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The influence of external and internal factors on stress corrosion cracking of low-alloyed pipe steel

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Abstract

The article presents investigation results of the regularities of stress corrosion cracking (SCC) of controllable rolling X70 pipeline steel under the influence of various factors: corrosion-active environment, potential, pre-accumulated stresses, periodic wetting, etc. Factors, acting in the conditions of the gas pipe mains operation, were simulated in the laboratory conditions and their influence on the SCC susceptibility of X70 pipe steel was investigated. It was found that in NS4 solution, potential shifting to the cathode area promotes the increasing of the SCC susceptibility of X70 steel. Under cathodic protection at potential equal to -1.0 V, the fracture characteristics change, a brittle component appears in the fracture, and the coefficient K_S increases compared to the breaking of samples without cathodic potential. Under such a potential there may appear some differences in the SCC susceptibility of X70 steel, which have a minor structural features: steel with less contamination of non-metallic inclusions is less susceptible to brittle cracking. Accumulated cyclic stresses, periodic wetting, the presence of coatings with different transient resistance and the stress concentrator promote the increase of the degree of SCC susceptibility of X70 pipeline steel at a potential of -1.0 V.

Keywords: *alternating wetting; cathodic polarization; low alloyed pipe steel; near-neutral environment; slow strain rate test; stress-corrosion cracking.*

The system of trunk oil and gas pipelines significantly affects the ecological state of the environment, which is especially evident in accidents, therefore, studying the laws of the phenomena that lead to them is of great scientific and practical importance. The most dangerous phenomenon, which is difficult to predict and prevent, is stress corrosion cracking, the occurrence and development of which reduces the stable operation of the gas transmission system. Operational experience shows that even with proper functioning of the cathodic protection system, both on straight-seam and spiral-seam pipes with film and rubber-bitumen insulation, stress corrosion cracking (SCC) can develop in the places of its defects and disbondments. The importance of a more detailed study of this phenomenon determines the relevance of research in this direction.

Analysis of recent research and publications

The mechanism of the flow of corrosion processes under the conditions of a comprehensive corrosion protection differs from other types of corrosion and destruction, since a number of factors influence stress corrosion cracking. Researchers from different countries found that SCC develops under the simultaneous action of three groups of factors: mechanical stress, specific environmental influences and properties of metal [1].

The influence of the external environment on the emergence and development of SCC, regardless of the mechanism of influence, is possible only in conditions of pipeline insulation destruction [2–4]. This position underlies all research in this direction. World experience and statistics on accidental damage resulting from SCC show that gas pipe mains with a polymer tape cover are most prone to the emergence and development of SCC, especially those on which insulation is applied under operating conditions.

Corrosion damage under the influence of stresses can occur and develop in various types of soils, with different aggressiveness and degree of moisture [5]. Moreover, their formation occurs by various mechanisms depending on the corrosiveness of the medium [6–9].

A number of works [10–13] have also been devoted to studying the effect of cathodic protection of trunk gas pipelines, but no direct relationship between the value of the protective potential and the probability of the occurrence and development of stress-corrosion defects has been found. There is an opinion that the state of “overprotection” causes hydrogen evolution, which activates embrittlement processes. According to the author [14], such assumptions are not confirmed in practice.

The study of the influence of metallurgical factors is given special attention due to the fact that statistically and experimentally, both foreign and domestic researchers have confirmed the tendency to stress

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corrosion cracking of metal pipes made using certain technologies [14]. The main factor provoking the emergence and development of the SCC is the accumulation of nonmetallic inclusions, which are cathodes with respect to the metal matrix. This leads to electrochemical “dissolution” of the metal around the inclusions caused by the action of soil electrolyte. Modern researchers say that the imperfection of the structure and the presence of dislocations are the main manifestations of metallurgical factors. Moreover, both the situation, in which structural defects are formed during the manufacture of pipes, and cases of the development of structural imperfections under the influence of operational factors are equally recognized as dangerous. There is an opinion [16] that the microstructure of the material is much greater than the level of strength, and it affects the sensitivity to brittle fracture [15, 16].

The purpose of the work is to establish the influence of a complex of factors, acting in the conditions of trunk pipelines operation, on the sensitivity of pipe steel to stress corrosion cracking.

The tasks of work are as follows:

to substantiate the methodology and develop a methodological approach to accelerated research of stress corrosion cracking in laboratory conditions by modeling operational and metallurgical factors that may be present on the trunk gas pipeline section;

to study the influence of individual factors and their combinations on the patterns of stress corrosion cracking of controlled-rolled pipeline steel (for example, X70 pipeline steel).

Materials and research methods

For the manufacture of samples, there were used fragments of a two-seam pipe with a diameter of 1420 mm with a wall thickness of 15.7 mm from X70 steel (pipe A) and a single-seam pipe with a diameter of 1420 mm with a wall thickness of 17.5 mm from controlled steel X70 (pipe B), respectively. The chemical composition of the base metal of the studied pipes is given in Table 1.

The microstructure of the steels of both pipes is similar – ferrite-pearlite [17]. However, there are some differences: pipe A is characterized by a large contamination with non-metallic inclusions, larger ferrite grains (9–10 number for pipe A and 10–11 numbers for pipe B according to the State Standard GOST 5639–82), slightly more banding (4 points, row B for pipe A and 2 points, row B – for pipe B according to GOST 5640–68).

Mechanical properties: yield strength is in the range from 498 to 513 MPa (according to technical specifications, not less than 441 MPa); tensile strength is in the range from 600 to 603 MPa (according to technical specifications, not lower than 588 MPa), elongation is in the range from 21.5 to 24.2 % (standard value is not lower than 20 %).

Treatment solution: NS_4 solution (0.037 KCl g/l + 0.559 $NaHCO_3$ g/l + 0.008 $CaCl_2$ g/l + 0.089 $MgSO_4$ g/l) with sodium-potassium phosphate buffer solution in the ratio 9 : 1. Phosphate buffer solution contained 1/15 M of $Na_2HPO_4 \cdot 2H_2O$ and 1/15 M of K_2HPO_4 [18].

The samples were stretched in the air and in solution at a speed of 10^{-6} s^{-1} on an AIMA-5-1 tensile testing machine. The cross-sectional area of the samples in the operating part was 3×3 mm^2, and the length of the working part was 42 mm.

During the studies, various internal and external factors that may be present on the existing gas pipeline were modeled. A more detailed methodological approach to reproduction under laboratory conditions is given in previous works [17, 19, 20].

The tests were carried out at a corrosion potential and at potentials of -1.0 and -2.0 V (relative to the chloride-silver electrode, ch.s.e.). The potential was set using a PI-50-1.1 potentiostat and a PR-8 programmer.

The sensitivity to SCC was evaluated by the dimensionless coefficient, which was calculated as the ratio of the relative narrowing of the sample in the air and in solution $K_s = \frac{\Psi_{air}}{\Psi_s}$ [21].

Research results and their analysis

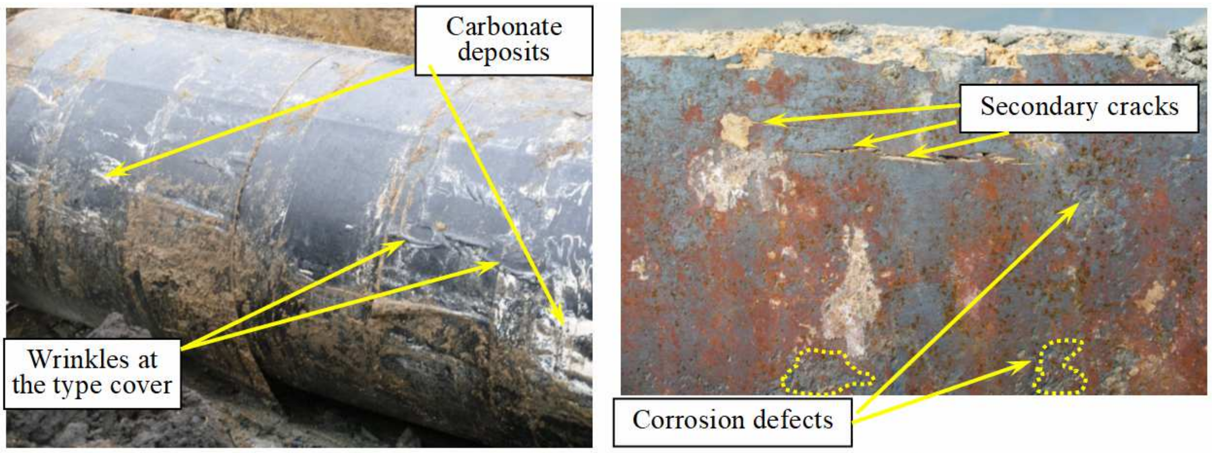
When conducting studies to establish the causes of gas pipelines destruction in Ukraine, the specialists of E. O. Paton Electric Welding Institute discovered factors, which led to the development of stress corrosion cracking. For example, for the Urengoy–Pomary–Uzhgorod gas pipeline, the list of factors is presented in Table 1.

Figure 1 shows photographs of a pipe section with a tape cover and the pipe surface at the point of rupture of the gas pipeline.

So, the gas pipe mains are of a long-term operation. The section is located near the compressor station, and there are laid pipes from controlled rolled X70 steel. Soil corrosion activity is medium (resistivity (21–28) Ohm·m, pH value is 7.8). For protection against corrosion, there were used a Polyken 980-25 tape coating with a wrapper Polyken 955-25 of construction

Table 1 – The chemical composition of the base metal of the studied pipe samples

Sample characteristics	Mass fraction of elements, %											
	C	Mn	Si	S	P	Al	Ni	Mo	Ti	B	Nb	Cr
Pipe A	0.089–0.101	1.33–1.45	0.238–0.272	0.004–0.005	0.012–0.017	0.031–0.032	0.04	0.03	0.004	0.05–0.06	0.027	0.04
Pipe B	0.119	1.48	0.357	0.003	0.016	0.034	0.05	0.03	0.005	<0.02	0.028	0.05
TU 14-3-995–81	Not more than											
	0.12	1.70	0.50	0.010	0.020	0.050	–	0.30	–	0.08	0.06	–



a *b*

Figure 1 – Photos of a pipe section with a tape cover (*a*) and the pipe surface of the destroyed pipe at the rupture section (*b*)

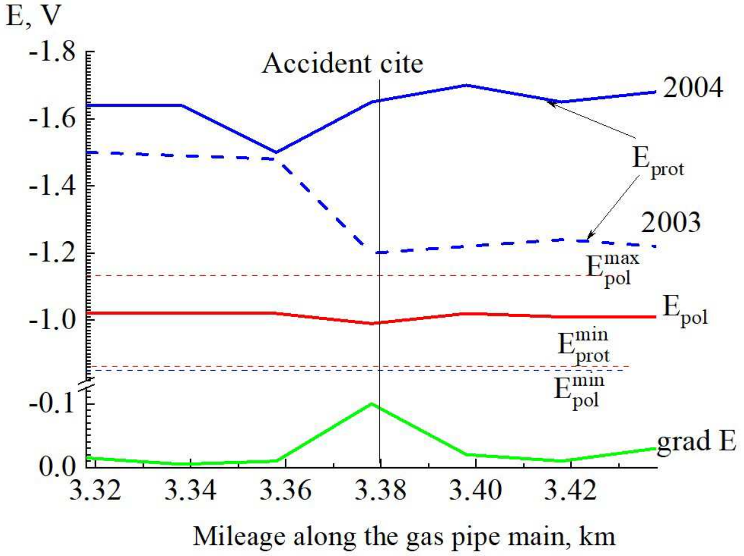


Figure 2 – Protective potentials (with ohmic component, E_{prot}, and polarizing, E_{pol}), the potential gradient, grad E, measured during ground-based technical diagnostics in 2003 and 2004

(2+2) and electrochemical protection. According to the results of surveys of the corrosion protection level, the value of protective potentials is within the normalized State Standard DSTU 4219–2003 (Fig. 2).

Corrosion activity of the soil (estimated by the rate of corrosion of the pipe metal during the period of maximum increase in groundwater level) is from 0.30 to 0.36 mm/year, that is, it is high; there are formed corrosion ulcers on the pipe surface under an exfoliated coating.

The transient electrical resistivity of the protective cover is probably less than a normalized one, given that the value of the transverse potential gradient reached 100 mV in some places. The gas pipeline is rooted in a ravine, that is, in difficult climatic and technogenic conditions. In addition, the site has a deflection.

Based on the aforementioned, operational factors are simulated in laboratory conditions and their influence on the characteristics of corrosion cracking of X70 pipeline steel has been investigated.

By means of corrosion and mechanical studies at the corrosion potential, at a cathodic protection potential of -1.0 V, which was in the range of protective polarization potentials normalized by DSTU 4219–2003 [22], and a potential that was greater in absolute value than the maximum protective potential, -2.0 V (Fig. 3), it was found that the shift of the potential to the cathodic area from the corrosion potential contributed to an increase in the sensitivity of X70 pipeline steel to SCC. This was confirmed by the increase in the share of the brittle component in the fracture and the coefficient of propensity to K_S .

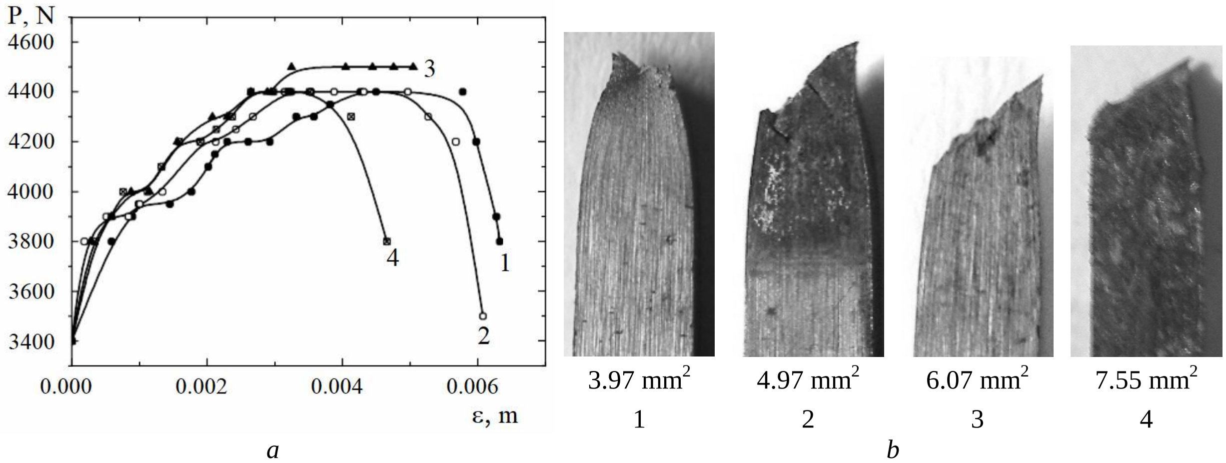
Since, in accordance with the regulatory documents of Ukraine [22] the normalized value of the protective potential without an ohmic component is in the range from -0.85 to -1.05 V (relative to c.s.e.), which corresponds to from 0.75 to -1.05 V (relative to ch.s.e.), it has been of interest to investigate the influence of various factors on the sensitivity of steel to the SCC at a potential that lies precisely in this range, for example, -1.0 V.

Table 2 – Characteristics of factors at a pipeline section

Factors	Characteristics of factors
Information on a pipeline and characteristics of the area	
Pipeline category according to Construction Standards and Regulations SNiP 2.05.06 (para. 2.1)	I
Stationing, km	3.178 from the compressor station
Start of operation	1982
The date of failure or accident	2003
The date of last examination	2005
The distance from the compressor station, km	3.178
Gas pressure, MPa	6
Location of the pipeline section	In the ravine
Interchangeable wetting (thaw)	The pipeline section is located under a water body
Highways, power lines (voltage above 30 kV), railways within a radius of 1000 m	Highway, power lines
Intersection with other technological facilities	No technological facilities
Depth of the section, m	1.2-1.6
Soil type	Loam and loess-like sandy loam, from soft to stiff ones
Electrical resistivity of the soil, Ohm·m	From 21 to 28
Soil pH	7.8
The rate of instantaneous corrosion of the pipe metal at the occurrence level, mm/year	0.36
Information about the production technology and mechanical properties of pipes	
Production technology	Single-seam
Steel grade	X70
Diameter, wall thickness, mm	1420×15.7
Information about the production technology and mechanical properties of pipes	
Standard tensile strength, MPa	588
Standard yield strength, MPa	461
Protective Cover Information	
Type of protective cover design	Polyken 980-25 wraping tape with a Polyken 955-25 wraping tape (2+2)
Survey Data	
Information on the results of previous inspections, accidents	Corrosion cracking in 2003
Protective potential with ohmic component at the section of destruction, B	From -1.4 to -1.56
Protective potential polarizing, B	From -1.0 to -1.05
Transverse gradient of potential, mV	From -3 to -100
Place of pipe defect on the conditional dial, hours	between 5 and 7, pipe rupture
Rupture orientation	At a distance of 2.5 mm from the weld along the axis of the pipeline

The effect of pre-cycling when completely immersed in a solution. There is a short area of viscous fracture on the curve of the sample fracture after the process of cycling (Fig. 4, curve 2), while there is no such area on the curve of the sample fracture in the initial state (curve 3). There can be noted similar characteristics of the samples destruction: there is a brittle component in the fracture of both samples (Fig. 4, sample 3). But it was cycling that had little effect on the index of corrosion and mechanical stability of X70 pipeline steel: the coefficient of propensity for SCC practically has not change and has amounted to about 1.65 (1.7 for the sample in the initial state) (Fig. 5).

The influence of microstructure features when completely immersed in a solution. When laying pipe mains, pipes that are connected may differ, for example, in production technology, have a slightly different microstructure, and the like. The results of comparative studies of the sensitivity to stress corrosion cracking of samples made of A and B pipes were examined in detail earlier, where it was found that at a potential of -1.0 V, which approaches the maximum protective potential, some differences in the sensitivity to SCC sensitivity of X70 pipeline steel may appear, which have minor structural features (Fig. 4, curves 2 and 4, samples 2 and 4). It has been suggested that higher bonding properties of steel with respect to the cathodic potential may be



a *b*

1 – in the air; 2 – at corrosion potential; 3 – when potential is -1.0 V; 4 – when potential is -2.0 V

Figure 3 – The curves of mechanical fracture of X70 pipeline steel samples in the air and corrosion-mechanical fracture in an NS4 solution at various potentials (a) and photos of samples fractures (b) under these conditions

associated with less pollution by non-metallic inclusions [17].

The effect of a stress concentrator when completely immersed in a solution. It is seen from Fig. 4, curve 5, that the relative elongation of the sample in the presence of SC is less compared to the samples that have been tested under the influence of other factors. A brittle component is present in the nature of its destruction, which is confirmed by an increase of the K_S coefficient to ~1.87 (Fig. 4, sample 5).

The effect of periodic wetting with a solution. As it is known from the experience of the operation and maintenance of GMs, an abnormally large number of corrosion lesions in the form of cracks on the outer surface of the pipe is formed when crossing rivers, in ravines and wetlands. In addition, the intensity of the SCC process in these areas increases over time: new defects appear in those areas where they were not previously, and continue to form in those areas where they have already been detected and removed [23]. Therefore, the effect of this factor has been investigated. As noted above, at a potential of -1.0 V, samples of X70 pipeline steel are sensitive to brittle fracture in the initial state and after cycling with complete immersion: K_S coefficient values are 1.7 and 1.65, respectively. Under conditions of periodic wetting with a protective potential of -1.0 V, B samples also break at almost maximum load, there is no area of viscous fracture (Fig. 4, curve 6). This is accompanied by a significant increase in sensitivity to SCC (K_S coefficient value increase to ~2.15) (Fig. 4) and, accordingly, an increase in the share of brittle fracture (Fig. 4, sample 6).

The effect of polymer primers during periodic wetting with a solution. The pipe mains are operated in the conditions of complex protection: anti-corrosion coatings and with the help of electrochemical protection, but it is impossible to completely protect the pipe metal from the influence of the external environment. Since SCC occurs on electrochemical protected pipelines under the exfoliated cover, during long-term operation with cathodic polarization, there can occur its destruction, the products of which can affect the steel's tendency to SCC [24]. To do this, we studied the patterns of corrosion-mechanical destruction of samples in the presence of a polymer primer under conditions of periodic wetting. In the presence of a cover (Fig. 4, curve 7), the nature of the samples destruction is similar to the nature of the destruction of samples without a cover (curve 2), that is, the rupture of the samples occurred almost without plastic deformation. This correlated with a coefficient K_S value of 1.7. Therefore, under conditions of periodic wetting, the presence of a polymer primer at a potential close to the maximum protective value, -1.0 V, only slightly changes the coefficient K_S value (Fig. 5).

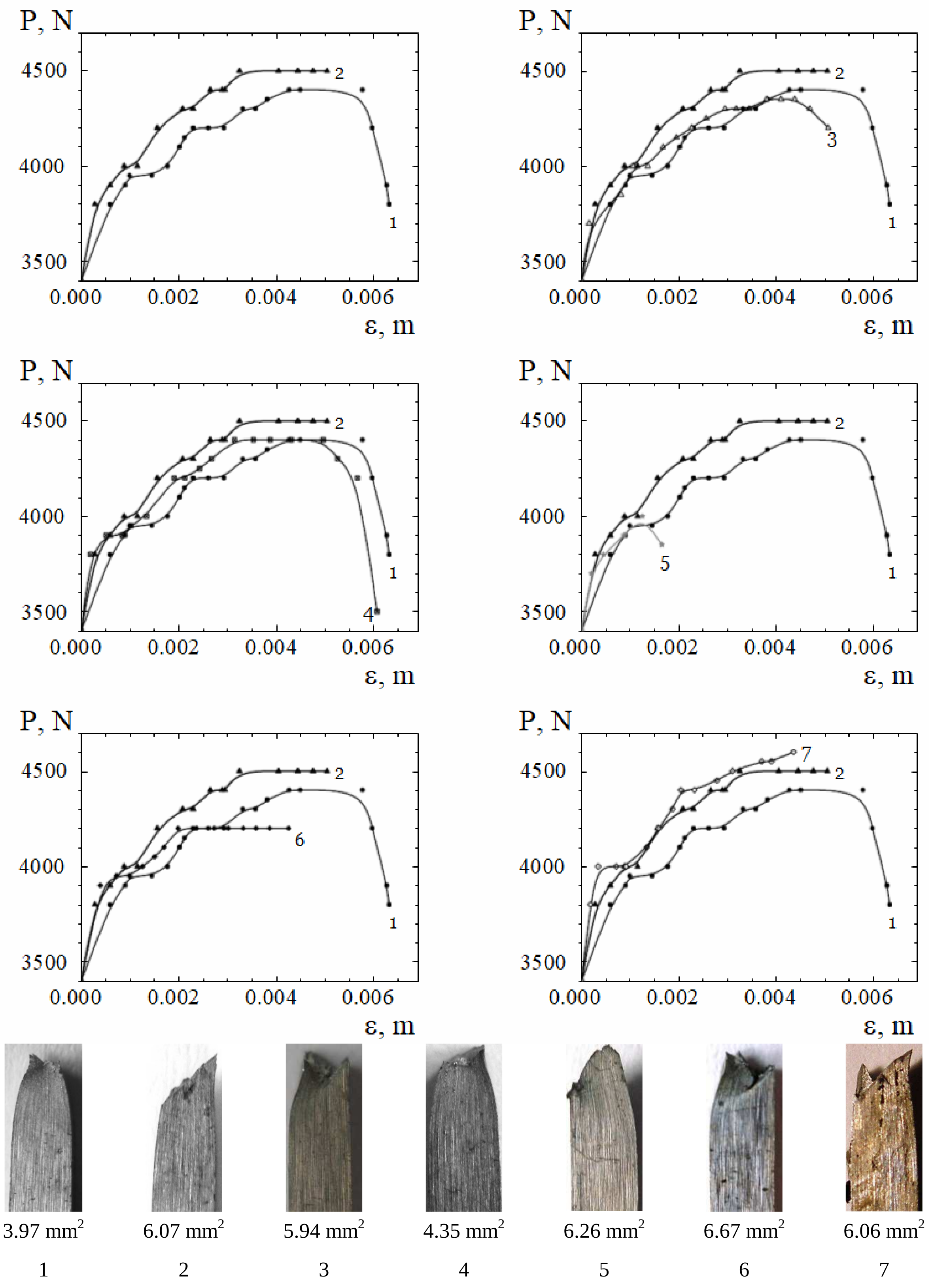
Summing up the results of experimental studies, we can draw the following conclusions.

Conclusions

There has been developed a methodological approach to accelerated research of the stress corrosion cracking in laboratory conditions by modeling operational and metallurgical factors, which may be present on the section of the pipe mains.

Studies have found that in a solution with a pH close to neutral at a potential of -1.0 V, which approaches the maximum protective potential, fracture characteristics change as compared with fracture at a corrosion potential. The rupture of the samples at this potential occurs at the maximum stress, there is a brittle component in the fracture, and K_S coefficient of sensitivity to brittle fracture rises from 1.24 (at a corrosion potential) to 1.7 (at the potential -1.0 V).

It has been experimentally proven that, at a potential of -1.0 V, the presence of factors such as the previous cycling of the samples in the elastic section, periodic wetting, the presence of coatings with different



3.97 mm^2 1

6.07 mm^2 2

5.94 mm^2 3

4.35 mm^2 4

6.26 mm^2 5

6.67 mm^2 6

6.06 mm^2 7

1 – in the air, 2 – a pipe A sample in the initial state when completely immersed in a solution, 3 – a pipe A sample after preliminary cycling when completely immersed in a solution, 4 – a pipe B sample when completely immersed in a solution, 5 – a pipe A sample with SC when completely immersed in a solution, 6 – a pipe A sample in the initial state, with periodic wetting with a solution, 7 – a pipe A sample in the initial state with a layer of polymer primer, with periodic wetting with a solution

Figure 4 – Curves of the corrosion-mechanical fracture of X70 pipeline steel at a potential of -1.0 V and photos of samples fractures under the following conditions

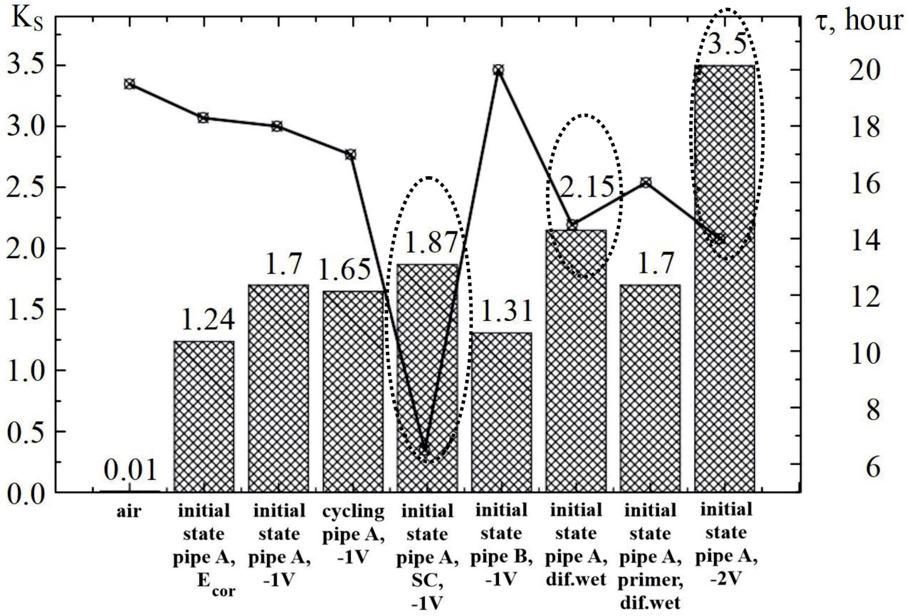


Figure 5 – The influence of operational and metallurgical factors on the sensitivity of X70 pipeline steel (columns) to the SCC and the time to destruction (line) of samples under various conditions

transition resistance, and the presence of stress concentration additionally increase the sensitivity of X70 steel to the stress corrosion cracking. According to this potential, all other factors being equal, some differences in the sensitivity to brittle fracture of X70 pipes with different manufacturing techniques of steel pipes, such as with less contamination by non-metallic inclusions, may be less sensitive to brittle fracture.

The sensitivity of X70 steel to stress corrosion cracking increases significantly if the cathodic potential significantly exceeds the maximum protective value, -2.0 V. K_S coefficient value almost doubles, to ~3.5, the cracking morphology becomes brittle.

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УДК 620.194.22

Вплив зовнішніх та внутрішніх чинників на корозійне розтріскування низьколегованої трубної сталі

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Наведено результати дослідження впливу експлуатаційних та металургійних чинників: корозійно-активного середовища, потенціалу, попереднього напрацювання, періодичного змочування на корозійне розтріскування (КР) низьколегованої трубної сталі Х70. В лабораторних умовах змодельовані фактори, що діють в умовах експлуатації магістральних газопроводів, та досліджено їх вплив на чутливість трубної сталі Х70 до КР. Встановлено, що у розчині NS4 зміщення потенціалу в катодну область сприяє підвищенню схильності трубної сталі до КР. За потенціалу катодного захисту -1.0 В змінюються характеристики руйнування, з'являється крихка складова в зламі та збільшується коефіцієнт K_S порівняно із руйнуванням без наведення потенціалу. За цього потенціалу можуть проявлятися деякі відмінності у схильності до КР сталі типу Х70, які мають незначні структурні особливості: сталь з меншою забрудненістю неметалевими включеннями менш схильна до крихкого руйнування. Накопичені цикли змін напружень, періодичне змочування, присутність покривів з різним перехідним опором, наявність концентратора напружень сприяють підвищенню ступеню схильності сталі Х70 до КР за потенціалу -1.0 В.

Ключові слова: *катодна поляризація; корозійне розтріскування; метод деформації з повільною швидкістю; низьколегована сталь трубного сортаменту Х70; середовища з рН, близьким до нейтральних; періодичне змочування.*