation of molecular hydrogen within pores, predominates followed by deformation-controlled pore growth and coalescence, while, in high-strength steels, hydrogen-assisted cracking caused by the reduction of cohesive and adhesive strength becomes the governing mechanism. Both mechanisms may operate simultaneously, thereby intensifying corrosion-mechanical damage [24]. Pipe steels have a pronounced rolling texture, in which ferrite bands alternate with thin pearlite layers, while nonmetallic inclusions are elongated along the rolling direction. During long-term service, adhesion between the inclusions and the matrix, as well as between ferrite and pearlite, progressively deteriorates, leading to delamination and a reduction in resistance to brittle fracture within the rolling plane [24].

Two principal stages of the service-induced degradation of ferrite-pearlite pipe steels can be distinguished: strain aging (stage I) and development of distributed damage (stage II) [24]. During the first stage, the yield strength, tensile strength, and hardness increase, whereas ductility, impact toughness, and fracture toughness decrease. During the second stage, the continued accumulation of damage results in reduction in both strength and hardness, eventually bringing the material to a critical condition. The distributed damage stage is further subdivided into two periods: formation of randomly oriented defects (stage IIa) and formation of defects aligned with the rolling direction (stage IIb) [32]. During stage IIa, strength, hardness, reduction in area, and resistance to brittle fracture decrease, whereas relative elongation may even increase due to the opening of multiple defects. Consequently, the elongation parameter (δ) loses its significance as a reliable measure of ductility. During stage IIb, delaminations oriented along the rolling direction develop and may propagate within the pipe wall without reaching the external surface. During

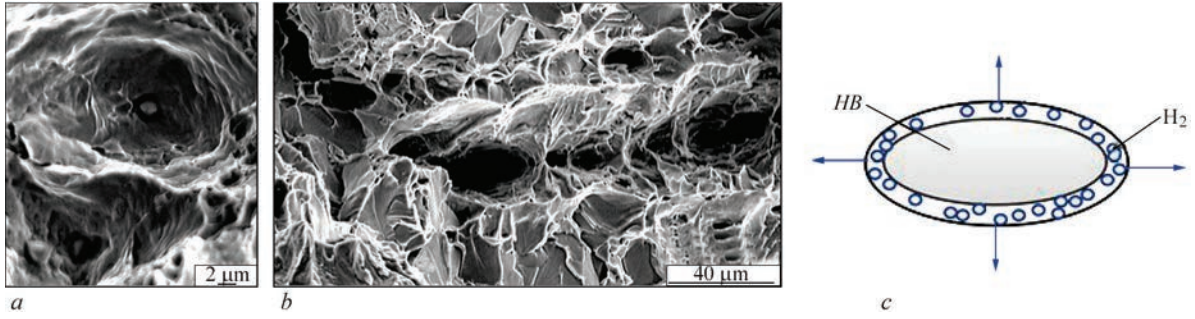


Figure 21. Fractographs (a, b) and schematic illustration (c) showing debonding of nonmetallic inclusions from the matrix (a), hydrogen-deformation-induced defects (b), and their formation mechanism (c): NMI — nonmetallic inclusion; H₂ — molecular hydrogen

testing of standard longitudinal tensile specimens, such delaminations artificially increase the measured impact toughness, so that this parameter no longer adequately characterizes of the actual resistance to brittle fracture. To eliminate this effect, the use of special radial specimens, which promote fracture in a plane parallel to the potential delamination, is recommended.

As discussed above, the elevated concentration of diffusible hydrogen in the metal of pipes transporting natural gas-hydrogen mixtures necessitates a re-assessment of integrity maintenance technologies. A representative example is the preservation of structural integrity during repair welding, particularly the prevention of cold cracking. It is well known that increasing the concentration of diffusible hydrogen in the weld metal increases its susceptibility to the initiation of this type of defect. The complexity of the physical phenomena governing the susceptibility of weld metal to cold crack formation makes it difficult to establish a precise quantitative fracture criterion. In this context, a probabilistic criterion based on the principles of Weibull statistical mechanics is considered the most appropriate approach for numerical assessment. The probability of cold crack initiation, expressed as a function of the diffusible hydrogen content V_H (ml/100 g) and the mechanical stresses in the material, can be quantitatively estimated using the following expression [33]:

$$p(V_H) = 1 - \exp \times \left[- \sum \left(\frac{\sigma - A(V_H)}{B} \right)^{\eta_p} \Delta V_H \right], \sigma > A(V_H). \quad (24)$$

The coefficients A , B and η_p of the three-parameter Weibull distribution are determined experimentally. A study was conducted to evaluate the influence of TP repair welding process parameters on the susceptibility of pipe metal to cold cracking, taking into account the effect of the diffusible hydrogen concentration V_H under the conditions of natural gas-hydrogen mixture transportation [34]. A straight section of a trunk gas pipeline with an diameter of 1420 mm and

a wall thickness of 20 mm, manufactured from X65 steel, was studied operating at a service pressure of 7.5 MPa and an internal pressure of 4.0 MPa during repair welding. The service defect considered was a localized wall-thinning defect measuring 150 mm in length, 100 mm in width, and 10 mm in depth. The welding parameters were a welding speed of 5 mm/s and a welding current of 100 A. Prior to welding, the repair zone was preheated to a prescribed temperature T_{pr} . The interpass time between successive weld beads was carefully controlled to prevent the metal temperature from dropping below the specified pre-heating temperature.

Finite element analysis of the kinetics of the temperature field, phase transformations, hydrogen distribution, and SSS under TP repair welding conditions revealed a pronounced spatial heterogeneity of the corresponding physical fields within the repair zone [35]. This finding justifies the application of an integral probabilistic criterion for cold cracking, which accounts for both the physical complexity of the process and the technological characteristics of repair welding, thereby improving the accuracy of cold crack risk assessment.

Analysis of criterion (24) confirmed its effectiveness for predicting the probability of cold crack initiation [36]. The initial diffusible hydrogen content is the which is determining factor governing the susceptibility to cold cracking. An increase in hydrogen concentration may raise the probability of crack initiation by several times (Figure 22, a). In contrast, preheating the repair zone to approximately 100 °C significantly reduces this risk, maintaining the probability below $5 \cdot 10^{-3}$ over a wide range of hydrogen concentrations, which is in agreement with current engineering standards. Furthermore, the relationship between the probability of cold cracking and the preheating temperature at a diffusible hydrogen concentration of $V_H = 20$ ml/100 g demonstrates that preheating to approximately 80 °C is the most affective (Figure 22, b). These results emphasize the critical role of optimiz-

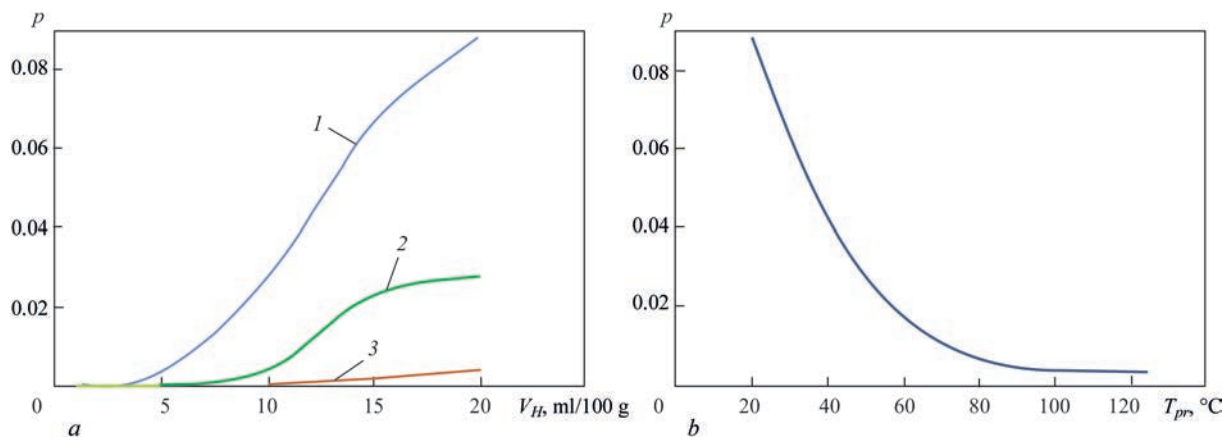


Figure 22. Calculated dependence of the probability p of cold crack initiation in pipeline metal on the initial diffusible hydrogen content V_H (a) and the repair zone preheating temperature T_{pr} (b): 1 — $T_{pr} = 20$ °C; 2 — $T_{pr} = 50$ °C; 3 — $T_{pr} = 100$ °C

ing repair thermal regimes to ensure the reliability of welded joints.

For engineering applications, the results are most conveniently presented as diagrams relating the cold cracking risk to the composition of the natural gas-hydrogen mixture, the diffusible hydrogen content, and the preheating temperature of the repair zone. Such diagrams enable the determination of operating conditions corresponding to specified target probabilities of cold cracking (10^{-5} to 10^{-4}) (Figure 23). The obtained results indicate that the use of existing GTS for transporting natural gas-hydrogen mixtures requires a revision of current standards specifying the repair technologies and structural integrity assessment criteria.

PROSPECTS FOR DEVELOPMENT OF DIGITAL-INTELLIGENT INTEGRITY MANAGEMENT OF THE UKRAINIAN GAS TRANSMISSION SYSTEM

The further development of science-based and adaptive integrity management of the Ukrainian GTS under conditions of decarbonization and the transition toward the Industry 4.0/5.0 paradigm cannot be considered without the transition to a fully digitally integrated,

sensor-rich, and autonomously controlled infrastructure. Within this evolutionary framework, the GTS is transformed from an object of periodic engineering inspection into a continuously operating cyber-physical system, in which critical operational decisions are generated on the basis of real-time data streams, multiscale modeling, and intelligent analytics.

A key technological driver of this transformation is the large-scale deployment of automated structural health monitoring systems for the GTS facilities including distributed sensor networks, acoustic and fiber-optic monitoring systems, and sensors for corrosion potential, strain, temperature, and hydrogen concentration. Integrating these data into a unified digital platform enables the creation of a continuous information space describing the condition of the pipeline systems, compressor stations, and underground gas storage facilities, thereby providing the foundation for implementing the concept of digital twins of critical energy infrastructure.

In this context, digital twins are viewed not as static models but as a dynamic, multilevel systems synchronized with their physical counterparts through continuous sensor data streams. Such systems enable predictive simulations of degradation processes, including corrosion-hydrogen mechanisms, damage accumulation, fatigue, and the evolution of the SSS. This capability establishes the basis for transitioning from conventional maintenance practices to predictive and proactive integrity management.

An equally important component of this framework is the robotization of repair and maintenance operations on operating pipelines while minimizing personnel exposure to hazardous environments. The deployment of remotely operated welding systems, robotic cladding platforms, and automated weld quality inspection systems enables implementation of the zero-human-exposure maintenance concept, which is

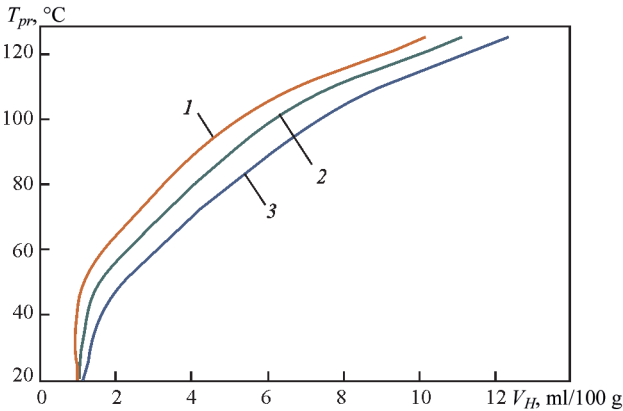


Figure 23. Calculated relationships between the repair zone preheating temperature T_{pr} and the diffusible hydrogen content V_H in the pipeline for different allowable probabilities of cold cracking: 1 — $1 \cdot 10^{-4}$; 2 — $5 \cdot 10^{-5}$; 3 — $1 \cdot 10^{-5}$

fully consistent with the human-centric principles of Industry 5.0.

The Internet of Things (IoT) provides the technological backbone of this architecture by connecting field devices, analytical centers, and decision-support systems. Combined with machine learning techniques and physics-based modeling, IoT enables the development of adaptive operating strategies, in which GTS operating parameters, maintenance intervals, and selection of repair technologies are continuously adjusted according to the current and predicted condition of the system.

Thus, the future direction of this research lies in the development of a unified cyber-physical ecosystem for GTS integrity management, in which automated monitoring, digital twins, IoT infrastructure, and robotic repair technologies are integrated within a consistent asset lifecycle management logic. Such an ecosystem enables the transition from reactive maintenance to intelligent, safety-oriented operation of critical energy infrastructure.

CONCLUSIONS

1. A comprehensive scientific concept has been developed for ensuring the resilience, survivability, and functional reliability of the Ukrainian GTS as a multilevel integrated infrastructure combining TPs, compressor stations, and underground gas storage facilities into a unified interconnected system. Unlike conventional approaches focused on individual components operating under steady-state conditions, the proposed framework accounts for the systemic interaction of technological, energy-related, and reliability factors under reverse-flow operation, partial loading, cyclic changes in operating conditions, and abnormal impacts associated with wartime and energy-related challenges. This provides the scientific foundation for adaptive GTS management within the Industry 4.0/5.0 paradigm, where digitalization and intelligent decision support serve as the primary mechanisms for ensuring the resilience of critical infrastructure.

2. The scientific basis for the corrosion-mechanical reliability of TPs operating under cathodic protection and long-term service conditions has been further developed, enabling the transition from empirical and standards-based criteria toward a physics-based description of degradation processes. The proposed approach combines electrochemical diagnostics, accelerated degradation modeling, and material limit-state criteria, thereby improving the accuracy of predicting the mechanical property evolution and defect development risks throughout the service life of pipeline systems.

3. The fundamental principles of continuum mechanics have been extended through the integration of ductile fracture mechanics and thermomechanical deformation, resulting in a new class of methods for expert assessment of technical condition and structural failure risk in pipeline systems. Unlike conventional approaches based on simplified strength criteria, the proposed methodology accounts for the complex interaction among thermomechanical loading, damage evolution, and technological processes, including the effects of construction and repair welding, plastic, and micromechanisms of discontinuity development. This substantially expands the capabilities of engineering assessment for complex defective states and enables individualized decision-making regarding the TP reliability and maintenance planning.

4. A package of TP restoration technologies has been developed, including reinforcement using welded sleeves and multipass weld cladding, eliminating the need to remove pipelines from operation. These technologies expand the operational capabilities of the GTS under challenging service conditions while reducing the need for large-scale replacement of infrastructure components. The obtained results provide the technological basis for a new generation of repair and restoration solutions consistent with the principles of Industry 4.0/5.0, particularly in terms of improved efficiency, safety, and environmental sustainability.

5. A new scientific direction has been established in the field of the physicochemical mechanics of degradation and fracture of structural materials used in TPs. Within this framework, an integrated analysis of the interrelated corrosion-hydrogen, deformation, and structural-mechanical processes occurring in long-term operated pipeline steels has been performed. This provides the scientific and methodological basis for transition to physics-based, risk-oriented, and adaptive prediction of service life and operational safety of pipeline systems, including future scenarios involving the transportation of natural gas-hydrogen mixtures.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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SUGGESTED CITATION

S.Yu. Maksymov, O.I. Zvirko, O.S. Milenin, L.I. Nyrkova, I.I. Chudyk, V.B. Zapukhliak, V.V. Rudko (2026) Adaptive integrity management of the Ukrainian gas transmission system in the context of the Industry 4.0/5.0 paradigm. *The Paton Welding J.*, **09**, 3–27.

DOI: <https://doi.org/10.37434/tpwj2026.09.01>

JOURNAL HOME PAGE

<https://patonpublishinghouse.com/eng/journals/tpwj>

Received: 07.07.2026

Received in revised form: 10.08.2026

Accepted: 29.09.2026



Joint project
by OKOndt GROUP (Ukraine)
and GEISMAR (France)
“Measurement
and ultrasonic inspection of subway rails”
Taipei, Taiwan



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