

METHODS FOR THE EVALUATION OF FRACTURE AND STRENGTH OF PIPELINE STEELS AND STRUCTURES UNDER THE ACTION OF WORKING MEDIA. PART I. INFLUENCE OF THE CORROSION FACTOR

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We generalize contemporary methods used for the evaluation of strength and fracture hazard of elements of pipeline structures with the use of approaches of fracture mechanics of materials, by taking into account specific features of influence of corrosive factors. The stages of initial corrosion damage to the metal and of the surface corrosion-fatigue cracking in pipeline steels are analyzed. We discover the influence of the chemical composition of the medium, frequency and stress ratio of the loading cycle, and the time of operation on their cyclic corrosion crack resistance. For the expert evaluation of the serviceability and fracture hazard of pipeline systems with corrosion cracklike defects, we propose to use special diagrams containing three characteristics zones: zone of safe operation, zone of operation with predicted development of the existing cracklike defects, and zone of brittle fracture hazard.

Keywords: pipeline structures, steels for pipelines, corrosive media, static and cyclic loads, stress-corrosion cracklike defects, diagrams for the evaluation of the serviceability and fracture hazard.

The pipeline structures and pipeline transport as a whole are of great importance for the national economy of Ukraine. Moreover, their significance permanently increases due to the prospects of introduction of the European hydrogen-power infrastructure based on the use of the existing pipeline networks for the transportation of the mixtures of natural gas with hydrogen [1–3].

Moreover, pipelines used for the transportation of corrosive and hydrogen-containing media are regarded as critical objects [4], which are of great importance for the industrial and social infrastructure. From the engineering point of view, these are three-dimensional structures consisting of rectilinear sections of pipelines, pipe branches, bends, various types of welded joints, etc. In operation, they are subjected to the influence of internal pressure and cyclic loads (vibration) in combination with the action of internal and external media. Due to the potential synergism of the influence of these factors, the hazard of formation of unforeseen damages and fractures in the process of long-term operation increases, which may result in emergency situations with unpredictable engineering, economical, and social consequences [4]. This is why it is necessary to guarantee the reliability and integrity of pipeline structures. In what follows, we study the fracture processes in pipeline steels caused by the initiation and development of cracklike defects from stress concentrators under the action of corrosive and hydrogen-containing media. We analyze and generalize the experimental results obtained by the authors in recent years.

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Initial Stages of Damage and Fracture Resistance of Pipeline Steels Cyclically Loaded in Corrosive Media

At present, it is generally accepted that the corrosion fatigue of structural metals and alloys is a multistage process [5–11], including the fracture of passive films on the metal surface, the development of initial surface defects in the form of pits and dimples, the pit-crack transitions, and the development of cracks to the critical sizes. The importance of each stage for the general analysis of the corrosion fatigue of specimens or structural elements can be different and depends on the physicochemical characteristics of the “material–medium” system, loading mode, and the geometric sizes of the object [5, 12, 13]. The analysis of the in-service damage [9, 13–16] to the main structural elements of pipelines confirms the fact that these processes are characterized, first, by a certain localization depending on the state of the metal surface and, second, by the multistage character.

The initial localization of fracture is explained by the presence of heterogeneities or inclusions on the metal surface, which leads to the formation of local corrosion-active areas. This leads to the initiation of small and large stress-corrosion pits, which should be regarded as potential stress concentrators. In this case, the electrochemical processes activated by mechanical stresses play a decisive role. In the second stage of fracture of the material, the first cracklike defects are formed from the already existing small pits (these are the so-called physically short cracks whose length practically does not exceed the distances between microstructural barriers). In this case, the role played by the mechanical factor increases. The subsequent course of the process leads to the development and coalescence of microcracks. This, in turn, results in the formation of a macrocrack, which mainly propagates into the bulk of the material and, finally, attains the critical sizes and, hence, causes the spontaneous catastrophic failure of the analyzed structural element.

It should be emphasized that depending on the geometric sizes and operating conditions, any specific structural element is characterized by its own limiting stage of stress-corrosion fracture [9, 12]. Thus, in particular, the stages of formation of large stress-corrosion pits and initiation of the macrocrack are determining for the evaluation of the serviceability and service life of thin-walled pipelines. At the same time, the residual service life of the pipes with wall whose thickness is as large as several tens of millimeters (e.g., the feed-water pipelines of supercritical-pressure power units) is determined by the stage of development of a macrocrack into the bulk of the material. Therefore, for the efficient diagnostics of the serviceability of the structural elements of pipelines, it is necessary to develop and test various methods aimed at the evaluation of the stress-corrosion damage to the metal in each stage of fracture of the material.

Analysis of the Development of Stress-Corrosion Dimples and Pits. In this case, the methods based on the results of electrochemical scanning of the deformed surface by special probes prove to be especially efficient [17–19]. This enables one to obtain a map of the distribution of local corrosion currents around corrosion-fatigue defects in the form of small pits. It should be emphasized that the values of corrosion current density at the bottom of small pits are higher (by an order of magnitude) than the density of the integral corrosion current on the metal surface measured by standard potentiostatic methods.

Therefore, it is necessary to establish the regularities of formation of corrosion dimples and pits on the deformed metal surfaces. The problem of pitting corrosion is known for a long period of time, and its investigations are mainly focused on the electrochemical aspects of the “material–medium” system, i.e., on the determination of the pitting potential depending on the factors of the medium (chemical composition, pH value, oxygen concentration, etc.).

In what follows, we consider an absolutely different case [19], in particular, the initiation of pitting by cyclic stresses on the metallic surface for a constant polarization potential corresponding the passive state of the surface. The available results [12] on the influence of static deformation and cyclic stresses on the corrosion

activity of small pits initially initiated by the classical electrochemical method, i.e., by the application (to the surface) of the polarization potential equal to the pitting potential, indirectly confirm the possibility of existence of this phenomenon.

We study 08Kh18N12T steel in a 3% NaCl solution (pH 6.5). The frequency of cyclic loading was equal to $\omega = 0.27$ Hz for a stress ratio $R = 0$. In the first stage of the tests, the potentiodynamic polarization curves were obtained for different ranges of cyclic stresses $\Delta\sigma$ chosen with regard for the yield strength of the material $\sigma_{0.2}$: $\Delta\sigma/\sigma_{0.2} = 0, 0.3, 0.7$, and 1.0.

The obtained results reveal a noticeable influence of $\Delta\sigma$ on the electrochemical behavior of the cyclically deformed surface [19]. Integrating polarization curves, we evaluate the degree of pitting on a cyclically deformed surface by using the following parameter:

$$W = \int_{E_p}^{E_{rp}} I(E) dE, \quad (1)$$

where E_p and E_{rp} are the pitting and repassivation potentials, respectively.

The parameter W can be interpreted as the electrochemical energy required for the restoration of the passive state of the surface after the formation of a pit, i.e., as the energy of repassivation of the surface. Its values computed for the polarization curves plotted for different ranges of cyclic stresses $\Delta\sigma$ show [19] that the energy required for the restoration of the passive state of the surface may increase with the cyclic load. In the analyzed case [19],

$$W = W_0 \exp \left[A \left(\frac{\Delta\sigma}{\sigma_{0.2}} \right) \right], \quad (2)$$

where $W_0 = 6 \cdot 10^{-8} W$ is the electrochemical energy required for the restoration of the passive state of the unloaded ($\Delta\sigma = 0$) surface after the formation of a pit and $A = 0.606$ is a constant.

We also studied local corrosion processes (pitting) under the conditions of corrosion fatigue of a specimen at $\Delta\sigma = \sigma_{0.2}$ in the case of application of a constant polarization potential $E = 0.1$ V = const (corresponding to the passive segment of the polarization curve) to the surface. In other words, the conditions for the realization of pitting according to the classical electrochemical mechanism are absent.

We also discovered the following unobvious result: The initiation of pitting by cyclic stresses on the surface, which is integrally in the passive state. In this case, first, we observe the formation of an isolated pit (Fig. 1a) around which the corrosion-current density on the intact metal surface is higher by an order of magnitude and even more (Fig. 1b). Further, as the number of loading cycles increases, the intensity of pitting and, hence, the corrosion activity of the cyclically deformed surface increase (Fig. 2). Pits serve as a source of initiation of surface cracks and, therefore, the multistage character of the “pit–surface-crack” process can be compared with the initiation of corrosion-fatigue cracks near semicircular stress concentrators [5, 20], which can be regarded, on the one hand, as typical concentrators of mechanical stresses but, on the other hand, as objects where can expected the appearance of typical forms of localized corrosion [12, 17, 18, 21, 22].

After the application of cyclic stresses to the damaged metallic surface, corrosion is additionally intensified in the cavities of pits and dimples, which is explained by the increase in the electrochemical inhomogeneity of the surfaces of pits caused by the gradient of mechanical stresses. For this reason, the bottom of pits is the place of the most intense electrochemical dissolution of the metal and, hence, the pits can be regarded as a kind of “corrosion concentrators.”

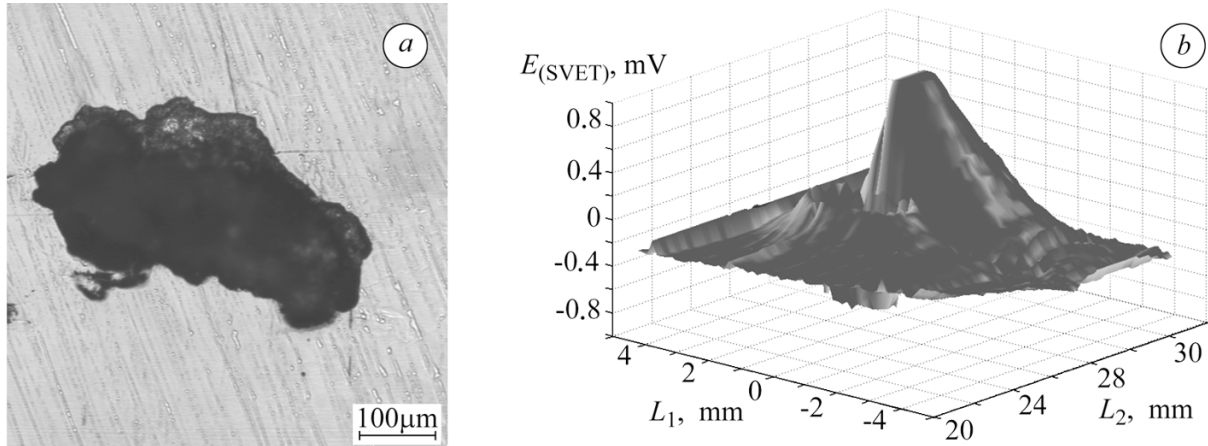


Fig. 1. Corrosion-fatigue pit on the surface of 08Kh18N12T steel in a medium with pH 6.5 (a) and the map of distribution of local corrosion currents around the pit (b).

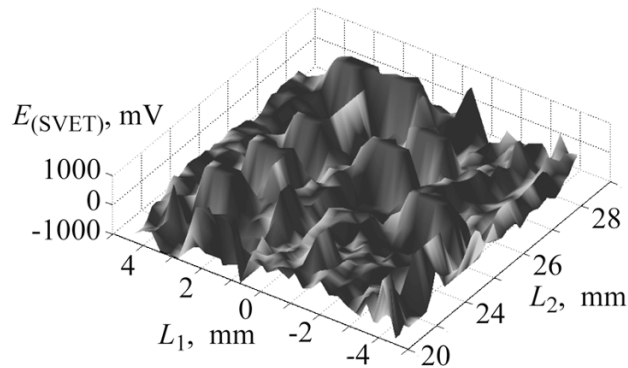


Fig. 2. Map of distribution of local corrosion currents on the cyclically deformed surface of 08Kh18N12T steel in a medium with pH 6.5 under the conditions of intense pitting.

This enables us to model the development of corrosion fatigue in the course of pitting as follows: The first stage is the initiation and growth of a small pit to a certain characteristic size $c = d$

$$c = F_{\text{pit}}(i_{\text{pit}}; \Delta\sigma; \tau) \quad \text{for} \quad 0 \leq c \leq d \quad (3)$$

by the mechanism of electrochemical dissolution of the metal intensified by the applied cyclic stresses.

The second stage is the initiation of a fatigue crack of length a from a small pit of size $c = d$ as a result of the joint action of local electrochemical corrosion and local “effective” cyclic stresses

$$a = F_{\text{crack}}(i_{\text{pit}}^*; \sigma_{\text{eff}}; N), \quad \text{if} \quad c \geq d. \quad (4)$$

This stage is characterized by the fact that the localized physicochemical action of the medium causes the local concentration of mechanical stresses near the bottom of the pit, which, in turn, intensifies its growth. In other words, there exists a synergism between the local mechanical and physicochemical interactions.

The initiation of a macrocrack near the small pit under the conditions of corrosion fatigue can be evaluated by modeling it with a semicircular stress concentrator. It was established [5] that the main determining feature of the process of formation of a macrocrack on the surface of such a concentrator is a certain reached critical density q_* of surface cracks with a constant (characteristic) length $a = a_*$. After reaching this critical state, a fast stage of coalescence of these cracks is observed that leads to the appearance of a macrocrack near the tip of the stress concentrator [12, 17, 18, 21, 22]. For this reason, as the time of initiation of a macrocrack, we took the number of loading cycles $N = N_*$ after which the condition $q = q_*$ is reached. It is known [20, 23] that the criterion relation evaluating the period of initiation of a macrocrack is a certain combination of parameters of the stress-strain state of the material in the process zone and parameters of the electrochemical surface dissolution of the deformed metal near the stress concentrator, i.e.,

$$(\Delta\sigma_{\text{eff}})^m \left[\frac{M}{zF\rho} \left(\frac{1}{\omega} \right) \int_0^{N_*} i(N) dN \right] = C = \text{const}, \quad (5)$$

where $\Delta\sigma_{\text{eff}}$ is the range of effective stresses, m , C , M , z , F , and ρ are the constants of electrochemical dissolution of the metal for the “metal–medium” system under consideration, ω is the frequency of cyclic loading, $i(N)$ is the current density of electrochemical dissolution of the metal as a function of the number of loading cycles N , and N_* is the number of loading cycles after which the critical density q_* of surface cracks with a length $a = a_*$ is reached.

From relations (5), for $i(N) = i_{\text{corr}} = \text{const}$, we get

$$N_* = \frac{zF\rho}{Mi_{\text{corr}}} \omega \frac{C}{(\Delta\sigma_{\text{eff}})^m}, \quad (6)$$

where the parameters $\Delta\sigma_{\text{eff}}$ and i_{corr} are variables, and the other parameters are known constants of electrochemical metal dissolution for the given “metal–medium” system.

Evaluation of the Surface Corrosion-Fatigue Cracking. This type of defects is typical of important and critical objects, such as various pipeline systems of power units. For example, there exists a serious problem of stress-corrosion defects in the metal of the inner surfaces of feeding pipelines of the supercritical-pressure power units of thermal power plants (TPP). They have the form of corrosion dimples and grooves that, in part, became cracks with a depth of several millimeters [5–7, 24–28].

They can be evaluated with the use of the proposed model scheme [25] of corrosion fatigue of a material in the case where the formation of surface corrosion-fatigue cracks is related to the intensity of electrochemical dissolution of a cyclically deformed surface. For this purpose, we used the established relationship between the length of the surface crack a , the characteristic value of the applied stress σ_s [25, 29], and the parameters of electrochemical dissolution of the metal

$$F(a) = \left(\frac{\sigma_s}{\sigma_{\text{max}}} \right)^m Q, \quad Q = \frac{M}{zF\rho} \frac{1}{\omega} \int_0^N I_{\text{corr}}(N) dN, \quad (7)$$

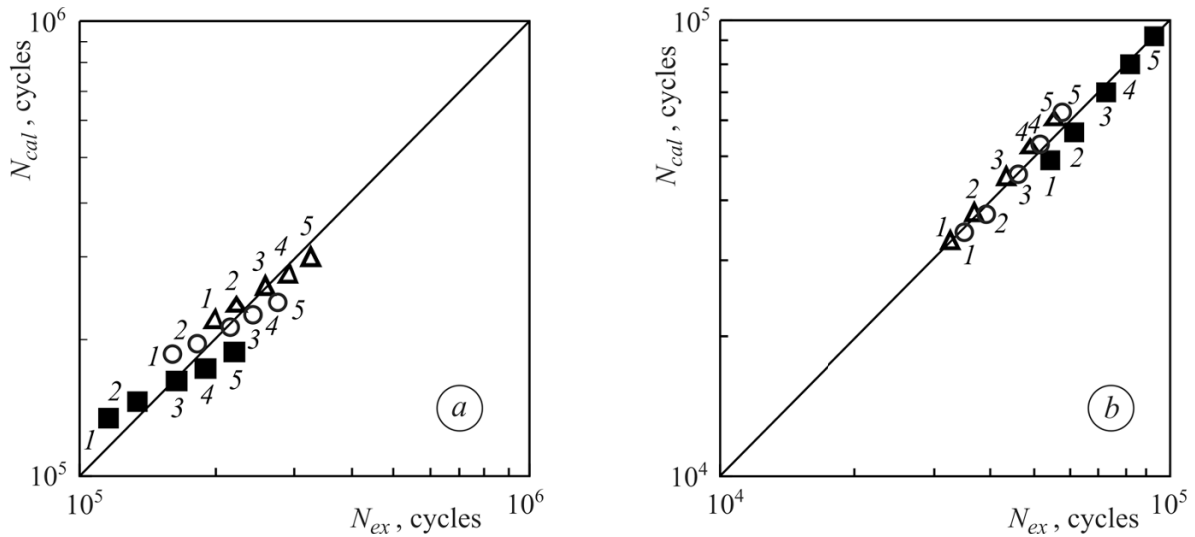


Fig. 3. Comparison of experimental and computed values of the period of initiation of surface corrosion-fatigue macrocracks of different lengths in 12Kh1MF steel (a) and 08Kh18N12T steel (b): (1) $a = 1$ mm, (2) 2 mm; (3) 5 mm; (4) 10 mm, (5) 20 mm; (Δ) pH 3.0; (\blacksquare) pH 6.5; (\circ) pH 9.0.

where $F(a)$ is a function of the crack length, σ_s is the characteristic stress value at which the metal surface within a loading cycle becomes to be electrochemically activated significantly, σ_{max} is the maximum stress of the loading cycle, m is a constant of the “material–medium” system, Q is the integral volume of the dissolved metal from the unit surface area for given number of loading cycles N , $I_{corr}(N)$ is the dependence of integral corrosion current upon the cyclically deformed surface on the number of loading cycles N , and this dependence, for all considered cases, is satisfactorily described by the power law $I_{corr} = I_0 N^k$ [7, 25], where I_0 and k are constants of the “material–medium” system. It was established [30] that, for the corrosion-fatigue surface macrocrack from relation (7), the calculated estimates of the period of initiation agree with experimental estimates satisfactorily (Fig. 3).

This approach to the evaluation of corrosion-fatigue surface cracking that takes into account the simultaneous action of cyclic stresses and electrochemical processes is efficient for engineering applications and used to obtain the predictive estimation of the residual service life and serviceability of pipeline systems for power units of TPP [8, 9, 15, 31].

Influence of the Physicomechanical and Physicochemical Factors on the Growth Resistance of Cracklike Defects in Pipeline Steels

In what follows, as an example, we consider three characteristics types of steel, which are used for the production of pipeline systems in thermal power-generating equipment, and study the influence of the main operating factors (such as the composition of working media, frequency of cyclic loading, stress ratio, the time of operation, and technogenic impurities) on the fatigue crack-growth resistance.

Influence of the Chemical Composition of the Medium on the Growth Rate of Corrosion-Fatigue Cracks. It is shown [6, 8, 16, 32] that relatively insignificant changes in the compositions of working media can lead to substantial changes in the propagation patterns of corrosion-fatigue cracks in the material as compared with

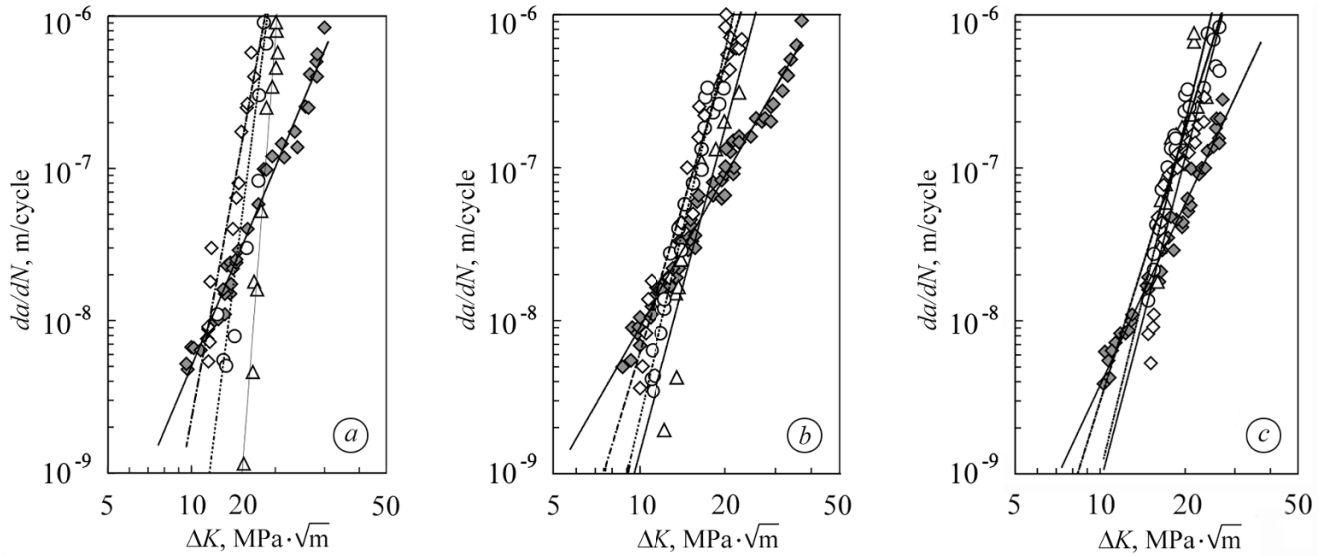


Fig. 4. Influence of the composition of media on the fatigue crack-growth rate in 20 steel (a) and 12Kh1MF steel (b) ($R = 0$, $f = 1.0$ Hz, $T = 80^\circ\text{C}$: (\blacklozenge) air; (\triangle) $\text{H}_2\text{O} + \text{NH}_3$ to pH 9; (\circ) $\text{H}_2\text{O} + \text{NH}_3$ to pH 9 + 100 mg/kg N_2H_4 ; (\diamond) $\text{H}_2\text{O} + \text{NH}_3$ to pH 9 + 100 mg/kg N_2H_4) and in 08Kh18N12T steel ($R = 0$, $f = 1.0$ Hz, $T = 80^\circ\text{C}$: (\blacklozenge) air; (\triangle) 1% solution of $\text{H}_3\text{BO}_3 + \text{KOH}$ to pH 8; (\circ) 1% solution of $\text{H}_3\text{BO}_3 + \text{KOH}$ to pH 8 + 5 mg/kg Cl^- (10.5 mg/kg KCl); (\diamond) 1% solution of $\text{H}_3\text{BO}_3 + \text{KOH}$ to pH 8 + 10 mg/kg NO_3^- (16.3 mg/kg KNO_3)).

samples in air. Hence, the crack-resistance characteristics of the material can deteriorate under given operating conditions.

The general trend in the influence of corrosive media on the growth of fatigue cracks as compared with air is as follows (Fig. 4): There exists a characteristic value of the SIF range ΔK such that the crack propagation is decelerated when the characteristic value is not exceeded, and the corrosive media accelerate this process when the characteristic value is exceeded. The point of intersection of the diagrams of cyclic crack resistance in air and in the medium belongs to the interval $da/dN = 10^{-8} - 5 \cdot 10^{-8}$ m/cycle. This is explained by the fact that, for small crack growth rates, the anodic corrosion processes (local electrochemical dissolution of the metal) become predominant and change the geometry of the crack tip and, consequently, decrease the effective stress concentration in its vicinity [5, 23].

In this case, insignificant changes in the composition of the working corrosive medium imply changes in the cyclic crack resistance diagrams of the steels. In particular, even in the presence of insignificant amounts of hydrazine (N_2H_4) in the base aqueous solution of ammonia, the cyclic crack resistance characteristics of 20 steel and 12Kh1MF steel decrease, in particular, in the near-threshold region (Figs. 4a, b). Here, these diagrams are steeper and the crack growth rate da/dN noticeably increases even for insignificant changes in ΔK .

Similar trends were also observed for 08Kh18N12T high-alloy steel (Fig. 4c). Even for minor impurities in the form of chlorides and nitrates in the base aqueous medium, the cyclic crack resistance characteristics in this steel are noticeably changed. In this case, the most negative influence is observed for chlorine ions, they increase the fatigue crack-growth rate in steel by a factor of about 5–8 and facilitate corrosion processes (local anodic dissolution of the metal), due to which the effective stress concentration at the crack tip decreases [5, 11, 33]. On the other hand, as corrosion is activated and pH value of the medium decreases, the corresponding cathodic processes are accelerated and, as a result, we observe the formation of hydrogen, which facilitates the embrittlement of the material and this, in its turn, intensifies the process of crack propagation [5, 33, 34].

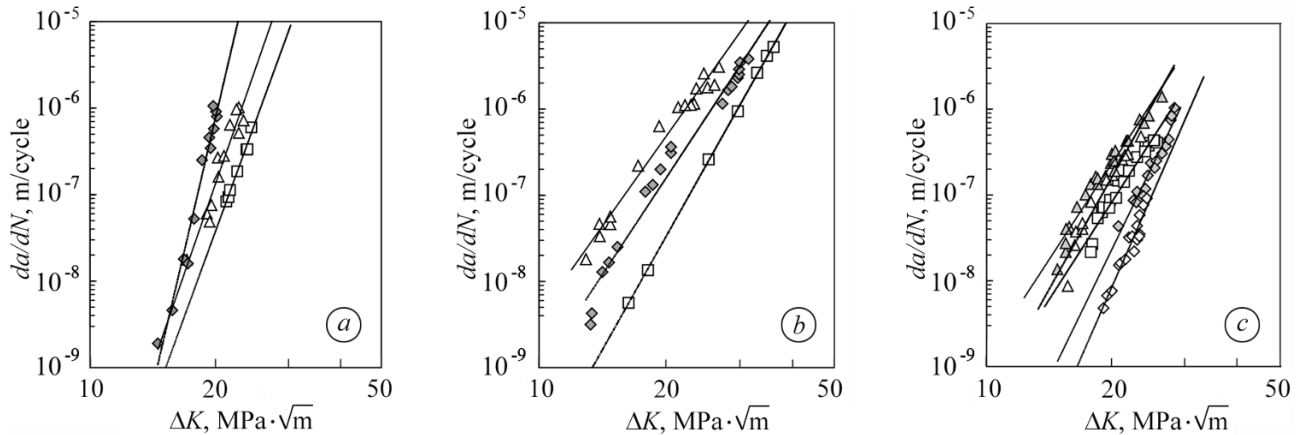


Fig. 5. Influence of the frequency of cyclic loading on the fatigue crack-growth rate in 20 steel (a) and 12Kh1MF steel (b) ($R = 0$, $T = 80^\circ\text{C}$; (\square) $f = 0.017$ Hz; (\triangle) $f = 0.17$ Hz; (\blacklozenge) $f = 1.0$ Hz ($\text{H}_2\text{O} + \text{NH}_3$ to pH 9)) and in 08Kh18N12T steel (c) ($R = 0$, $T = 80^\circ\text{C}$; (\blacklozenge) $f = 0.1$ Hz; (\square) $f = 0.33$ Hz; (\blacktriangle) $f = 1.0$ Hz; (\triangle) $f = 2.0$ Hz; (\diamond) $f = 6.5$ Hz (1% solution of $\text{H}_3\text{BO}_3 + \text{KOH}$ to pH 8 + 10.5 mg/kg KCl)).

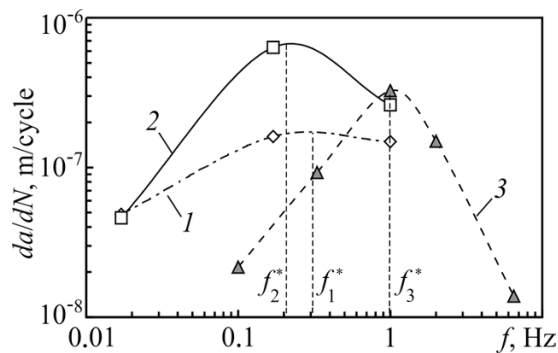


Fig. 6. Dependences of the corrosion-fatigue crack-growth rate on the frequency of cyclic loading ($\Delta K = 20 \text{ MPa}\sqrt{\text{m}}$): (1) 20 steel; (2) 12Kh1MF; (3) 08Kh18N12T.

Influence of the Frequency of Loading Cycles and Stress Ratio on the Growth Rate of Corrosion-Fatigue Cracks. It was established [16, 35] that, for each “material–medium” system, there exists a value $f = f^*$ for which the cyclic corrosion crack resistance of the material reaches its minimal value (Figs. 5–7). This minimum point in the frequency dependence corresponds to a certain ratio between the rates of electrochemical reactions in the vicinity of the crack tip and the formation of a new electrochemically active surface as a result of crack propagation [5–7, 33].

For 20 steel, in the range of loading frequencies 0.017–1.0 Hz, cyclic crack resistance diagrams shift to the region of smaller values of ΔK (Fig. 5a). For 12Kh1MF steel, there also exists an ambiguous dependence of the cyclic crack resistance characteristics on the frequency of loading in this range (Fig. 5b).

For the “material–medium” system at a loading frequency $f^* = 0.17$ Hz, we observe the maximal effect of reduction by the medium (Fig. 6, curve 2). For 08Kh18N12T steel, under the conditions of influence of the water mode of boron control with deviations in chlorides within the range 0.017–6.5 Hz, the extreme frequency is $f^* = 1.0$ Hz. In this case, the crack growth rate is accelerated at the most value, and the characteristics of cyclic crack resistance take its lowest values (Fig. 5c).

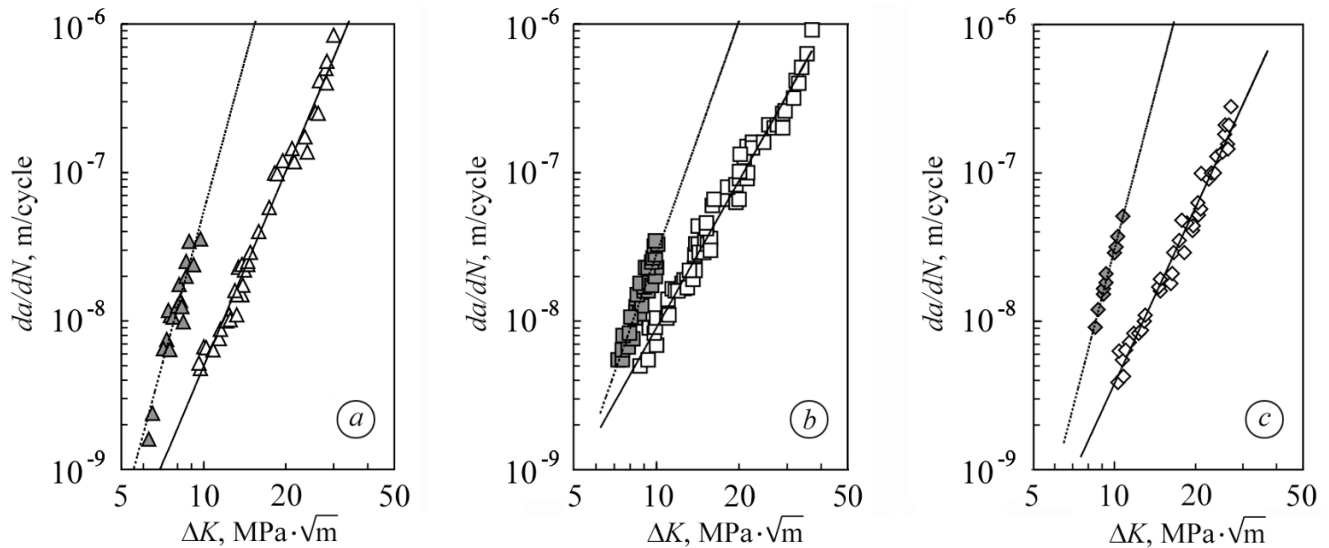


Fig. 7. Influence of the stress ratio on the fatigue crack-growth rate in 20 steel (a), 12Kh1MF steel (b), and 08Kh18N12T steel (c) in air for $f = 0.1$ Hz: (\triangle , \square , \diamond) $R = 0$; (\blacktriangle , \blacksquare , \blacklozenge) 0.7.

The presented values of loading frequencies $f = f^*$ determine extreme testing conditions, i.e., conditions under which we observe the maximal influence of the corrosive medium on the growth of corrosion-fatigue cracks. We have to use these data in order to construct basic diagrams of cyclic corrosion crack resistance.

The influence of the stress ratio on the propagations of fatigue cracks under the action of corrosive working media was studied for 20, 12Kh1MF, and 08Kh18N12T steels [16, 35]. For all these steels, it was established that the characteristics of cyclic corrosion crack resistance decrease substantially as the stress ratio increases from 0 to 0.7, (Fig. 7). In this case, the corresponding diagrams shift to the region of lower values of ΔK and become steeper. Therefore, this parameter should be taken into account when we construct basic diagrams of cyclic corrosion crack resistance of steels (in order to evaluate the service life of structural elements).

Influence of the Time of Operation on the Cyclic Crack Resistance of Steels. In the course of long-term operation, the mechanical, physicochemical, and other properties of structural materials undergo substantial changes. For this reason, it is important in this case to diagnose the actual state of the metal of structural elements [5, 13, 16]. The characteristics of cyclic crack resistance of structural materials are particularly sensitive to such degradation processes [13].

The influence of the time of operation on the corrosion cyclic crack resistance of the metal of feeding pipelines of supercritical-pressure power units of TPP (16GS steel) in high-purity water was investigated in [6].

The comparison of the diagrams of cyclic corrosion crack resistance for the intact metal and metal after operation in the TPP “V” and “L” (Fig. 8) reveal the following facts: All these diagrams are characterized by high steepness (insignificant changes in the parameter ΔK_I correspond to noticeable changes in the velocity da/dN), which is an unfavorable factor if we have to guarantee the strength and long service life of pipelines in terms of crack resistance because random operating overloads can speed up the development of cracklike defects.

It was established that the crack resistances of the tested steels differ significantly. This means the degradation of the initial properties of the metal of pipelines under long-term influence of operating conditions and different degrees of the degradation depending on the specific operating conditions of TPP. This is especially true for metal “L” (Fig. 8, curve 3).

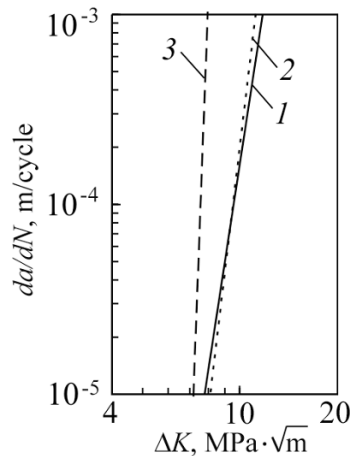


Fig. 8. Diagrams of cyclic crack-growth resistance of the metal of feeding pipelines of power units of TPP (16GS steel) under corrosion in high-purity water: (1) intact metal; (2, 3) metal after operation (145,000 h) from TPP “V” and TPP “L”.

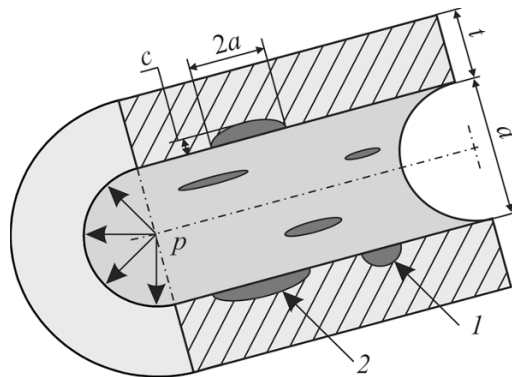


Fig. 9. Schematic diagram of a defect in the pipe wall in the form a semielliptic crack: (1) corrosion pit $(c/a)_i$; (2) corrosion groove $(c/a)_i$.

Thus, to obtain a reliable prediction of the time of safe operation of structural elements of critical objects intended for long-term operation in the presence of cracklike defects, we have to take into account the specific features of the analyzed system and, first of all, the actual state of the metal and changes in its crack resistance characteristics.

Criteria for the Evaluation of Strength and Hazard of Fracture of Structural Elements of Pipelines with Cracklike Defects

The characteristics of cyclic crack-growth resistance of the materials of structural elements provide a base for the numerical evaluation of the strength and service life of pipelines [5, 11, 13, 14]. The corresponding diagrams (namely, the dependences of the growth rate of corrosion-fatigue cracks dc/dN on the SIF ΔK_I at the crack tip) are plotted by using the experimental results obtained by the well-known test methods [5, 11]. These diagrams are located between two limiting values: the lower threshold value ΔK_{th} that corresponds to the value ΔK_I in the case where the corrosion-fatigue crack does not grow, and the upper value ΔK_{fc} that corresponds to the value ΔK_I of the onset of spontaneous (catastrophic) propagation of the crack.

We model cracklike defects in the pipeline wall with thickness t and internal diameter of the pipe d by a semielliptic crack with semiaxes of lengths a and c (Fig. 9). The corresponding values of the SIF ΔK_I at the crack tip are computed by using the well-known dependence [5, 16].

Criterion of Safe Operation in Terms of the Threshold Crack Depth. The stress-corrosion cracklike defects are estimated according to the criterion of threshold depth c_{th} and shape c/a of a semielliptic crack on the basis of their relationship with the threshold values of the SIF ΔK_{th} . This enables us to analyze the potential crack growth in the course of subsequent operation and the level of fracture hazard for the pipeline [8, 9, 15, 24, 36] taking into account the experimental data on the cyclic crack resistance of the material of the pipe and the results of diagnostics of the state of pipeline (i.e., the sizes and shapes of the cracks). Here, the size of the semielliptic crack of fixed shape c/a and depth $c = c_{th}$ at the tip of which the SIF is equal to the threshold value $K_I = K_{th}$ is regarded as threshold. Thus, the condition

$$c \leq c_{th}(\Delta K_{th}), \quad \text{for} \quad \frac{c}{a} = \text{const} \quad (8)$$

serves as a criterion of safe cracklike defect. In other words, all defects with depths $c \leq c_{th}$ detected in the course of diagnostics are believed to be safe because they do not exhibit any potential ability of subsequent development.

Criterion of Safe Operation of a Pipeline in Terms of the Limiting Crack-Growth Rate. In this case, the admissible crack depth c_* is evaluated with an aim to guarantee trouble-free operation of the pipeline between two consecutive scheduled inspections [9, 24, 36]. Here, one can use the criterion of admissible increment of length Δc of the detected cracklike defect of depth c_0 , i.e.,

$$\Delta c \leq \Delta c_*, \quad \text{for} \quad \Delta N = \Delta N_*, \quad (9)$$

where Δc_* is the admissible increment of crack length in depth, ΔN_* is the scheduled number of loading cycles in the course of operation of the pipeline between two scheduled inspections. From the physical point of view, this corresponds to the estimation of a certain maximum growth rate of corrosion-fatigue cracks within a given period of operation of the pipeline $(dc/dN)_*$:

$$\frac{dc}{dN} \leq \left(\frac{dc}{dN} \right)_*. \quad (10)$$

Thus, in particular, if we choose the value $(dc/dN)_* = 10^{-4}$ mm/cycle, then this means that the cracks with depth c_i present in the pipeline may increase their length by at most 1 mm within the next 10,000 loading cycles. The procedure of determination of admissible crack depth c_* in the pipeline wall in the case where the values Δc_* and ΔN_* are known can be described as follows: First, we find the limiting growth rate

$$\left(\frac{dc}{dN} \right)_* = \frac{\Delta c_*}{\Delta N_*}. \quad (11)$$

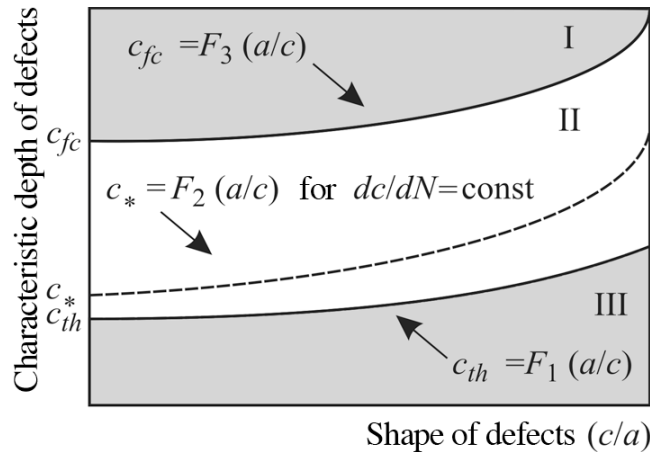


Fig. 10. Schematic diagram for the evaluation of the serviceability and fracture hazard of a pipeline with cracklike defects: (I) brittle fracture zone; (II) operation with predicted fracture hazard; (III) zone of safe operation.

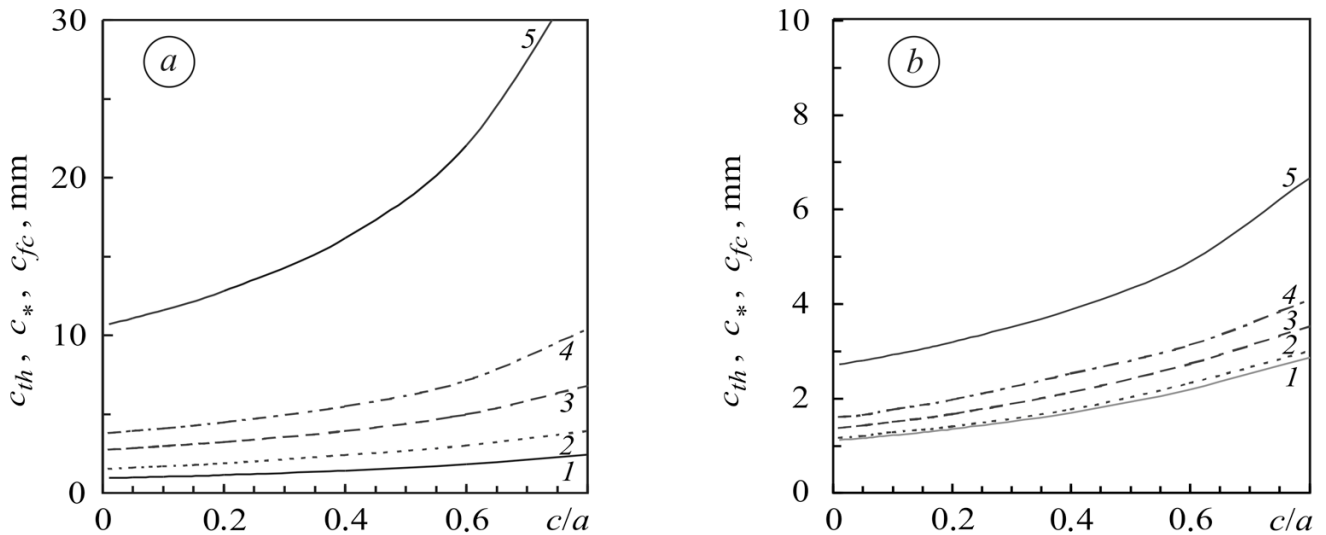


Fig. 11. Diagrams for the evaluation of the serviceability and fracture hazard of a new feeding pipeline of TPP (a) and a pipeline after operation (b) (16GS steel; 526 × 50 mm pipe): (1) c_{th} ; (2–4) c_* ($dc/dN = 10^{-5}$ mm/cycle, 10^{-4} mm/cycle, and 10^{-3} mm/cycle, respectively); (5) c_{fc} .

Further, the diagram of cyclic corrosion crack resistance of the material is used to find the corresponding range of the SIF ΔK_* with the help of which we find the admissible crack depth c_* as a function of the working load acting upon the pipeline, its geometric sizes, and the geometry of the defect according to the formula for the SIF ΔK_I .

In our calculations, we take the following admissible increment of crack length in depth c_i : $\Delta c_* = 1.0$ mm. The value ΔN_* is chosen with regard for the statistical data on the operation of power units at some electric power plants in Ukraine according to which the number of loading cycles per power unit is about several thousands [13].

Evaluation of the Hazard of Catastrophic Brittle Fracture. For this purpose, we use the well-known criterion of brittle fracture [5, 37, 38]:

$$\Delta K_I \leq \Delta K_{fc}, \quad (12)$$

where ΔK_{fc} is cyclic fracture toughness. In this case, the size of the semielliptic crack of fixed shape c/a and depth $c = c_{fc}$ at the tip of which the SIF is equal to the critical value $K_I = K_{fc}$ is regarded as critical. Thus, the condition

$$c = c_{fc}(\Delta K_{fc}) \quad \text{for} \quad \left(\frac{c}{a} \right) = \text{const} \quad (13)$$

serves as the criterion of critical cracklike defect.

All defects detected in the course diagnostic inspection whose depth is close to the value c_{th} are critically dangerous because they are potentially capable of spontaneous propagation, which leads to the catastrophic failure of the pipeline.

Diagram for the Evaluation of the Serviceability and Fracture Hazard of Pipelines with Cracklike Defects. The expert analyses of the hazard of possible failures of pipelines subjected to the action of pulsed pressure of working media can be performed by using the presented criteria.

On the basis of these criteria, for each considered pipeline, we construct special diagrams on the “characteristic values of depth of cracklike defects–shape of the defect” coordinates (Fig. 10) containing three typical zones [8, 9, 24]. First, the zone of safe operation of the pipeline is located under the curve $c_{th} = F_1(a/c)$. This corresponds to the case where the depth of all defects detected in the course of diagnostics is smaller than the threshold value, i.e., $c \leq c_{th}$. These defects are regarded as safe because they do not exhibit any potential ability of subsequent development.

The second zone is the zone of operation with predicted development of the existing cracklike defects. This means that, within a certain scheduled time of operation of the pipeline, the growth of existing cracks at rates that do not exceed a certain established ultimate rate is admitted, i.e., $dc/dN \leq (dc/dN)_{*}$. The values of $(dc/dN)_{*}$ are chosen depending on the requirements and norms of operation of the pipeline and specific operating conditions. These factors are chosen to plot the curve $c_* = F_2(a/c)$. All cracklike defects with depths $c_i \leq c_*$ present in the pipeline develop at rates lower than the ultimate rate and remain conditionally safe in this case.

The third zone is the zone of hazard of brittle fracture and lies above the curve $c_{fc} = F_3(a/c)$. In other words, for all defects with depths $c_i \geq c_{fc}$ detected in the course of diagnostic inspections, the criterion of catastrophic fracture is realized and the operation of the pipeline not allowed.

Thus, in Fig. 11, we present a diagram intended for the evaluation of the serviceability a feeding pipeline of TPP in making expert conclusions concerning the possibility of its subsequent operation. Here, we take into account the following factors: the actual state of the metal, the actual composition of the working medium, the geometric sizes of the element, the specific features of operating loads, and the shape of the cracklike defect. It should also be noted that, in calculations, we can also take into account the type of a section of the pipeline

(rectilinear section–bend) by using the coefficient k_f taking into account the the deviations of the transverse cross-section of the pipe from a circular cross section [8, 13].

CONCLUSIONS

We generalize contemporary methods aimed at the evaluation of strength and fracture hazard of the elements of pipeline structures according to the criteria of fracture mechanics of materials with regard for the specific features of the influence of corrosive factors. The stages of the initial corrosion damage of the metal and surface corrosion-fatigue cracking in pipeline steels are considered. We have discovered the influence of the chemical composition of the medium, frequency of the loading cycles, stress ratio, and the time of operation on the cyclic corrosion crack-growth resistance of pipeline steels. For the expert evaluation of the serviceability and fracture hazard of pipeline systems with cracklike defects, we propose to use special diagrams containing three characteristic zones: the zone of safe operation, the zone of operation with predicted development of cracklike defects, and the zone with significant hazard of brittle fracture.

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