

NUCLEATION AND GROWTH OF CORROSION-FATIGUE CRACKS FROM SEMICIRCULAR NOTCHES

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The initial stages of corrosion fatigue on the surfaces of semicircular notches are studied for the system of low-strength carbon steel and a 3% NaCl solution under different loading and electrochemical conditions on the notch surface. It is shown that the process of electrochemical dissolution of the metal plays the predominant role in the first stages of growth of short corrosion-fatigue crack. We suggest an expression for the prediction of the characteristic density of corrosion-fatigue cracks as a function of the synergistic action of cyclic stresses and parameters of the process of electrochemical dissolution on the notch surface.

Introduction

The structural integrity of equipment operating under the conditions of combined action of mechanical fatigue and corrosion continues to provide a challenge for practical engineers. At present, it is generally accepted that the corrosion fracture of structural materials and alloys includes numerous microscopic processes, which can be described as localized processes of formation and development of crack-like defects from notches of various types [1]. The so-called "notch effect" is well known and the major part of works in this field have been devoted to the investigation of this phenomenon [1, 2]. The attention of many researchers was permanently given to the analysis of various aspects of this problem, which, finally, resulted in the appearance of a new branch of science—notch fracture mechanics—whose main concepts were formulated within the last decade [2].

However, in the available literature, corrosive environments are, as a rule, regarded as independent factors characterized by the testing conditions despite the existing principal difference between the physical and chemical conditions inside different localized objects (including the notches) and on smooth open surfaces [1, 3].

The present work is thus focused on the relationship between the electrochemistry of the deformed notch surface and the processes of nucleation and growth of corrosion fatigue cracks.

Experimental Procedure

For our studies, we used a low-strength carbon steel (with monotonic uniaxial yield stress $\sigma_{YS} = 270$ MPa). The nominal chemical composition of this type of steel is as follows (in wt.%): C = 0.17–0.24, Si = 0.17–0.37, Mn = 0.35–0.65, Cr < 0.25, Ni < 0.25, Cu < 0.25, S < 0.04, P < 0.04, As < 0.08, balance Fe. A 3% aqueous solution of NaCl at ambient temperature was used as a corrosive environment. This material–environment system is a typical corrosion-active system for which the processes of dissolution of a metal play the predominant role [4].

Parallel electrochemical and mechanical studies were carried out under the conditions of fatigue loading. The schematic diagram of the tests is presented in Fig. 1a. We used beam specimens with semicircular notches. For the geometry of the specimens, see Fig. 1b.

The electrochemical tests were carried out according to the standard polarization procedure from [1, 4] and the notch cavity was used as a corrosion minicell (see Fig. 1a). The solution was open to the atmosphere and stagnant. The reference and auxiliary electrodes were connected with the minicell via special electrolytic capillaries [3, 5].

The corrosion fatigue tests were carried out at a loading frequency f of 1.0 Hz, for the stress ratio $R = 0$ and two different levels of the stress amplitude σ_a , namely $\sigma_a = 159.8$ MPa and $\sigma_a = 127.8$ MPa.

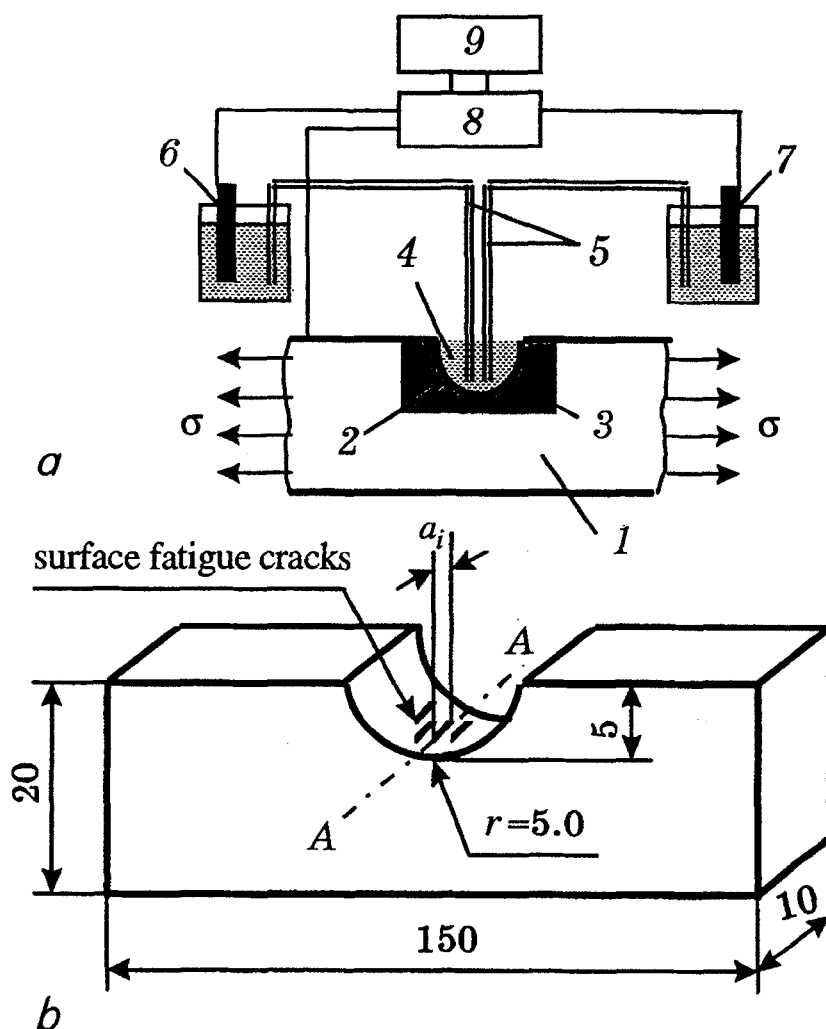


Fig. 1. Schematic diagram of the tests (a) and the geometry of specimens (b): (1) specimen, (2) semicircular notch, (3) protective film, (4) corrosive environment, (5) electrolytic capillaries, (6) reference electrode, (7) auxiliary electrode, (8) potentiostat, (9) X-Y recorder.

These levels correspond to the following two stressed states at the bottom of the notch:

$$\frac{\sigma_{\max}}{\sigma_{YS}} = 1.0 \quad \text{and} \quad \frac{\sigma_{\max}}{\sigma_{YS}} = 0.8,$$

where $\sigma_{\max} = K_{\sigma} \sigma_{\sigma}$ is the maximum stress at the bottom of the notch and $K_{\sigma} = 1.69$ is the stress concentration factor.

The constancy of electrochemical conditions on the notch surface was guaranteed by a constant value of the electrode potential and by periodic replacements of the solution in the notch cavity. The tests were carried out for three different values of the polarization potential $E = \text{const}$, namely, $E = -400$ mV, $E = -600$ mV, and $E = -800$ mV corresponding to the following characteristic cases: the active dissolution of the metal from the notch surface, the conditions formed for potentials close to the corrosion potential, and the conditions of hydrogen release from the notch surface.

For each tested specimen, the notch surface was periodically observed (Fig. 1b) and the corresponding images were fixed by using the technique of plastic replication [6]. A system used to measure the surface crack length a_i for given replicas included a microscope, an attached TV camera, and a personal computer equipped with a special software system for the analysis of images.

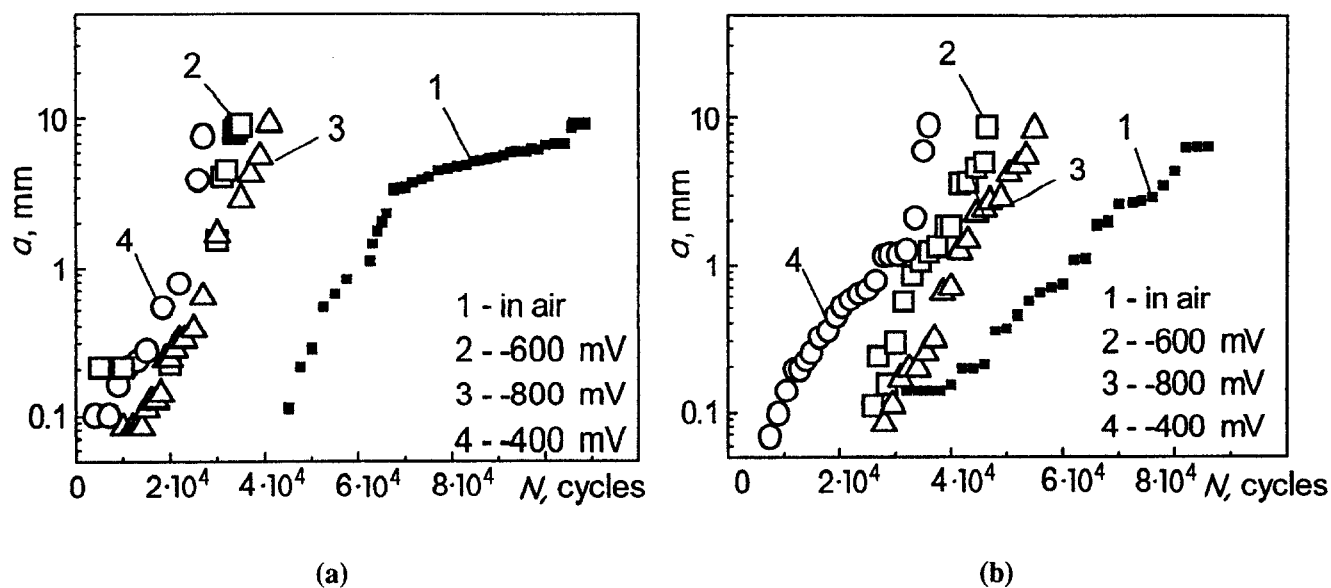


Fig. 2. Crack length vs. the number of loading cycles under different testing conditions for two levels of the stress amplitude: (a) $\sigma_a = 159.8$ MPa, (b) $\sigma_a = 127.8$ MPa.

Table 1. Parameters of Corrosion-Fatigue Crack Nucleation and Growth under Different Electrochemical Conditions

Stress amplitude σ_a , MPa	E , mV	Stage I					Stage II
		a^* , mm	N_i , cycles	N_* , cycles	q_i , cracks/mm ²	q^* , cracks/mm ²	$(da/dN)^*$, mm/cycle
158.8	-400	0.14	2000	6000	0.015	0.90	$1.15 \cdot 10^{-5}$
	-600	0.20	4000	14,000	0.045	0.83	$3.85 \cdot 10^{-5}$
	-800	0.20	10,000	15,000	0.039	0.72	$3.46 \cdot 10^{-5}$
	air	0.20	40,000	52,000	0.023	0.38	$7.20 \cdot 10^{-5}$
127.8	-400	0.17	7000	20,000	0.018	4.56	$2.38 \cdot 10^{-5}$
	-600	0.20	24,000	29,000	0.085	0.47	$4.82 \cdot 10^{-5}$
	-800	0.18	28,000	37,000	0.070	0.74	$3.45 \cdot 10^{-5}$
	air	0.21	42,000	56,000	0.029	0.44	$6.04 \cdot 10^{-5}$

Results and Discussion

Nucleation and Growth of Corrosion Fatigue Cracks

By using special observations based on the technique of plastic replication, we plotted the dependences of the

surface crack length a on the number of loading cycles N for various testing conditions (Fig. 2). These plots were compared with the data obtained in air (curves 1a and 1b) to show the influence of environments on the fatigue process. We also showed that the processes of nucleation and growth of corrosion-fatigue cracks drastically accelerate under the conditions of active metal dissolution ($E = -400$ mV).

Let us now give a general description the investigated processes (see Table 1). In each test, after a certain number of loading cycles N_i , we observe the initiation of short cracks. This stage is characterized by low values of the density of cracks q_i on the notch surface and the cracks are mainly located along the line of maximum stress concentration. In this case, the average crack length a_* varies within the range 0.1–0.21 mm [12]. The main observation that can be made by using the plots in Fig. 2 is a delay of crack growth for a certain value a_* of the length of surface cracks characterized by the duration $N_i \leq N \leq N_*$. Within this period, the density of surface cracks increases to a certain maximum value q_* . For $N \geq N_*$, the process of crack growth is stable. It can be characterized by a certain average crack growth rate (da/dN). The numerical values of this crack growth rate are presented in Table 1 for all testing conditions. Finally, a macrocrack is formed across the specimen thickness and this process is realized as a result of both growth and coalescence of cracks.

The data presented above enable us to conclude that the process of formation of a corrosion-fatigue macrocrack consists of the following two main stages: Stage I is a continuous process of initiation, growth, and deceleration of numerous small cracks of a certain fixed characteristic size a_* . This process is terminated as soon as the critical density of cracks q_* is attained. Stage II is a process of stable crack growth and coalescence resulting in the formation of a macrocrack at the bottom of the notch.

Electrochemical Conditions and the State of the Metal Surface in Notches Subjected to Corrosion Fatigue

The notch surface was electrochemically detected in each test. For this purpose the corresponding potentiodynamic polarization curves were recorded for the notch surface as functions of the number of loading cycles [7, 8]. This experimental procedure makes it possible to compare the electrochemical states of the notch surface in different stages of the corrosion-fatigue process by analyzing the following parameters: the corrosion potential E_{cor} , the density of the corrosion current i_{cor} , and the anodic Tafel coefficient b_a (see Fig. 3).

Despite some natural scatter, the behavior of these parameters can always be represented as the following series of consecutive events:

The first period of evolution of the monitored parameters is characterized by their stable values and is very short as compared with the time of formation of the macrocrack. This period corresponds to low levels of corrosion damage to the notch surface. The salient feature of the second period is a shift of the corrosion potential E_{cor} in the negative direction and an increase in the densities of corrosion currents i_{cor} . It results in the formation of visible fresh (nonoxidized) surfaces, which leads to the beginning of the corrosion-fatigue process. In this case, the mechanism of electrochemical dissolution of the metal differs from that observed in the first period, thus demonstrating a decrease in the anodic Tafel coefficient b_a . It is worth noting that the indicated distinctive features are especially pronounced if the tests are performed at $E = -400$ mV. The last step is characterized by a significant increase in the densities of corrosion currents i_{cor} for constant values of the parameters E_{cor} and b_a . The dissolution of the metal on the notch surface obeys the same electrochemical mechanism [9]. The accumulated data enables us to conclude that the minimum intensity of i_{cor} in the second step coincides with the delay of crack growth recorded in monitoring the process of crack growth. The process of intense crack growth is also accompanied by a significant increase in i_{cor} . This observation means that there exists a relationship between the behavior of corrosion-fatigue crack initiation and growth and the electrochemical state of the deformed notch surface. This is also confirmed by the images of the notch surfaces corresponding to different electrochemical testing conditions and different stages of the corrosion-fatigue process (see Fig. 4). As follows from these pictures, for the potential $E = -400$ mV, the notch surfaces are more damaged than at $E = -600$ mV [10]. The same tendency is observed for both Stage I and Stage II, i.e., the presented data show that the process of anodic dissolution of the metal plays the determining role in the early stages of corrosion-fatigue crack growth from the notch surface.

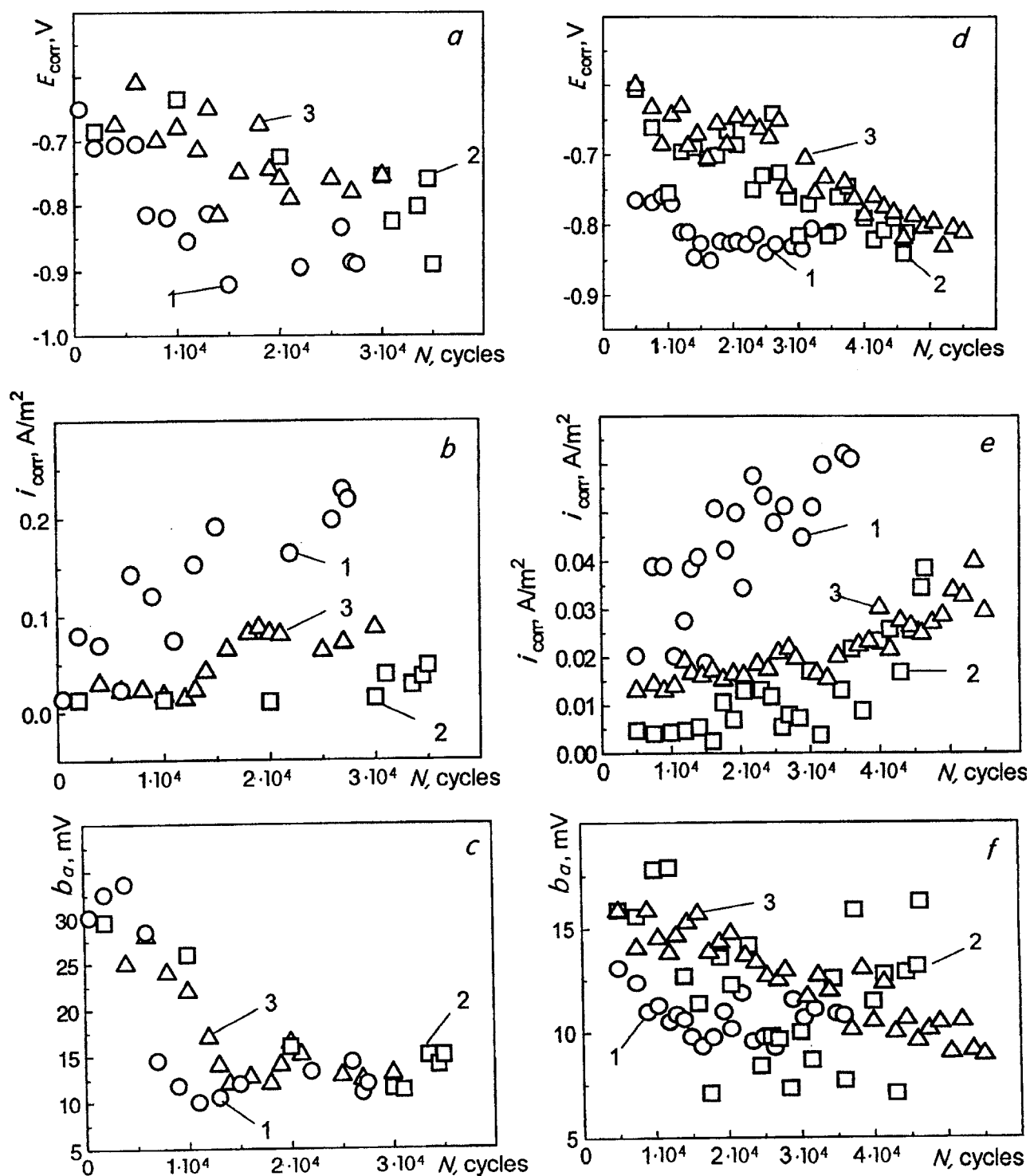


Fig. 3. Corrosion potential E_{cor} (a, d), the density of the corrosion current i_{cor} (b, e), and the anodic Tafel coefficient b_a (c, f) for the damaged notch surface under various electrochemical conditions: $E = -400$ mV (1), $E = -600$ mV (2), and $E = -800$ mV (3), as functions of the number of loading cycles for two levels of the stress amplitude: $\sigma_a = 159.8$ MPa (a–c) and $\sigma_a = 127.8$ MPa (d–f).

General Features of the Formation of a Corrosion-Fatigue Macrocrack at the Bottom of the Notch

On the basis of the analysis of the accumulated data, we can formulate the following general features of the process of formation of a corrosion-fatigue macrocrack at the bottom of the notch:

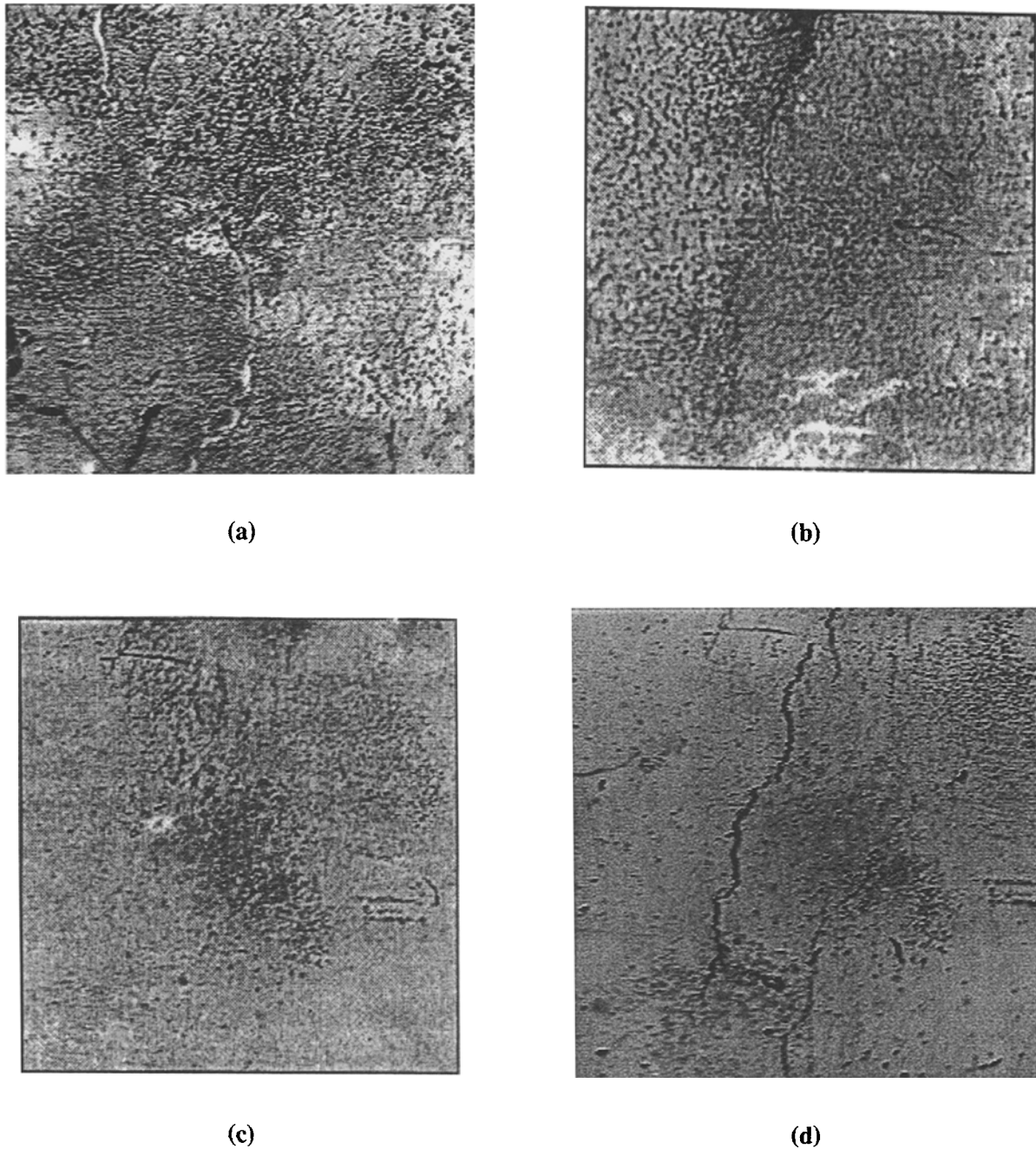


Fig. 4. Corrosion fatigue on the surface of a semicircular notch for $\sigma_a = 159.8$ MPa under different electrochemical conditions: $E = -400$ mV (a, b) and $E = -600$ mV (c, d); (a, c) Stage I, (b, d) Stage II.

The process of macrocrack formation is originated by corrosion damage to the notch surface resulting in the initiation of solitary cracks of characteristic length a_* ($N \leq N_i$). The next period is characterized by an increase in the crack density from q_i to a certain critical value q_* ($N_i \leq N \leq N_*$). As soon as the critical crack density on the notch surface is attained ($N \geq N_*$), we observe the intense process of crack growth and coalescence, which finally leads to the formation of a macrocrack at the bottom of the notch across the specimen thickness ($N = N_c$).

For the estimation of the relative durations of the stages of macrocrack formation at the notch bottom, we plotted the dependences of the number of loading cycles N for tested specimens on the ratio N/N_c (see Fig. 5). It follows from these plots that Stage I covers about 60% of the total period of macrocrack initiation and Stage II covers about 40%. Note that this proportion is approximately true for both types of electrochemical testing conditions.

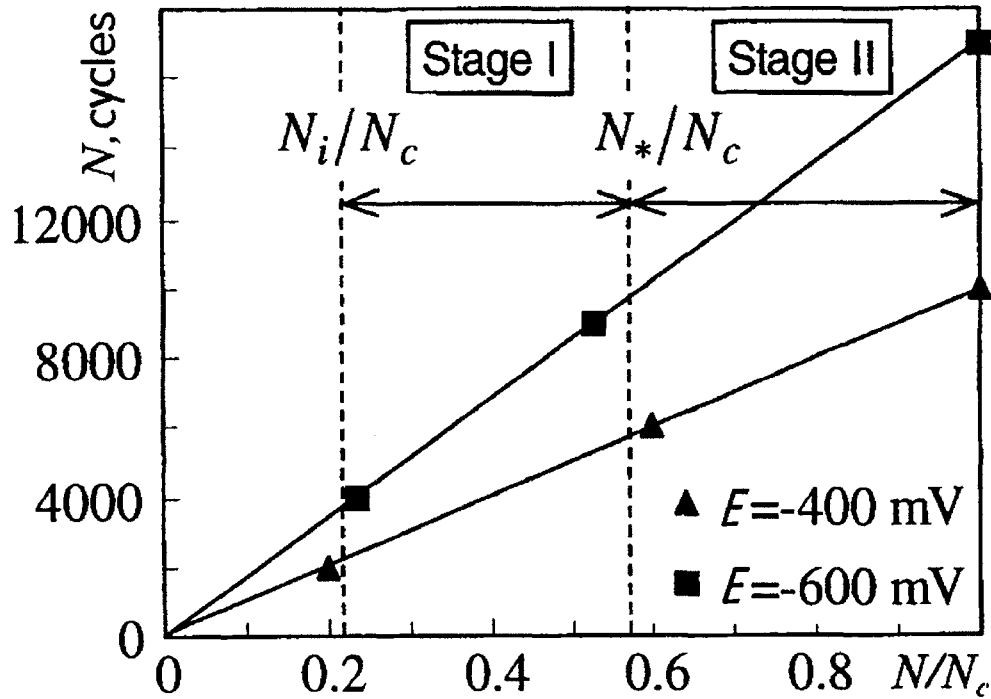


Fig. 5. Dependences of the number of loading cycles N for tested specimens on the ratio N/N_c .

Prediction of the Number of Loading Cycles N_* Required for the Formation of the Surface Crack Density q_*

The relationship between the processes of growth of short corrosion-fatigue cracks and electrochemical dissolution of the deformed surface under the conditions of cyclic torsion was established in [6, 11, 12] on the basis of the data of extensive investigations of "carbon steel-artificial seawater" systems. These data showed that the phenomenon of deceleration of short corrosion-fatigue cracks is observed for cracks of almost the same length a_* . This length may be regarded as a spacing factor for major microstructural barriers d present in the material.

These results made it possible to suggest an experimental-data-based criterion of the formation of short corrosion fatigue cracks of length $a_* = d$ associated with the spacing of major microstructural barriers [12]. This criterion is a function of both cyclic stresses and the parameters of anodic dissolution of the metal and can be used for the description of the experimental data presented above.

The indicated criterion is applicable to the cases under consideration, i.e., to the prediction of the number of loading cycles N_* for which the required surface crack density q_* is attained. In view of the relationship between shear and tensile stresses, the criterion developed in [12] can be rewritten in the following modified way:

$$(\sigma_a)^m \left[\frac{M}{zF\rho} \left(\frac{1}{\omega} \right) \int_0^{N_*} i(N) dN \right] = C_0 = \text{const}, \quad (1)$$

where σ_a is the amplitude of tensile stresses, m and C_0 are constants depending on the material-environment system and the mode of cyclic loading, M is the molecular weight of the metal, z is the number of electrons released in the process of anodic dissolution of the metal, F is Faraday's constant, ρ is the density of the metal, ω is a cyclic frequency, i is the current density of dissolution of the metal, N_* is the number of cycles corresponding to the formation of the surface crack density q_* .

We assume that, in the considered cases, the corrosion-current density is constant, i.e., $i = i_{\text{cor}} = \text{const}$. This enables us to rewrite Eq. (1) in the form

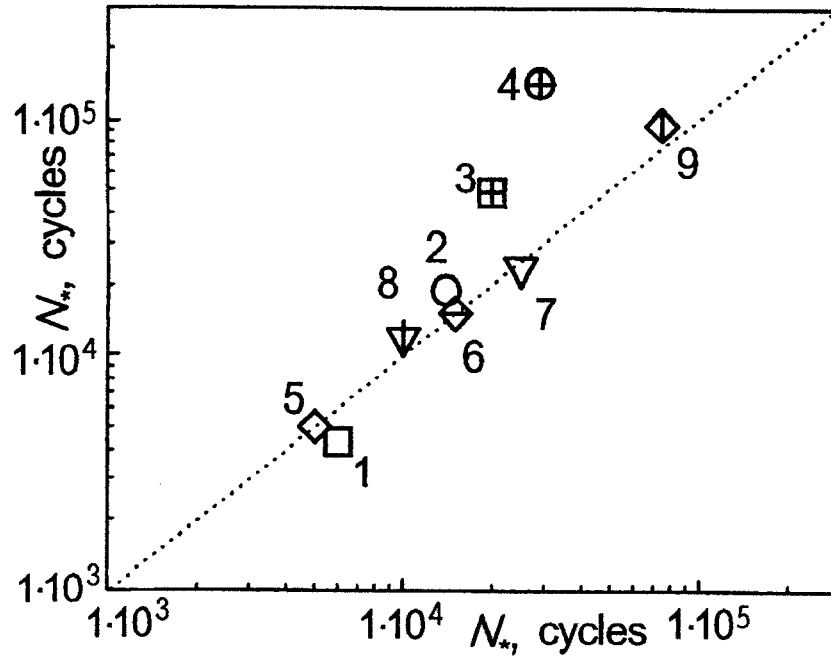


Fig. 6. Comparison of the experimental and predicted values of N_* for different combinations of the amplitudes of tensile or shear stresses and corrosion-current densities: (1) $\sigma_a = 160$ MPa, $i = 0.082$ A/m², (2) $\sigma_a = 160$ MPa, $i = 0.031$ A/m², (3) $\sigma_a = 160$ MPa, $i = 0.042$ A/m², (4) $\sigma_a = 160$ MPa, $i = 0.012$ A/m², (5) $\tau_a = 180$ MPa, $i = 0.410$ A/m², (6) $\tau_a = 180$ MPa, $i = 0.135$ A/m², (7) $\tau_a = 140$ MPa, $i = 0.410$ A/m², (8) $\tau_a = 140$ MPa, $i = 0.820$ A/m², (9) $\tau_a = 100$ MPa, $i = 0.820$ A/m². The data corresponding to (5)–(9) were taken from [12].

$$(\sigma_a)^m \left[\frac{M}{zF\rho} \left(\frac{1}{\omega} \right) i_{\text{cor}} N \right] = C_0 = \text{const.} \quad (2)$$

For a given stress amplitude σ_a and corrosion-current density i , the number of loading cycles $N = N_*$ can be found by using Eq. (2) as follows:

$$N_* = \frac{zF\rho}{Mi_{\text{cor}}} \omega \frac{C_0}{(\sigma_a)^m}. \quad (3)$$

For the considered material–environment system, the constants in relation (3) are as follows:

$$m = 6.19, \quad C_0 = 2.99 \cdot 10^7 \text{ m} \cdot (\text{MPa})^m, \quad \omega = 1.0 \text{ Hz}, \quad M = 56 \cdot 10^{-3} \text{ kg/mole},$$

$$z = 2, \quad F = 9.65 \cdot 10^4 \text{ Cl/mole}, \quad \text{and} \quad \rho = 7.8 \cdot 10^3 \text{ kg/m}^3.$$

By using relation (3), we determined the values of parameter N_* . The comparison of the experimental and predicted values of N_* presented in Table 2 for the analyzed electrochemical testing conditions reveals their acceptable agreement.

To summarize the arguments presented above, the experimental and predicted values of N_* for different combinations of the amplitudes of tensile or shear stress and corrosion-current densities were compared for various systems of low-strength carbon steel and corrosive environments (Fig. 6). For this purpose, we used the additional data from [12]. The generalized plot in Fig. 6 demonstrates that the agreement between the experimental and predicted values of N_* for different considered cases is satisfactory, which proves the validity of the suggested approach.

Table 2. Experimental and Predicted Values of N_* for Different Electrochemical Conditions

Stress amplitude σ_a , MPa	Potential on the notch surface E , mV	Corrosion-current density i_{cor} , A/m ²	Experimental values of N_* , cycles	Predicted values of N_* , cycles
159.8	−400	0.166	6000	4313
	−600	0.038	14,000	18,842
127.8	−400	0.058	20,000	49,140
	−600	0.020	29,000	42,507

CONCLUSIONS

The results obtained in the present work reveal the general features of corrosion-fracture processes on the surfaces of semicircular notches, including both the electrochemical and fatigue aspects of crack-growth behavior.

1. The process of formation of a corrosion-fatigue macrocrack on the notch surface consists of two main stages. Stage I is a continuous process of initiation, growth, and deceleration of small cracks of a certain fixed characteristic size a_* terminated as soon as the crack density attains its critical value q_* . Stage II is a process of stable growth and coalescence of cracks leading to the appearance of the macrocrack.

2. A criterion of the formation of short corrosion-fatigue cracks of characteristic length a_* associated with the spacing of major microstructural barriers is proposed for the considered cases. This criterion is based on the experimental data and depends both on cyclic stresses and on the parameters governing the process of anodic dissolution of the metal on cyclically deformed surfaces.

3. We suggest an expression aimed at the prediction of the formation of the characteristic density q_* of corrosion-fatigue cracks of size a_* on the notch surface taking into account the synergistic action of cyclic stresses and the corrosion process. The validity of this relation is established by comparing the experimental data with the data of numerical calculations.

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