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IMPACT OF LONG-TERM OPERATION ON THE RELIABILITY AND DURABILITY OF TRANSIT GAS PIPELINES

OKIPNYI Igor[1], POBEREZHNY Lyubomyr[2], ZAPUKHLIAK Vasyl[2], HRYTSANCHUK Andrii[2], POBEREZHNA Liubov[3], STANETSKY Andrij[2], KRAVCHENKO Viktoria[2], RYBITSKYI Ihor[2]

[1] *Ternopil Ivan Puluj National Technical University, Ruska str. 56, Ternopil, Ukraine, i.okipnyi@gmail.com*
[2] *Ivano-Frankivsk National Technical University of Oil & Gas, Karpatska str. 15, Ivano-Frankivsk, Ukraine, lubomyrpoberezhny@gmail.com*
[3] *Ivano-Frankivsk National Medical University, Galytska str. 2, Ivano-Frankivsk, Ukraine, physics@ifnmu.edu.ua*

Abstract: Corrosion and corrosion-fatigue tests of the material of the pipeline, which was in operation for 41 years. It has been shown that prolonged operation reduces the parameters of resistance to fatigue and prolonged static loading in corrosive environments. It was established that the degradation of physical and mechanical properties is insignificant, Ukraine's main gas pipelines are ready to operate at full capacity provided that timely monitoring measures are carried out.

KEYWORDS: gas transportation system, diversification of gas supply, operational degradation, underground gas storage. gas hub

1 Introduction

Ukraine's gas transportation system is one of the largest in the world [1]:

- Total length of the GTS - 38.55 thousand km, incl. 22.16 thousand km - main gas pipelines;
- Capacity of the GTS: "at the entrance" - 288 billion cubic meters / year, "on the way" (border with the EU) more than 140 billion cubic meters;
- Pressure in the GTS provides 72 compressor stations with a total capacity of 5443 MW;
- The balancing of the GTS takes place thanks to 13 underground gas storage facilities with a working volume of gas storage of 32 billion cubic meters, of which 5 underground stores of gas (over 25 billion cubic meters) are located on the EU-Ukraine border;

The branching up of the GTS creates the possibility of gas supply from one point on the Ukraine-EU border to 6 countries.

However, the gas transportation system of Ukraine has been in service for a significant period of time. Long-term operation, as a rule, causes structural-mechanical damage and degradation of the mechanical properties of pipe steels [2-4]. The density of dislocations increases in the pipe metal, local micro-stresses and microcracks occur. All these negative phenomena reduce the resistance to the origin and propagation of cracks in pipe steels [5]. Additional damaging factors are the influence of corrosive media, saturation of the pipe wall with hydrogen due to the occurrence and propagation of electrochemical corrosion [5-7]. The technical condition of the gas pipeline system of Ukraine can be evaluated, and its further operation can be predicted only with due account of the degradation phenomena in the

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pipeline steels [7]. This will allow predicting the conditions for reaching the ultimate state, preventing brittle fracture of gas pipelines, and optimizing the cost of its repair.

The purpose of this work is to evaluate the effect of long-term degradation processes on the resistance of pipe steels to static and cyclic deformation.

2 Research methods

For corrosion-fatigue tests unit MV-1K was used and to study stress corrosion processes designed unit KN-1 was used (Fig. 1) [7, 8]. Corrosion-mechanical tests were conducted in air and in corrosion environments (Table 1).

Table. 1 Chemical composition of solutions for corrosion tests

ME	Concentration, mol/l	
	NaCl	Na_2SO_4
1	0.01	-
2	0.05	-
3	0.1	-

The installation (Fig. 1) provides:

- static load of the specimen-model 8 according to the four-point bending scheme and cyclic with the symmetric cycle of stresses at its additional rotation, transmitted from the motor 2 through the worm gearbox 3 to the drums 4 and 10 with a frequency of 0.1 ... 1 Hz;
- a combined static load with a net bend from the load 16 through the traction 15 and the axial tensile strength of the load 14 through the cable 12, the roller 13 and the converter 11;
- low-frequency load with given coefficient of asymmetry of cycle R;
- Investigate the magnitude factor by changing the length or diameter of the working part of the specimen model;
- study of the influence of liquid working environment on the behavior of the pipeline material under the selected scheme and the specified load modes using a removable working chamber 7 and a chloride electrode of comparison 6;
- carrying out the comparative studies of the bearing capacity of welded-specimen models and stress concentrators at static and low-frequency loads in air, seawater, liquid petroleum products, etc.

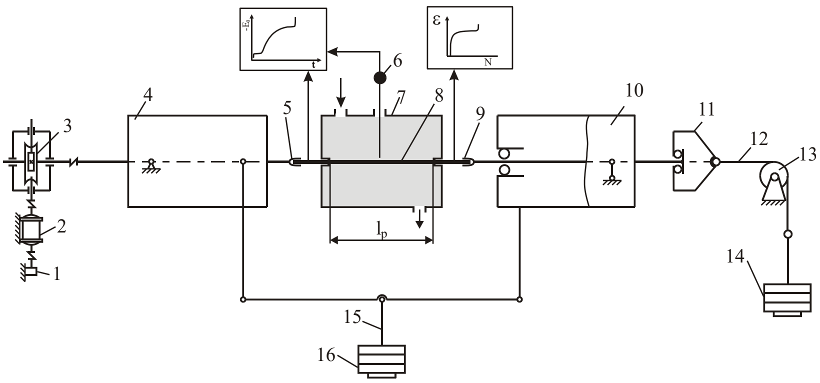


Fig. 1 Installation scheme of MV-1K

1 – counter, 2 – electric motor, 3 – speed reducer, 4,10 – reels 5,9 – clamps, 6 – chlorine silver electrode comparison, 7 – removable working chamber, 8 – experimental specimen, 12, 15 – traction, 13 – rolling element, 14, 16 – removable loads

Correct mounting of the 5, 9 specimen models installed in the clamp does not cause additional stresses from the beating and incompatibility of the specimens and clamps more than 1% of the main ones, which has been verified experimentally.

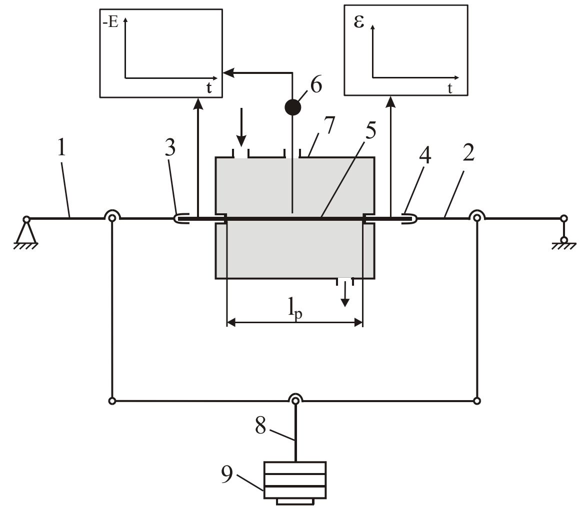


Fig. 2 Installation scheme of KN-1
1, 2 - rotary plates, 3, 4 - clamps, 5 - experimental specimen, 6 - chlorine silver electrode comparison, 7 - removable working chamber, 8 - traction, 9 – removable loads.

Cylindrical model specimens of the length l 100–150 mm and with the test portion diameter d 5–10 mm were tested on a setup, whose peculiarities are described in [8]. Smooth solid (Fig. 1a, b) and tubular specimens with the zero length of the test portion, l_p, design stress raisers (Fig. 1c), and induced cracks, as well as special smooth cylindrical specimens with a blind axial hole and a cap, and insulating coatings for the simulation of the operation of a subsea pipeline with the transported product were investigated.

Figure 2 shows one of the possible schemes of loading, viz by the pure rotational bending of a model specimen, when drums with the specimen fastened in them form a doubly supported beam of variable stiffness. It is considered that the stiffness of the drums with the specimen heads clamped in them is much higher than that of the specimen test portion.

At the same time, strains were measured according to the scheme in Fig. 3 with needle indicators with scale-division values of 0.001 and 0.01 mm for the indicators *1–3* and *4*, respectively, and by means of spring elements with bonded strain gauges [8].

In the course of cyclic loading, the parameter y_4, from which the bending deflection of the specimen can be determined using calibration curves, is continuously recorded. The parameters, l_p, and the radius of curvature min are interrelated (Fig. 3) [2]

For the study of creep and corrosion creep, a computerized installation of KN-1 [8], developed on the basis of the installation of MV-1K [9], was developed. Testing of specimen from the pipe material of oil and gas pipelines in air and in liquid working environment was carried out in a static and re-static load with a net bend with automatic specimen blanking and electrodes potential change using a computer using 24-bit analog-to-digital conversion.

In the process of static loading and creep, a parameter is continuously recorded for which the deflection arc of the specimen δ can be determined. The parameters δ, the length of the working part l_p and the minimum radius of curvature of the specimen ρ_{min} are bound by the relation.

$$\rho_{\min} = \frac{l_p^2}{8\delta} + \frac{\delta}{2}$$

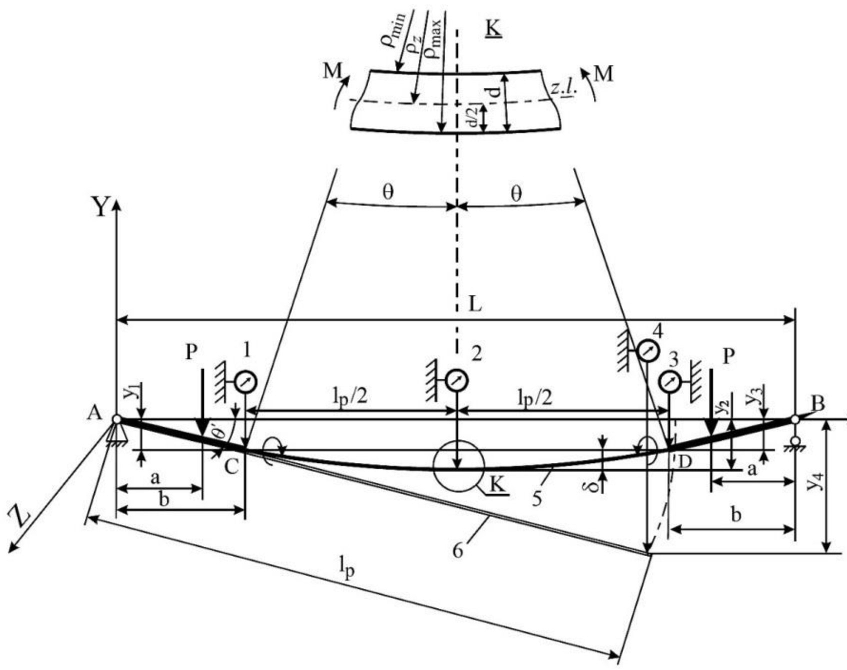


Fig. 3. Scheme of measurement of the displacements of a model specimen loaded by pure rotational bending

(1–4) indicators, (5) specimen, (6) strip; l_p is the length of the specimen test portion. To the left drum is rigidly fastened a strip *6*, which can only rotate about the axis *Z* together with the drum.

The relative deformation of the extreme fiber is determined by the formula.

$$\varepsilon = \frac{1}{\frac{2\rho_{\min}}{b} + 1}$$

where b - specimen thickness.

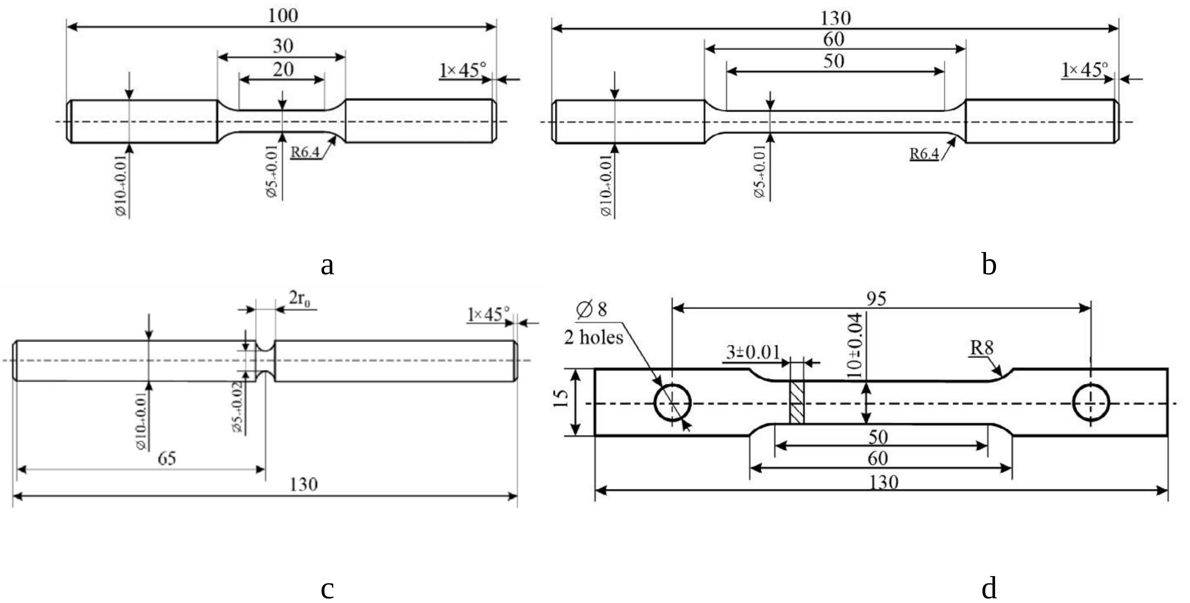


Fig. 4. Basic designs of model specimens for tests on the setups MV-1K (*a*–*c*) and KN-1 (*d*): (a) short specimens (l_p/d 4); (b) long specimens (l_p/d 10); (c) specimens with stress raiser; (d) flat specimens for the study of stress corrosion.

The study uses automated devices that record data and analog digital converters that capture a deformation device in the visual period when tested in air ($\Delta\varepsilon_c$) and in corrosive cases ($\Delta\varepsilon_{cc}$). At each instant t it will be equal to:

$$\Delta\varepsilon = \varepsilon_t - \varepsilon_0$$

where ε_0 – deformation at the time of loading completion, ε_t – deformation after *t* minutes.

The fatigue and corrosion-fatigue tests were carried out according to the net load curve. Since cyclic loads on pipe material associated with changes in pumping mode and daily and seasonal fluctuations in consumption, which are insignificantly low, the optimal frequency f = 0.8 Hz was chosen in terms of the similarity of the load mode and the duration of the model experiment. Used cyclic a clean bend loading with frequency 0.8 Hz and R= – 1.

5 Results and their discussion

In the air, we observe the growing kinetics (Fig. 5) with the attenuation of the process at the last stage and the output of a stable area both for the material in the state of delivery and for the exploited. Growth of the deformation is within 15... 20%. Such tendencies are not a danger, from which it can be concluded that the carrying capacity of the pipeline, which during 40 years of operation was not exposed to the corrosive environment, will change slightly. However, in practice, taking into account the imperfection of corrosion coatings that were used in the construction of main pipelines in the late 60's and 70's of the last century, this situation is rather hypothetical. The air test was intended to be primarily a starting point for distinguishing the effects of the corrosive environment on the kinetics of the steel pipe deformation at the later stage of operation.

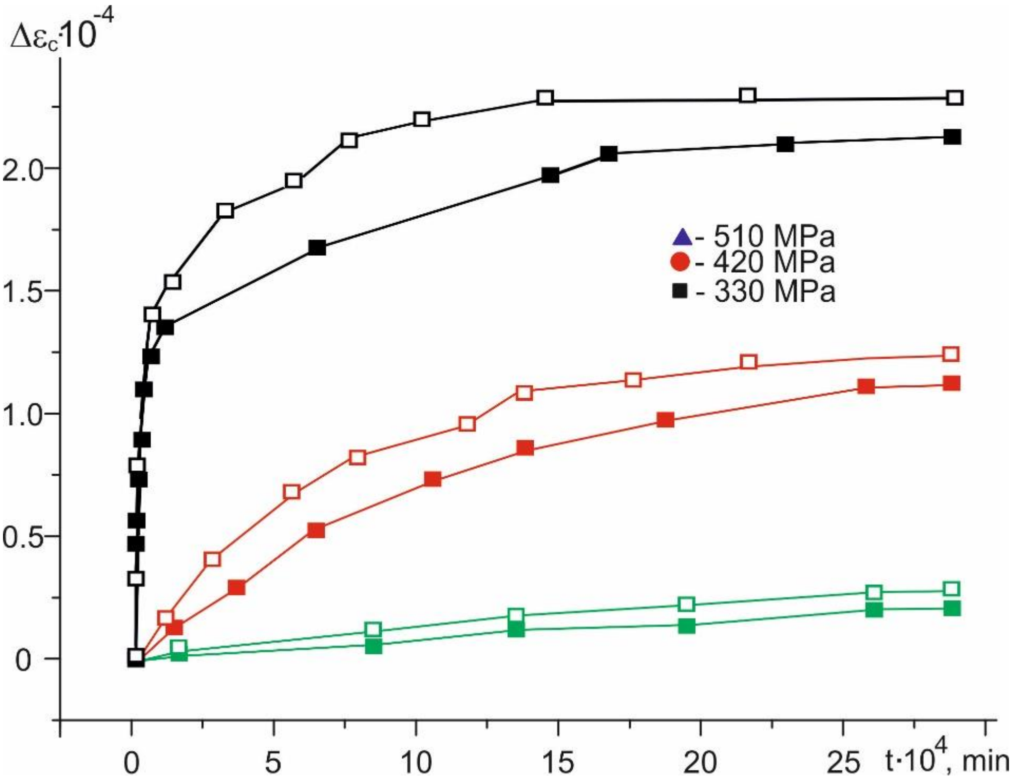


Fig. 5 The deformation kinetics of the pipeline material in the air:
■ - steel in the state of supply, □ - 41 years of operation.

As the magnitude of the stresses increases, the deformation processes take place at a higher rate. At the highest levels of stress on the deformation curve, cyclic accelerations are observed. Moreover, it is characteristic that for degraded material they are sharper and begin to appear at lower levels of stress. This behavior of longexploited steel pipelines may be explained by the development of cracks and internal structural defects, the result of which is accelerated deformation [10-12].

Since in the longexploded material pipeline the integral index of the number of damage is much higher, including microcracks in the embryonic state, the magnitude of the applied stresses required for their development will be lower. This behavior of longexploited steel pipelines was also described in works [12-14]. Separately, structural degradation of the metal, formation of microcavity and probable flooding as a result of prolonged operation of the operating environment should be taken into account [11-14].

The combination of these factors leads to a decrease in the ability to withstand deformations, and the deterioration in the process of long-term exploitation of crack resistance characteristics entails the risk of increased sensitivity to the action of corrosive environments and the development of corrosion cracking processes.

The question of forecasting the development of detected deformation processes during long-term operation of pipelines arises. One of the parameters here can be the angle of inclination of the final section of the deformation curve. By its indicator, one can judge the degree of attenuation of the process. The low indicators will correspond to the insignificant danger of the development of the process, while the high will indicate rather high risks of emergencies.

This indicator can be used not only to test the air, but also for corrosion and mechanical studies.

In this case, this indicator will further serve as a marker for the sensitivity of the pipe material to a long-term operating environment. The development nature of deformation processes in ME1-ME3 (fig. 6-8) compared with air does not change significantly. We fix the growth of deformation increments with increase of applied stresses. Unlike air, in the studied environments there are no cyclical acceleration-decay deformations, which may be explained by the effect of the Rebinder effect. The inclination angles of the final sections are increasing, which indicates a greater predicted development duration of deformation processes under the influence of the operating environment.

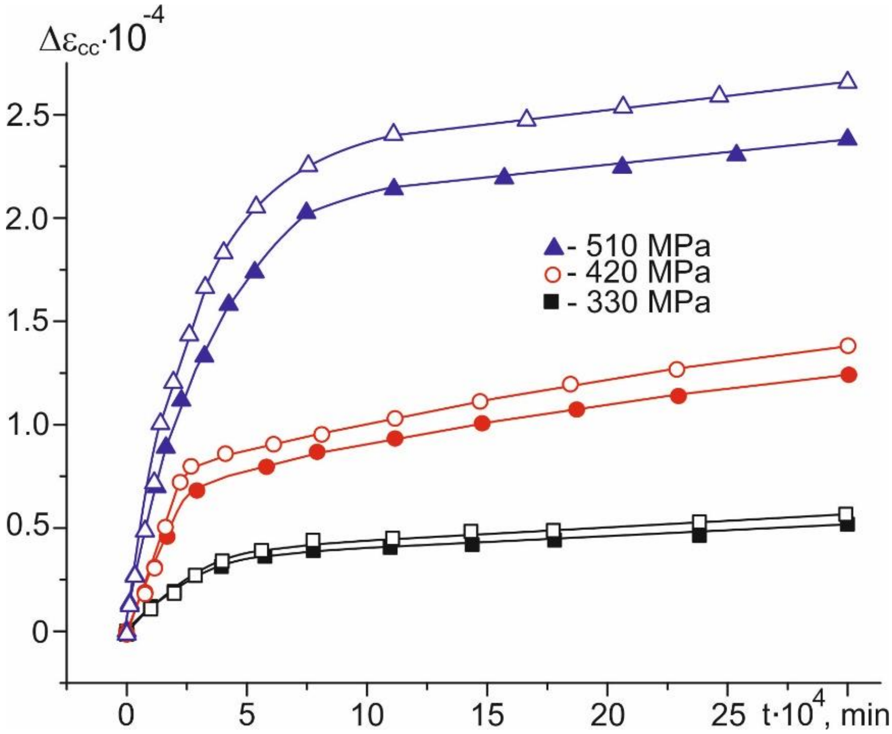


Fig. 6 The material deformation kinetics of the pipeline in ME-1:
■ - steel in the state of supply, □ - 41 years of operation.

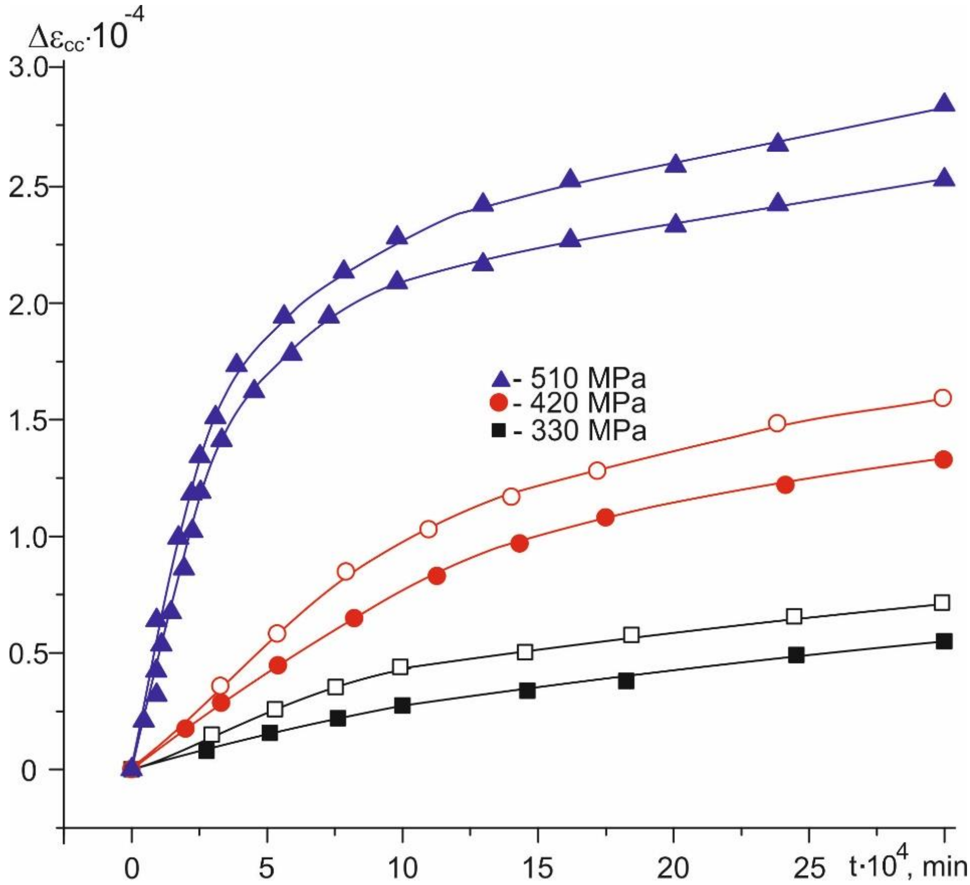


Fig. 7 The material deformation kinetics of pipeline in ME-2:
■ - steel in the state of supply, □ - 41 years of operation

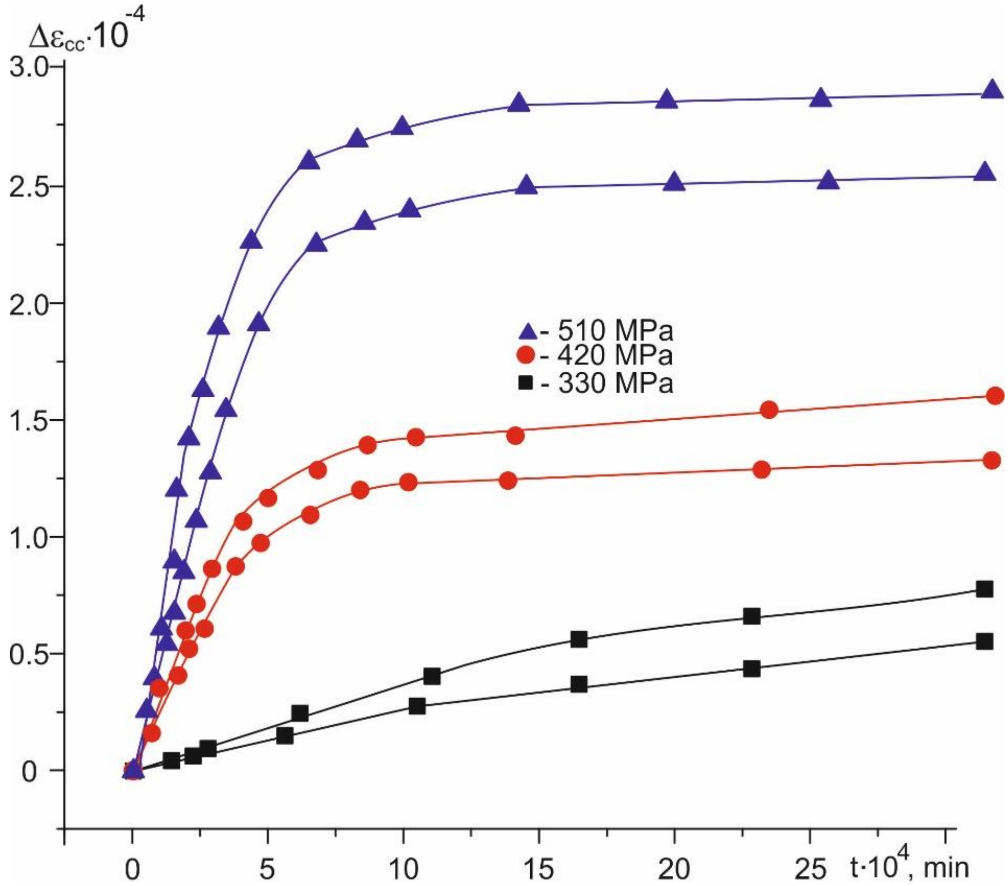


Fig. 8 The material deformation kinetics of pipeline in ME-3:
■ - steel in the state of supply, □ - 41 years of operation.

Such changes in the nature of deformation processes can be explained by the joint action of two factors - the level of applied mechanical stresses and corrosive action of the environment. Moreover, the role of the corrosive environment is decisive, as shown by the comparison with the kinetic curves in the air. Having analyzed the growth rates of the deformations and the inclination angles of the final sections of the curves, we can conclude that for the 17GS tubular steel in the state of supply, ME2 and ME3 will be the most dangerous in this group of environments.

The processes of prolonged action of soil electrolyte on steel pipeline facilitate the development of surface defects obtained at the stage of production and laying. Also, the interaction with the corrosive environment causes an increase in the damage to the pipe surface, which is manifested in the formation and development of corrosive lesions. Therefore, when assessing the pipeline's efficiency and in order to ensure its long-term operating environment, it is necessary to take into account the effect of corrosion and mechanical factors on the operational characteristics of the pipes, which entails the need for additional monitoring measures on sites passing through highly mineralized soils.

If we compare the deformation behavior of the exploited and non-extruded material, it is easy to see the preservation of the air-creep tendency of the absolute magnitude of the creep deformation. At the same time, in all model environments, unlike the air, with the naked eye we fix the tendency to increase the absolute increase in the creep deformation with the increase in the level of nominal stresses.

An increase in the concentration of corrosive components in model environments causes a slight increase in the absolute value of the creep deformation, and the increase in the inclination angle of the final part of the creep curve at the lowest stress levels is more dangerous (Table 2). This trend is especially dangerous considering that the pipeline in this mode should be operated for a significant period of time, which may increase the risk of emergencies.

Anxiety is not only the fact of increasing the inclination angle of the final sections of the curves for the longexploited metal pipeline, but also the magnitude of this increase, which, during extreme loads can reach 2.5-3.2 times, which is a dangerous decrease in survivability for longexploited steel. Even for the smallest studied stresses, the indicators of the slope gain are in the range of 28-41%, which indicates an increased sensitivity to the prolonged use of operating environments and requires taking precautionary measures to ensure the operability of pipelines in such conditions. It is necessary to constantly expand the assortment of investigated steel for accumulation of data array with the purpose of developing the corrosion monitoring concept of the pipelines and a set of measures to ensure their reliable operation during prolonged use of operating environments (soil electrolytes, substandard water, etc.).

Tab. 2 The inclination angles of the final sections of the deformation curves of steel 17GS in ME

ME	State of supply			41 years of operation		
	330 MPa	420 MPa	510 MPa	330 MPa	420 MPa	510 MPa
1	2.95	6.6	5.74	4.15	7.8	7.05
2	5.7	8.75	9.4	7.32	10.09	10.5
3	6.4	4.2	1.45	8.85	6.2	4.6

Thus, as a result of the studies, the effect of prolonged operation on the deformation behavior of the pipeline material in chloride model environments has been studied, and it has been shown that, depending on the level of nominal stresses, the increment of creep deformation, as compared to unexposed steel, can amount to 30%.

The main task of the second stage was to determine the basic physical and mechanical characteristics of the pipeline material (steel 17GS) during cyclic loading. The complete curves of fatigue and the curve of corrosion fatigue of the steel pipeline are constructed (Fig. 9). Used cyclic a clean bend loading with frequency 0.8 Hz and R= – 1. Shown that the presence of aggressive chloride environment significantly reduces the fatigue life of the material pipeline, in the area of operational loads this value reaches 1000 times.

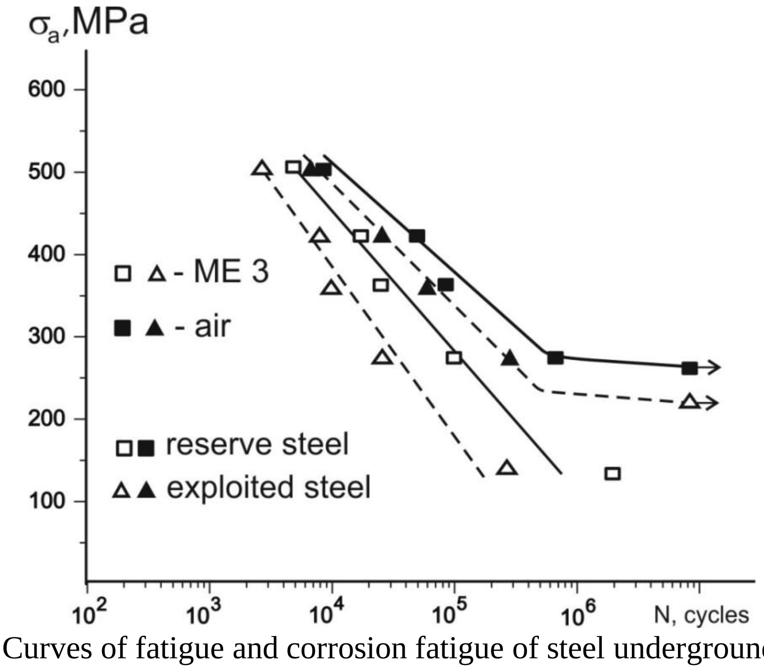
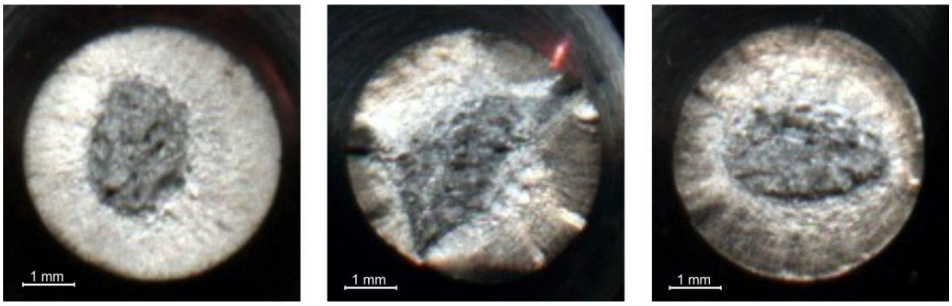


Fig. 9 Curves of fatigue and corrosion fatigue of steel underground pipeline.

The deformation and fracture kinetics is similar to that in offshore pipelines made of steel 20 [15, 16]. The appearance of the fracture surface indicates that for large σ_a in parallel a large number of cracks is developed and only at the last stage there is one trunk with decreasing amplitude of stress and this selection occurs almost immediately (Fig. 10, a and b). Pre-load also contributes to the formation of one main crack (Fig. 10). In all investigated cases, the crack originated on the specimen surface, and its growth occurred under cyclic bending. Under low amplitudes of deformations, its propagation was "uniform", which is noticeable from the flat surface relief, Fig. 10 a. Under greater amplitudes of deformation and overloading, Fig. 10b, the propagation of several competing defects (microcracks) is noticeable, the fronts of which interacted during opening, with the formation of "scars" on the fracture surface [17]. The propagation of the crack to a significant depth caused the loss of the specimen stability and its quasi-static fracture, which is why the area in the specimen center has an uneven granular microstructure.



a b c

Fig. 10 The appearance of the destruction surfaces, depending on the mode of loading and the amplitude of stress (environment - air): a - 360 MPa, b - 480 MPa, in - 480 MPa (1 cycle of preload).

The results of corrosion-mechanical tests indicate an increased sensitivity of longexploited steel pipelines to the action of corrosive environment. This behavior, in our opinion, is explained by accelerated dissolution of passive films under the influence of chlorides, which contributes to the origin and propagation of corrosion defects. In the area of operating loads, durability is reduced to 10 times, which can cause failure of main gas pipeline [18].

CONCLUSIONS

It has been experimentally proven that long-term operation of gas pipelines causes a slight deterioration of standardized mechanical and electrochemical properties of low-alloy pipe steel, for which adequate control of changing the geometry of the pipe wall is not threatening and does not reduce their performance. At the same time, subject to timely monitoring and maintenance activities, long-term operation is not critical to the health of pipelines. Absolute deformation increases are in the range of 7-12%, which is not dangerous, provided a timely monitoring and maintenance activities, as well as optimization of pumping modes.

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