DETERMINATION AND PREDICTION OF CORROSION FATIGUE CRACKS NUCLEATION FROM SURFACE OF A SEMICIRCULAR NOTCHES

V.V. Panasyuk* and I.M. Dmytrakh*

Corrosion fatigue cracks nucleation and growth behaviour are considered with take into account of an electrochemical conditions and state of metal surface in the semicircular notches for system "low strength carbon steel - 3% NaCl solution". It has been shown, that a process of metal electrochemical dissolution plays an determining role in first stages of the short corrosion fatigue crack growth behaviour. An experimental based criteria, involving the development of the short corrosion fatigue cracks, of characteristic size d, which is associated with the spacing of the major microstructural barrier is adopted for considered cases. An expression predicting the formation on notch surface the characteristic density of corrosion fatigue cracks is presented which takes into account the synergistic action of cyclic stress and the corrosion process.

INTRODUCTION

Already so-called "notch effect" is well-known and the vast majority of investigations were devoted of this phenomenon (1, 2). However in prevailing numbers of studies the corrosive environment is accepted as independent factor which characterizes of the testing conditions despite on existing principal distinguishing between physical and chemical conditions in different localized objects (including the notches) and on smooth open metal surface (2- 4).

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

EXPERIMENTAL PROCEDURE

For presented studies the low strength carbon steel (yield stress for tension $\sigma_{YS} = 270MPa$) was used. This material have the next chemical composition (in weight %): 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; remainder Fe. The 3%NaCl aqueous solution under ambient temperature was taken as a corrosive environment. A simultaneous electrochemical and mechanical studies were conducted under static and fatigue loading conditions.

*Karpenko Physico-Mechanical Institute of National Acad. of Sci., Lviv , Ukraine,

The principal scheme of tests is shown in Figure 1a. The beam specimens with the semicircular notch were used (5). The specimen geometry is given in Fig. 1b. An electrochemical tests were carried out according to a standard polarisation procedures and notch cavity was used as corrosion minicell (see Fig. 1a) Here solution was open to atmosphere and was stagnant. Reference and auxiliary electrodes were connected to the minicell using special electrolytic capillaries (2, 6).

The first electrochemical tests were carried out using specimens deformed under a static load. For these tests the stress level was changed from $\sigma_{\max}/\sigma_{YS} = 0$ to $\sigma_{\max}/\sigma_{YS} = 1.2$. Here $\sigma_{\max} = K_\sigma \cdot \sigma$ is maximum stress at the notch bottom, where K_σ is a stress concentration factor and σ is a nominal applied stress. Corrosion fatigue tests were carried out under constant mechanical conditions, namely frequency of loading $f = 1.0Hz$; stress ratio $R = 0$; and stress amplitude $\sigma_a = \sigma_{YS}/K_\sigma$. The constant electrochemical conditions on the notch surface were provided by a constant value of the electrode potential and by a periodic replacing of a solution from a notch cavity. For each tested specimen the notch surface was periodically observed (Figure 1b) and its corresponding images were fixed using a plastic replication technique (7). The system used for measurement of surface crack length a_i from replicas involved a microscope with an attached television camera and a PC coupled to an image analysis software system.

RESULTS AND DISCUSSION

Previously, an electrochemical tests were carried out for comparison of an electrochemical metal dissolution in notches and on open smooth deformed surface. The received results showed that under transition from smooth surface to notch and then to notch with small crack-like defect, the intensifying of metal dissolution process is occurred. In particular, it can be seen in Figure 2 where the corresponding trends of corrosion current density i_{corr} are presented as function of a ratio $\sigma_{\max}/\sigma_{YS}$. Also these data show on acceleration of metal dissolution process with increasing of a stress level and also that a highest intensity of this process is observed when a local plastic deformations are present on the metal surface.

Based on above electrochemical studies, the cyclic stress amplitude σ_a for the corrosion fatigue tests is determined as $\sigma_a = \sigma_{YS}/K_\sigma = 159.8MPa$, (where $K_\sigma = 1.69$) that corresponds to occurring on the notch surface the local plastic deformations. Two series of tests were carried out for two different polarisation potentials $E = const.$, namely, $E = -400mV$ and $E = -600mV$, that respectively correspond to two characteristic cases: an active metal dissolution from notch surface and potential corrosion conditions. Such testing conditions were chosen to maximize the metal dissolution process which influences the early stages of corrosion fatigue crack growth in carbon steels (8, 9).

Surface crack length a versus number cycles of loading N for given polarisation potentials is shown in Figure 3 and the some characteristic parameters of studied processes are given in TABLE 2. The received data reflect the next main tendencies. For each considered case after the number cycles of loading N_i the short cracks initiation are occurred. This stage is characterized by low meanings of a cracks density q_i on the notch surface and cracks are mainly located along the line of the maximum stress concentration. Here the average crack lengths a_* are between 0.1-0.2mm.

TABLE 1 - Parameters of corrosion fatigue cracks nucleation and growth under different electrochemical conditions.

	Stage I					Stage II
E, mV	a_*, mm	N_i, $cycles$	N_*, $cycles$	q_i, $cracks/mm^2$	q_*, $cracks/mm^2$	$(da/dN)_*$, $mm/cycle$
-400	0.14	2000	6000	0.046	0.216	$9.60 \cdot 10^{-3}$
-600	0.20	4000	9000	0.041	0.262	$2.55 \cdot 10^{-4}$

The main observation to be made from these plots is the delay of crack growth around the surface crack length a_*, and which have a duration $N_i \leq N \leq N_*$. This period is characterized by increasing of the surface cracks density to some extreme value q_* (see TABLE 1). Under $N \geq N_*$ the stable crack growth process is occurred. It may be determined by a some average crack growth rate $(da/dN)_*$. The numerical values of this crack growth rate are given in TABLE 1 for each testing conditions. Finally the macrocrack is created across specimen thickness and this process is realized through both cracks growth and their coalescence.

As summary of above data, it may be concluded, that process of a corrosion fatigue macrocrack creating consist of two main stages. Stage I is the continuous process of initiation, growth and deceleration of a lot small cracks of some constant characteristic size a_* until their critical density q_* is achieved. Stage II is the process of the stable cracks growth and coalescence, that lead to macrocrack creating on the notch bottom. It has been estimated that Stage I has about 60% in total duration of macrocrack creation and Stage II - about 40% and this trend is approximately the same for both electrochemical testing conditions.

During each test the notch surface has been electrochemically detected using a standard polarisation procedure. This detection showed that a relationship exists between corrosion fatigue crack initiation and growth behaviour and the electrochemical state of a deformed notch surface. It also was confirmed by images of notch surfaces, which correspond both different electrochemical testing conditions and different stages of corrosion fatigue process. These data gave the base for conclusion that a process of metal anodic dissolution plays an determining role in early stages of the corrosion fatigue crack growth behaviour from the notch surface.

Besides that given results opened the possibility to predict the number of loading cycles N_* which corresponds to the formation of corrosion fatigue cracks density q_* on the notch surface from both fatigue and corrosion positions. Recently on the base of wide studies for systems "carbon steel-artificial sea water" the experimental data based criteria for the formation of a short corrosion fatigue cracks of size $a_* = d$, which is associated with the spacing of major microstructural barriers has been proposed. (10). This criteria is a function of both cyclic stress and the parameters of anodic metal dissolution and it has been adopted for description of presented above experimental data. Accounting the relationship between shear and tensile stress, the developed criteria (10) may be rewritten in next modified view:

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

where σ_a is the tensile stress amplitude; m and C_0 are the constants, that depend on system "material- environment" and mode of cyclic loading; M is molecular weight of metal; z is the number electrons, released during anodic metal dissolution; F is Faradays constant; ρ is metal density; ω is the cyclic frequency; i is metal dissolution current density; N_*, is the number of cycles which corresponds to the formation of corrosion fatigue cracks density q_* on the notch surface.

For constant corrosion current density conditions $i = i_{corr} = const.$, the equation (1) is presented as

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

From equation (2) for a given stress amplitude σ_a and corrosion current density i_{corr}, the number of loading cycles $N = N_*$ may be calculated:

$$N_* = \frac{zF\rho}{Mi_{corr}} \omega \frac{C_0}{(\sigma_a)^m} \tag{3}$$

The constants in equation (3) for the given "material-environment" system are next: $m = 6.19$; $C_0 = 2.99 \cdot 10^7 m \cdot (MPa)^m$; $\omega = 1.0 Hz$; $M = 56 \cdot 10^{-3} kg/mol$; $z = 2$; $F = 9.65 \cdot 10^4 Cl/mol$; $\rho = 7.8 \cdot 10^3 kg/m^3$.

TABLE 2. - Experimental and predicted values of N_* for different electrochemical conditions.

Potential on notch surface E, mV	Corrosion current density, $i_{corr}, A/m^2$	Experimental value $N_*, cycles$	Predicted value $N_*, cycles$
-400	0.122	6000	5820
-600	0.086	9000	8256

Using the expression (3) the values of parameter N_* were calculated. It can be seen from TABLE 2, that comparison an experimental and predicted values of N_* for considered electrochemical testing conditions show on their good correlation. It confirms the validity of presented approach for carbon steels.

CONCLUSIONS

The results received in this study, reflect the generalized features of corrosion fracture processes from the surface of a semicircular notches including both an electrochemical and fatigue cracks growth behaviour aspects. Comparison of an electrochemical metal dissolution in notches and on open smooth deformed surface is considered and corresponding electrochemical mechanisms are identified. It has been shown that under transition from smooth surface to notch and then to notch with crack-like defect, the significant intensifying of metal dissolution process is occurred.

The process of a corrosion fatigue macrocrack creating on notch surface consist of two main stages. Stage I is the continuous process of initiation, growth and deceleration of a lot small cracks of some constant characteristic size a_* until their critical density q_* is achieved. Stage II is the process of the stable cracks growth and coalescence, that lead to macrocrack creating.

An expression predicting the formation on notch surface the characteristic density of corrosion fatigue cracks of size a_* is derived which takes into account the synergistic action of cyclic stress and the corrosion process. This relationship was confirmed by comparison of experimental and calculated data.

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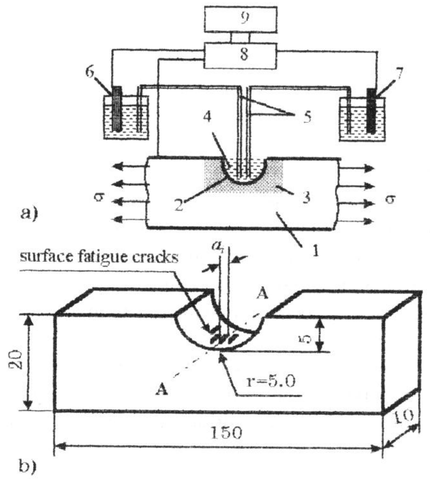

Figure 1 Principal scheme of tests (a) and specimen geometry (b): 1 - specimen; 2 - semicircular notch; 3 - protective film; 4 - corrosive environment; 5 - electrolytic capillaries; 6 - reference electrode; 7 - auxiliary electrode; 8 - potentiostat; 9 - XY recorder.

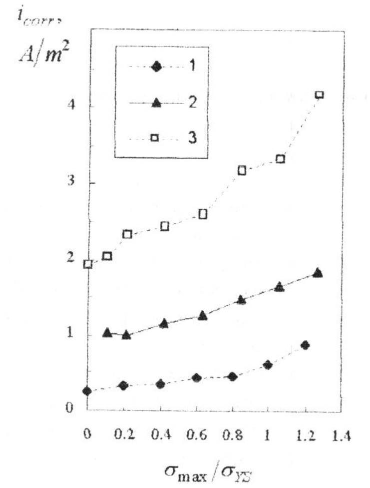

Figure 2 Dependencies of corrosion current density i_{corr} on the ratio σ_{max}/σ_{YS} for the studied cases: 1 - smooth surface; 2 - semicircular notch; 3 - semicircular notch with crack-like defect ($a \approx 0.5mm$).

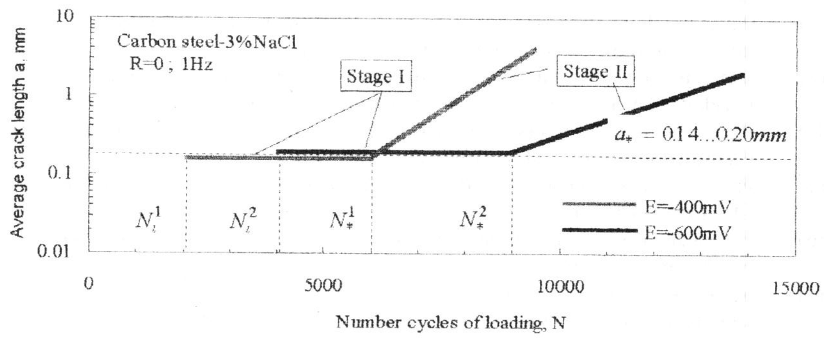

Figure 3 Average crack length versus number cycles of loading under different electrochemical conditions on the notch surface.