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Modeling the corrosive destruction of underground degassing pipelines

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Abstract:

The general frequency of development of pitting corrosion was established, taking into account the results of the analysis of mine waters and foreign materials, which are favorable conditions for the formation of corrosion of steel degassing pipelines. A base of initial data was created for modeling the corrosion process of a steel degassing gas pipeline at different points in time: the beginning of the corrosion process, its development, and the end of the process. Stress distribution, corrosion potential, as well as anodic and cathodic current densities depending on the size of the corrosion crack and the longitudinal deformation of the rocks of the sole of the production was analysed. It has been proven that the high level of corrosion processes of underground pipelines is the result of the interaction of the metal, which acts as an electrode, with groundwater, which acts as an electrolyte, while the determining factors of the corrosion process are the electrical conductivity of the rocks of the bottom of the mine and the deformation processes in the pipelines. The reason of low service life of underground degassing pipelines, which are constantly exposed to mechanical and electrochemical corrosion, have been established.

Keywords: degassing, underground vacuum gas pipeline, methane-air mixture, monitoring, corrosion, output

1. Introduction

An urgent task in the field of ensuring safe operating conditions of the greenhouse degassing gas pipeline is to predict the durability of the system and the formation of corrosion [1, 2]. Under the influence of an aggressive mine environment, mine degassing pipelines come into contact with aggressive fluids on their inner surface and have a short service life. The main problem that characterizes the failure of the degassing system is the critical corrosion wear of the steel segments of the gas pipeline.

To improve the quality of protective measures, predict and prevent the development of sudden emergency destruction, it became necessary to develop a model of the process of corrosion destruction of steel gas pipelines in the conditions of an aggressive mine environment [3, 4].

However, this task is little-studied and laborious in terms of execution time, as it requires the use of special approaches based on the construction of complex mathematical models of the behavior of steel degassing gas pipelines in complex mining and geological conditions of operation.

In this regard, special software have been developed, which allow to evaluate the durability of various structures in a short time. The basis of the operation of these software complexes (ABAQUS, ANSYS, COMSOL, SolidWorks, etc.) is the finite element method [5], which allows you to study the influence of external negative factors on the degassing gas pipeline and predict the formation of corrosion [6, 7]. The use of CAE systems (Computer Aided Engineering) helps designing organizations to significantly reduce designing time thus reducing the costs.

One of the widely used software packages for engineering analysis is Solid Works and COMSOL Multiphysics. Their multi-purpose orientation allows solving multi-physical tasks, such as modelling corrosion, strength under thermal load, impact of magnetic fields on the structure strength, testing the kinetics of electrochemical and chemical reactions, etc.

The aim of the work is to model the corrosion process on the degassing pipeline using Solid Works and COMSOL Multiphysics 5.6 software products.

To achieve the goal, the following tasks were solved:

- to establish patterns of changes in the profile of the mine degassing pipeline route in potentially dangerous zones of preparatory workings;
- to develop a mathematical model to determine the probability of distribution of corrosion pitting zones of a steel degassing pipeline in the conditions of an aggressive mine environment;
- to establish the maximum anodic current density under the constant impact of mechanical and electrochemical corrosion of steel degassing pipelines.

2. Methods

According to the results of diagnostics of the technical condition of mine gas pipelines and tests of the conditions of its interaction with the rock mass, it was established that in the areas of the flange joints of its segments under the impact of rock mass deformations, pipeline deflects and, as a result, zones of water accumulation, intense corrosion of the inner walls of the pipes and mechanical deposits of coal and rock dust ocurrs [8, 9].

The research work methodology includes development of a mathematical model for establishing the corrosion zones of a steel degassing pipeline and modelling the corrosion process in the conditions of a mine environment. The degassing pipeline is under the simultaneous action of a corrosive environment and permanent or temporary stresses. This process can be imagined as follows: first, local corrosion occurs on the surface of the pipe in the form of pittings, which begin to act as stress concentrators. The maximum stress will be at the bottom of the pittings, which has a more negative potential than the pipe walls, as a result of which the destruction of the metal will go deep, and the pitting itself will turn into a crack.

An aggressive environment that causes metal corrosion under normal conditions does not lead to its destruction, however, under the action of mechanical stresses, it can lead to the formation of cracks (Fig. 1).

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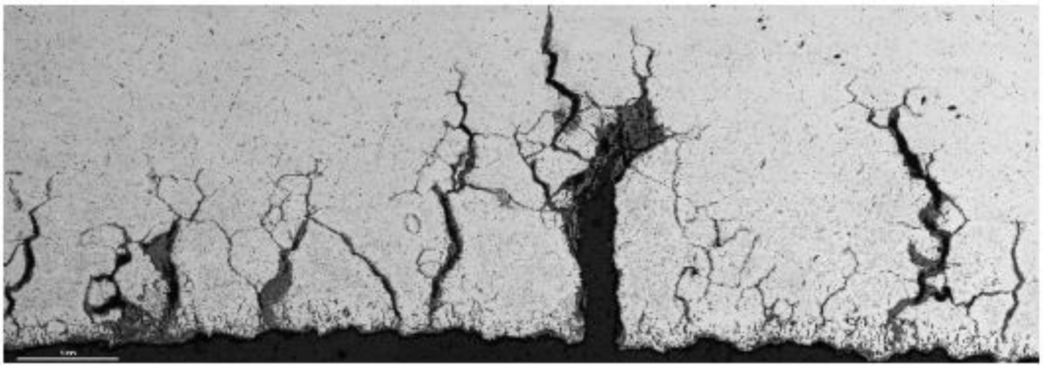

Fig. 1. Metal surface with the corrosion cracking

It should be noted that the process of corrosion fatigue of the steel links of the degassing pipeline is observed in the conditions of the mine environment. To a large extent, it is similar to how corrosion cracking occurs when static stresses are combined with corrosion. Corrosion fatigue occurs when cyclic loads are combined with corrosion. It is expressed in the destruction of metal at a significantly lower fatigue limit than in non-aggressive conditions.

Real data on the rock deformations of the bottom of the workings and modeling the technical condition of the mine degassing pipeline with the use of the SolidWorks licensed software complex, the features of the interaction of the components of the transportation and technological system of the mine gas pipeline - mine workings "ShG-GV" were established. It has been experimentally confirmed that the butt joints of the mine gas pipeline links are most susceptible to the rock mass deformations and mechanical destruction, which provokes a decrease in the output of the gas pipeline and requires development of new technical solutions for its modernization.

In accordance with the developed methodology for software modeling of mine degassing system operation modes, the elevation marks of the gas pipeline profile obtained as a result of the surveying survey became the basis for modeling the linear deformations of the pipeline under the impact of the crushed rocks of the floor.

According to the recommendations [10, 11], spatial changes of the route of the mine degassing pipeline take into account the isotropic properties and physical and mechanical characteristics of steel pipes, which are deformed in all directions equally. In this regard, deformations of the material of steel pipes in the process of spatial change of the route of the mine degassing pipeline take into account the impact of the rock mass behaviour.

3. Results

Analysis of the research work [12, 13] enabled to conclude that the operational reliability of mine degassing pipelines built in underground mine workings is influenced by the change in spatial position under the impact of deformations of the rock mass. It should be noted that underground water that enters the mine workings and the created mine space is contaminated with organic and mineral particles of varying degrees of dispersion, soluble mineral salts (including salts of heavy metals), various types of bacteria, and in some cases, they have an acidic reaction ($pH < 6$), and when in contact with moving and rotating mechanisms, they are contaminated with oil products and provoke corrosion of gas pipelines (Table 1) [14].

Table 1 shows the analysis of mine waters and their composition in various coal mining enterprises.

It should be noted that two electrochemical reactions take place on the walls of the steel gas pipeline, namely the oxidation of steel for the anodic reaction and the release of hydrogen for the cathodic reaction. This is due to aggressive mine waters, which are highly acidic.

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Table 1. Composition of mine water in different mines

List of physical and chemical indicators.	Results of mine water analysis by a mine			
	"Pavlogradska"	"Im. Heroes of the Cosmos"	Western Donbas	"Blagodatna"
Suspended substances, mg/dm^3	98.80	445.00	308.20	75.1
pH	8.55	7.36	8.09	7.75
Free chlorine, mg/dm^3	-	-	-	-
General hardness, mg-eq/dm^3	36.40	161.79	116.28	45
General alkalinity, mg-eq/dm^3	4.8	1.8	2.5	-
Permanganate oxidizability, mg/dm	-	-	-	-
Dry residue, mg/dm^3	6703.50	43807.00	28497.00	14136.5
Calcium, mg/dm^3	368.81	1621.15	1175.33	430.62
Magnesium, mg/dm^3	218.87	2983.69	700.88	285.89
Total iron, mg/dm^3	1.2	0.97	0.4	0.89
Chlorides, mg/dm^3	2642.97	22314.94	15351.41	8022.7
Sulfates, mg/dm^3	576.36	441.88	365.03	577.17
Petroleum products, mg/dm^3	0.75	0.65	0.63	0.8

It is known that the high level of corrosion processes of steel pipelines is the result of the interaction of the metal, which acts as an electrode, with groundwater as an electrolyte, and the determining factor of the corrosion process is the soil electrical conductivity. Electrochemical corrosion often has a local character, that is, it causes areas of corrosion and caverns of great depth on the pipeline, which can turn into fistulas in the pipe wall. Such corrosion is much more dangerous than continuous corrosion [15, 16].

The initial parameters (Table 1) were included in the mathematical model to determine the probability of the distribution of corrosion pitting zones for the first model and modeling the electrical conductivity of the soil under the influence of deformation, which lead to stresses in the pipelines for the second model.

The first model showed the frequency of development of pitting corrosion, taking into account the results of the analysis of mine water and foreign materials, which create favourable conditions for the corrosion process.

The degassing pipeline, which is curved in the profile and consists of 6 sections of pipes with a length of 4.0 m, diameter of 300 mm and a wall thickness of 4.0 mm, was selected as the tested object. Degassing pipes supplied to mines are made of typical carbon steel without a special coating.

Let's consider the first model of the formation process of pitting corrosion.

Papers [17-19] proposed the dependence of the formation of pitting corrosion on the content of chlorine ions in the mine water, which contribute to destruction corrosion of steel. The pitting potential is calculated using the following expression:

$$E_{po} = \Delta E_{po} + E_{cor}, \tag{1}$$

where:

E_{po} – pitting potential, V,

E_{cor} – corrosion potential, V,

ΔE_{po} – basis of pitting resistance.

$$E_{po} = b + a \cdot \log|Cl^{-}|, \tag{2}$$

where:

a, b – constants,

$|Cl^{-}|$ – concentration of chlorine ions.

It should be noted that the coefficients a, b are unknown to us, and their determination required a linear approximation based on known chloride ion concentrations from the work [20]. As a result, the following value was set for our initial concentration of Cl^{-} (table 1).

E_{cor} = -1.303 V.

The probability of pitting formation from the moment of starting the model Po(t) is calculated by the following expression:

$$P_0(t) = P_0(\tau \geq t), \tag{3}$$

$$P_0(t + dt) = P_0(t)P_0(dt) = P_0(t)(1 - \lambda dt)\,, \tag{4}$$

According to expressions (3, 4), we get that the change in Po(t) depends on the probability of formation of single pitting λ, according to the following recommendations

$$\frac{dP_0}{dt} = -\lambda P_0(t) \tag{5}$$

By solving equation (5), we get:

$$P_0(t) = \exp(-\lambda t), \tag{6}$$

where:

$P_o(t)$ – dependence of the probability of pitting formation on time,

t – time since model initialization,

λ – probability of formation of single pitting.

The average time of the moment of the beginning of pitting formation τ is defined as:

$$\tau = \frac{\int_0^\infty texp(-\lambda t)dt}{\int_0^\infty exp(-\lambda t)dt} = \frac{1}{\lambda}, \tag{7}$$

The obtained values were used as a base of initial data with introduction of relevant equations into the model, on the basis of which models of the profile of the degassing pipeline were built at different points in time (Fig. 2): the beginning of the corrosion process, its development and the end of the process. The period of observation of the sample was 3 months, the length of the cut was 1000 mm.

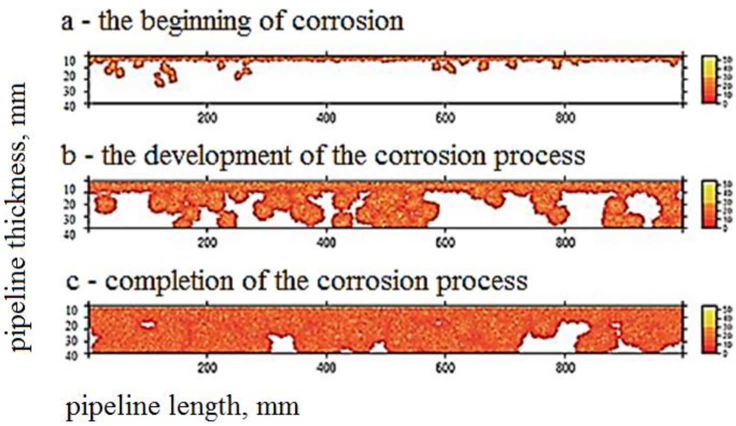

Fig. 2. Change in the dynamics of pitting corrosion depending on the time interval of contact with an aggressive environment

Modeling the electrical conductivity of the soil under the impact of deformation, which leads to stresses in pipelines, was considered in the second model. The physical and mechanical properties of the material of the degassing pipes considered in the generated CAD models are presented in Table 2.

Table 2. Basic properties of carbon steel

Properties	Value	Unit
Modulus of elasticity	$2{,}1 \cdot 10^{11}$	N/m^2
Shear modulus	$7{,}9 \cdot 10^{10}$	N/m^2
Mass density	7800	kg/m^3
Tensile strength limit	399826000	N/m^2
Poisson's ratio	0,28	
Liquidity limit	220594000	N/m^2
Coefficient of thermal expansion	$1{,}3 \cdot 10^{-5}$	
Thermal conductivity	43	W/(m·K)
Specific heat capacity	440	J/kg·K

The simulation was carried out using the Solid Works licensed software complex and the COMSOL Multiphysics 5.6 product, which made it possible to test distribution of stresses, the corrosion potential, as well as the anodic and cathodic current densities depending on the size of the corrosion crack and the longitudinal deformation of the floor rocks (Fig. 3)

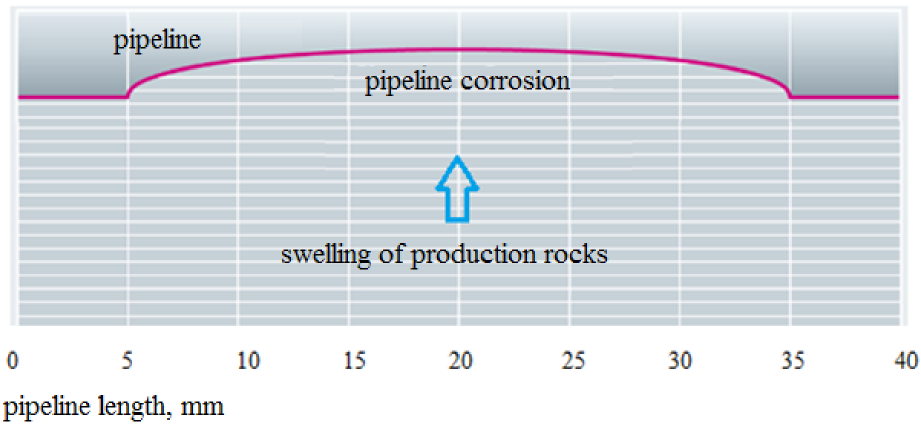

Fig. 3. Geometric model of a pipeline with a corrosion defect

Elastic-plastic stresses in a gas pipeline steel was modelled using the model of plasticity at small deformations and the von Mises flow criterion [21, 22].

The SolidWorks interface and a user-defined isotropic hardening model were used for modelling. The function σ_{yhard} was defined as:

$$\sigma_{yhard} = \sigma_{exp}(\varepsilon_{eff}) - \sigma_{ys} = \sigma_{exp}\left(\varepsilon_p + \frac{\sigma_e}{E}\right) - \sigma_{ys}, \tag{8}$$

where:

σ_{exp} – the experimental stress function obtained from the measured stress-strain curve of steel,
ε_{eff} – total effective strain,
σ_{ys} – the yield strength of steel is $803 \cdot 10^6$ Pa,
ε_p – plastic deformation,
σ_e – von Mises stress,
E – Young's modulus of elasticity equal to $207 \cdot 10^9$ Pa,
$\frac{\sigma e}{E}$ – elastic deformation.

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In the process of corrosion cracking, two electrochemical reactions take place [23] (and it is assumed that only the surface of the corrosion crack is electrochemically active):

1. anodic - dissolution of iron ($Fe \rightarrow Fe^{+2} + 2e$);
2. cathodic – release of hydrogen ($2H_2O + 2e \rightarrow H_2 + 2OH^-$).

The anodic Tafel expression of the following form was used to model the iron dissolution reaction:

$$i_a = i_{0,a} 10^{\frac{\eta_a}{A_a}} \tag{9}$$

where:

$i_{0,a}$ – exchange current density ($2.353 \cdot 10^{-3}$ A/m^2),

A_a – the slope of the Tafel curve (0.118 V), and the overvoltage η_0 for the anodic reaction is calculated by the following formula:

$$\eta_a = \phi_s - \phi_l - E_{cq,a}, \tag{10}$$

where:

ϕ_s, ϕ_l – electrostatic potential.

and the equilibrium potential of the anodic reaction $E_{cq,a}$ is calculated from the following formula:

$$E_{cq} = E_{cq0} - \frac{\Delta P_m V_m}{zF} - \frac{TR}{zF} \ln\left(\frac{\upsilon\alpha}{N_0}\varepsilon_p + 1\right), \tag{11}$$

where:

E_{cq0} – standard equilibrium potential of the anodic reaction (−0.859 V),

ΔP_m – excess pressure to elastic deformation ($2.687 \cdot 10^8$ Pa),

V_m – molar volume of steel ($7.13 \cdot 10^{-6}$ m^3/mol),

z – charge number for steel (2),

F – Faraday constant,

T – absolute temperature (298.15 K),

R – ideal gas constant,

ν – coefficient depending on the orientation (0.45),

α – coefficient ($1.67 \cdot 10^{15}$ m^{-2}),

N_0 – initial density of dislocations ($1 \cdot 10^{12}$ m^{-2}).

Tafel's cathodic expression was used to model the iron dissolution reaction, it establishes the local cathodic current density.

$$i_c = i_{0,c} 10^{\frac{\eta_c}{A_c}} \tag{12}$$

where:

$i_{0,c}$ – exchange current density,

A_c – the Tafel slope (−0.207 V), and the overvoltage ηc (V) for the cathodic reaction is calculated by the formula

$$\eta_a = \phi_s - \phi_l - E_{cq,c} \tag{13}$$

where:

$E_{cq,c}$ – standard equilibrium potential of the cathodic reaction (-0.644 V).

The exchange current density for the cathodic reaction was determined by the following formula:

$$i_{o,c} = i_{0,c,ref} 10^{\frac{\sigma_e V_m}{6(-A_c)}} \tag{14}$$

where:

$i_{0,c,ref}$ – eference exchange current density for the cathodic reaction without external stress ($1.457 \cdot 10^{-2}$ A/m^2)

The simulation was carried out in several stages: at the first stage, the types of physical solvers (solid mechanics and secondary current distribution) and the type of calculation (stationary) were selected. At the second stage, the geometric model of the underground pipeline with an elliptical crack (Fig. 3) was constructed, the model of isotropic hardening, the parameters of the electrochemical corrosion process, the mechanical properties of the pipeline material, the amount of longitudinal deformation of the pipeline, etc. were specified. At the third stage, a grid of finite elements was constructed and the von Mises stress distribution was calculated, as well as the distribution of corrosion potential, anodic and cathodic current densities along the length of the corrosion crack, depending on the degree of longitudinal deformation

Impact of longitudinal movements of the soil on the corrosion process of underground degassing pipelines has been demonstrated using various possible deformations of the pipeline [24, 25]. The Mises background voltage in the steel pipe, the electrolyte potential distribution, and the direction of the current in the surrounding soil are shown in Fig. 4.

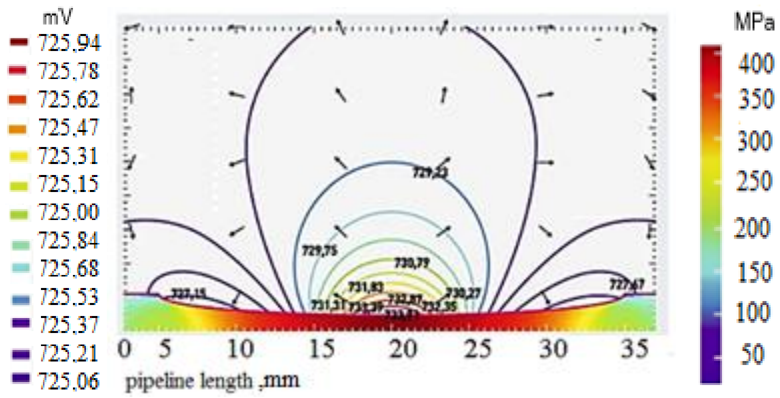

Fig. 4. Distribution of stress in the pipeline according to von Mises (MPa), electrolyte potential (mV) and current line in the soil

Fig. 4 presents the Mises background stresses, which increase with the increase of possible deformations of the pipeline and are maximal in the center of the corrosion defect and reach 300 and 350 MPa.

It should be noted that the electrolyte potential distribution is uneven near the corrosion defect. Arrows along the lines of current indicate the direction and distribution of current density in the soil.

A comparative analysis of the von Mises stress distribution results by the length of the corrosion defect for each strain value is shown in Fig. 5 a. It can be seen that the stresses increase with increasing tensile strain and are maximal in the center of the corrosion defect. For deformations of 2.0 and 2.25 mm, the local stress in the center of the corrosion defect exceeds the yield strength of high-strength alloy steel (403 MPa). This leads to plastic deformation in the center of the corrosion defect, while in the other area the corrosion defect remains in the elastic range.

Fig. 5 b shows the distribution of the electrode corrosion potential and the anodic and cathodic current densities along the length of the corrosion defect.

The graph of the local potential of the electrode along the length of the corrosion defect confirms that the even distribution changes to an uneven distribution with increasing the tensile strain, and a greater negative corrosion potential, in absolute value. is achieved in the center of the corrosion defect unlike at both edges. This effect is explained by the large absolute value of the negative potential of the equilibrium anodic reaction in the area of plasticity of the defect at the highest possible longitudinal deformations.

Increase in anodic current density for tensile strains of 2.0 and 2.25 mm is explained by the plastic deformation observed in the center of the corrosion defect (Fig. 5 c). The strongest negative current is found in the center of the corrosion defect, where the distribution of the cathodic current density is the most uneven for a tensile strain of 2.25 mm (Fig. 5 d).

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Total current density is a sum of the anodic and cathodic current densities, and for deformations of 2.0 and 2.25 mm, the total current density in the center of the corrosion defect is determined mainly by the anodic current density, and on both sides of the defect by the cathodic current density. Therefore, the distribution of the total current density is uneven for large tensile strains, and the direction of the current near the corrosion defect changes to the opposite.

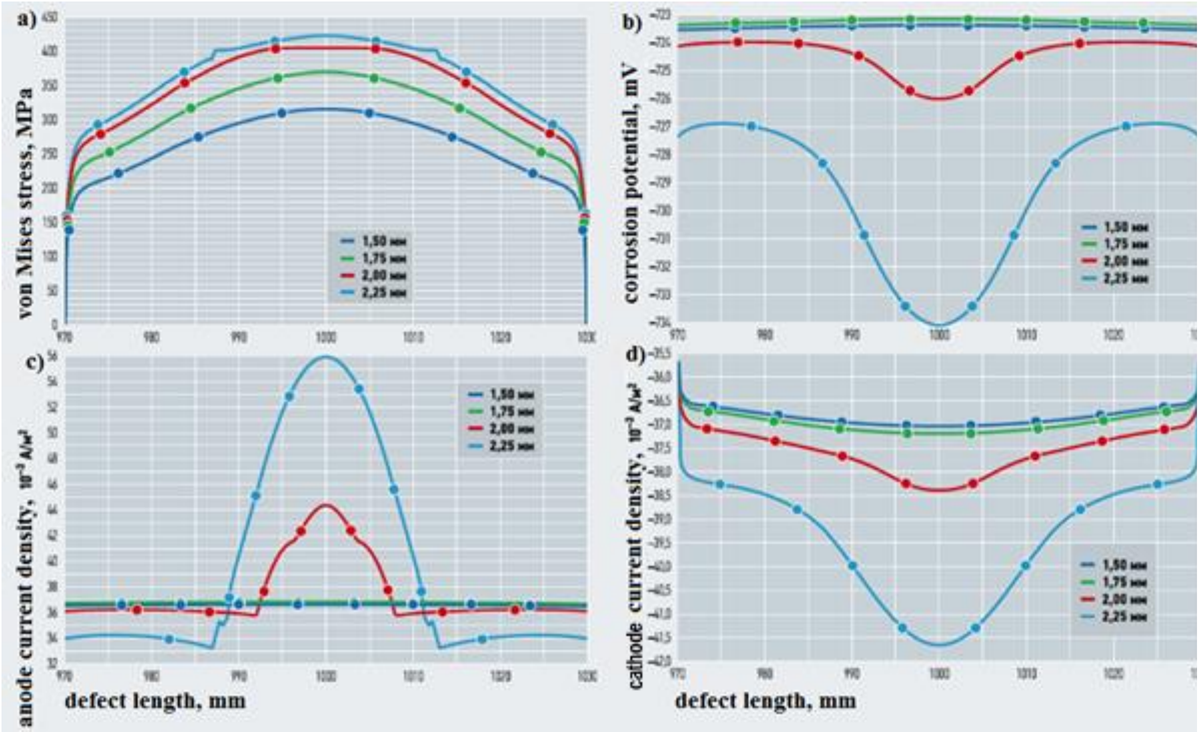

Fig. 5. Distribution of electrode's corrosion potential and anodic and cathodic current densities along the length of the corrosion defect

The results show that the higher deformations of the pipeline, caused by the deformation of the floor rocks, which lead to plastic deformation in the zone of the corrosion defect of the steel pipe and thereby to a greater absolute value of the negative potential of the local electrode and a higher density of the anodic current increase corrosion of the pipeline. This is one of the reasons for the short service life of underground degassing pipelines, which are under the constant impact of mechanical and electrochemical corrosion.

4. Conclusions

The modeling of corrosion failure showed that starting from a crack depth of 2 mm, the process of plastic deformation of the gas pipeline material at the crack tip starts. As the stress intensity factor increases, the crack growth rate increases. Starting from a crack depth of 3 mm, the probability of failure in the form of a mechanical break at an angle of 45º towards the hoop tensile stresses increases. When a depth of 4 mm is reached, the stress from the inner wall of the gas pipeline will exceed the yield strength of the material, which can lead to unstable operation with a subsequent accident. Consequently, safe operation of this gas pipeline is possible when the defect depth is less than 50% of the wall thickness, depending on the length. Defects with a depth of 50% or more are unacceptable, regardless of length.

The results of modeling and testing the underground pipelines corrosion process using the software products such as SolidWorks and COMSOL Multiphysics established that the degassing network of mines is constantly under the impact of mechanical-electrochemical interaction, which manifests itself in the longitudinal deformations of the mine floor rocks.

High intensity of corrosion in underground pipelines is the result of the interaction of the metal, which acts as an electrode, with groundwater, which acts as an electrolyte, while the electrical conductivity of the soil and the deformation processes in the pipelines are the determining factors of the corrosion process.

The primary corrosion protection of pipelines of underground degassing pipelines can be the improvement of the methods for control and the technical maintenance of mine degassing pipelines to eliminate mechanical deformations and impact of aggressive groundwater.

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