Model of Surface Fatigue Crack Nucleation as Result of Corrosion Deformation Interactions

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ABSTRACT: *The given work is focused on initial stages of corrosion fatigue and model of surface fatigue crack nucleation as result of corrosion deformation interactions is proposed. As result the criterion of surface corrosion fatigue crack nucleation that relates the number of loading cycles N, for crack initiation, maximum corrosion current per loading cycle* I_{corr} *, constants of electrochemical dissolution of metal surface and the characteristic stress* s_S *is derived. On the base of this criterion the expression for prediction of the number of loading cycles N, for surface corrosion fatigue crack initiation is received and which was verified by experimental data for considered electrochemical testing conditions.*

INTRODUCTION

Nowadays it is clearly that under certain circumstances corrosion fatigue lifetime may be controlled by the development and propagation of y small surface defects. Therefore the knowledge of initial stages of given processes become significantly is important for prediction of total durability of structure components under operating conditions [1].

Recently [2] in framework of this problem the specificity of electrochemical state variables of metal surface under cyclic deforming and the initial stages of corrosion fatigue was highlighted. As it has been shown that within each cycle of loading there is the some characteristic value of applied stress $s = s_S$, beginning from which the significant electrochemical activation of deformed surface is observed.

In presented work, on the ground of the mentioned results and expanded experimental studies the model of surface fatigue crack nucleation as result of corrosion deformation interactions has been developed and verified.

EXPERIMENTAL RESULTS AND THEIR ALALYSIS

Test programme for simultaneous electrochemical and mechanical studies of corrosion fatigue emanating from smooth surface was realised on the base of system “stainless steel - salt water”. The nominal chemical composition of material ($R_e = 250\,MPa$) was next (in weight percentage): C=0.08; Cr=18; Ni=12; Ti<1; remainder Fe. The 3% NaCl aqueous solution under ambient temperature was taken as a corrosion environment with the small admixtures of *HCl* and *NaOH* for achieving of different values of *pH*, namely 3.0; 6.5 and 9.0.

The specimens were tested under sinusoidal cyclic bending with constant stress range $s_{max} = R_e$ at frequency $\omega = 0.1 Hz$ and stress ratio $R=0$. During tests the constant electrochemical conditions within corrosion cell were provided by a constant value of the electrode potential of the specimens and by periodic replacing of the used corrosion solution on fresh for maintaining the constant *pH* value. The surfaces of specimens were periodically detected and their images were recorded using a method of plastic replication. Other details of given experimental technique can be found in works [2, 3].

During of each test the next parameters were recorded with respect to number cycles of loading *N*: surface crack length *a*; characteristic value of applied stress $s = s_S$ and maximum corrosion current per cycle of loading I_{corr}.

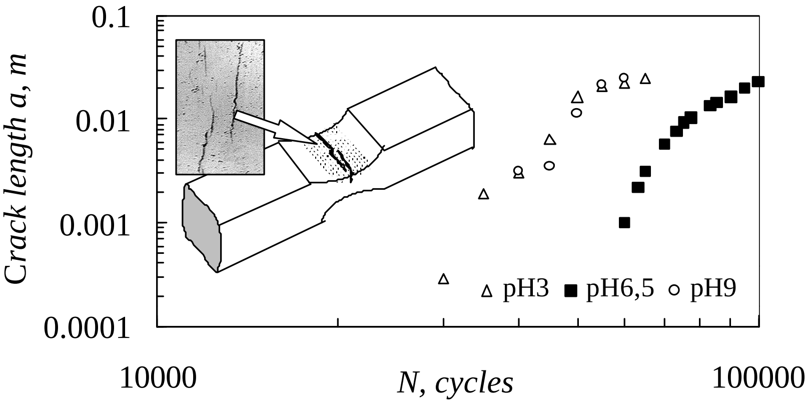

Figure 1: Surface crack length *a* versus number cycles of loading *N* for tests in environments with different *pH*.

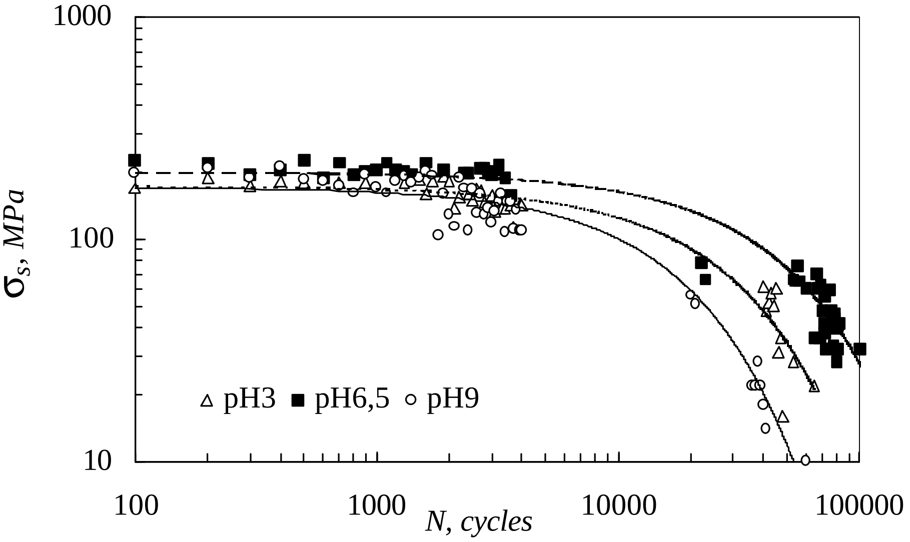

Figure 2: Parameter s_s versus number cycles of loading *N* for tests in environments with different *pH*. Lines: analytic description by function (1).

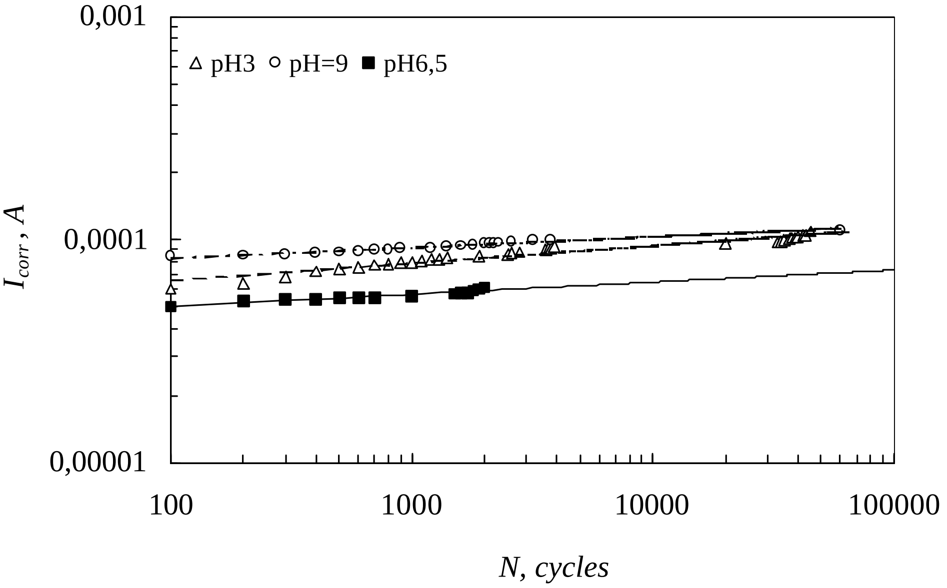

Figure 3: Corrosion current I_{corr} versus number cycles of loading *N* for tests in environments with different *pH*. Lines: analytic description by function (2).

Dependencies of surface crack length a on number cycles of loading N are presented in Figure 1. These results showed that for given material-environment system shifting the *pH* value to acidic or alkaline side with respect to approximately neutral solution (*pH* = 6.5) leads to deceleration of corrosion fatigue crack nucleation and growth.

Using the procedure that is described in our previous work [2], characteristic values of applied stress s_s were determined which indicate the significant increasing of corrosion current, e.g. the significant electrochemical activation of metal surface within each cycle of loading (Figure 2). These data were described by the next exponential function:

$$s_s = r \cdot e^{t \cdot N}, \tag{1}$$

where *r* and *t* are constants.

Corrosion current I_{corr} as function of number cycles of loading *N* for tests in environments with different *pH* was also received (Figure 3) and presented in analytic view by the power relation:

$$I_{corr} = I_0 \cdot N^u, \tag{2}$$

where I_0 and *u* are some constants of material environment system.

The analysis of these three groups of data presented in Figures 1-3 showed on their relationship which consists in the next. The increasing of corrosion fatigue crack length a causes the increasing maximum corrosion current per cycle of loading I_{corr}. It should be noted that location of curves $a(N)$ and $I_{corr}(N)$ has the same order with respect of *pH* values. The same order of plots location can be seen in Figure 2. Here may be also suggested that parameter s_s is able to define the corrosion fatigue process, i.e. nucleation and further growing of cracks. This can be explained by the fact that for electrochemical activation of damaged metallic surface the lower value of applied stress is needed than for undamaged [1, 2] and we can see the droped function $s_s(N)$.

MODEL DEVELOPMENT AND VERIFICATION

Accounting considered above results and also data and suggestions from our previous studies [4, 5], the model for surface fatigue corrosion crack nucleation and growth can be developed as results synergistic action of characteristic values of applied stress s_s and the process of electrochemical metal dissolution on cyclically deformed surface. The proposed model is based on the next statements:

- the surface corrosion fatigue is realised through electrochemical dissolution process of metal that is dominant;
- there is the relationship between metal electrochemical dissolution on a cyclically deformed smooth surface and surface corrosion fatigue crack nucleation process;
- the value s_S is assumed as some characteristic parameter that defines of specificity of surface corrosion fatigue process and for some cases it has been postulated that parameter s_S may be considered as the conventional surface yield stress limit.

The relationship between corrosion fatigue crack length a, characteristic values of applied stress s_s, number cycles of loading N and parameters of metal electrochemical dissolution is found in the next view:

$$F(a) = \left(s_S\right)^m \cdot Q\,; \tag{3}$$

$$Q = \frac{M}{zFr} \cdot \left(\frac{1}{f}\right) \cdot \int_0^N I_{corr}(N) \cdot dN\,, \tag{4}$$

where $F(a)$ is some function of crack length; m is constant, that depends on material-environment system and test condition; M is molecular mass of metal; z is the number electrons, released during anodic metal dissolution; F is Faradays constant; r is metal density; f is the cyclic frequency; I_{corr} is corrosion current function.

For determining of relationship between parameters Q and s_s for different crack length under given test conditions, the needed calculations on the base of formulae (3) and (4) were performed (see Figure 4). It has been received that there is negligible difference between values of power m in relation (3) for all considered cases. This can be seen in Figure 4a where there is approximately the same slope for graphs 1-5. This fact may be suggested as confirmation that for studied cases corrosion fatigue process has the same physical nature which not depend on environment composition. From this reason the function $F(a)$ can be described by the power expression (see Figure 5b):

$$F(a) = A\cdot a^{n}, \tag{5}$$

where constants A and n depend only on material-environment system.

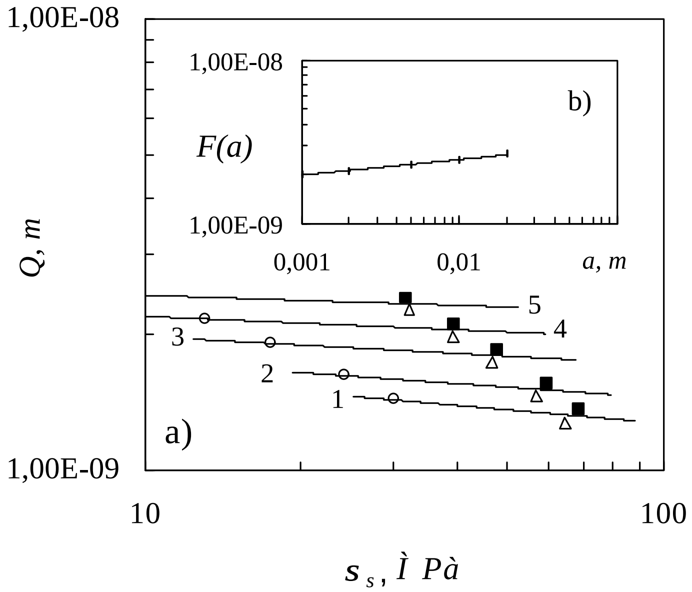

Figure 4: a) - Relationship between parameters Q and s_s for different crack length a: 1- 0.001m; 2- 0.002m; 3- 0.05m; 4- 0.01m; 5- 0.02m for tests in environments with different *pH*: triangles- *pH=3.0*; quadrats– *pH=6.5*; circles– *pH=9.0*. b) - Function *F(a)* for given corrosion fatigue crack lengths.

Based on criterion (3) with take into account the expression (2), (4) and (5), the next relation can be derived for determination of surface corrosion fatigue crack length:

$$a=\left[\frac{1}{A}\cdot\left(s_s\right)^m\cdot\frac{M}{z\cdot F\cdot r}\cdot\left(\frac{1}{f}\right)\cdot\left[\frac{I_0}{u+1}\cdot N_i^{u+1}\right]\right]^{\frac{1}{n}}. \tag{6}$$

Formula (6) was verified for different electrochemical conditions of tests (Figure 5). Here it should be noted that the best coincidence experimental and calculated data are observed for cracks by length of few millimetres.

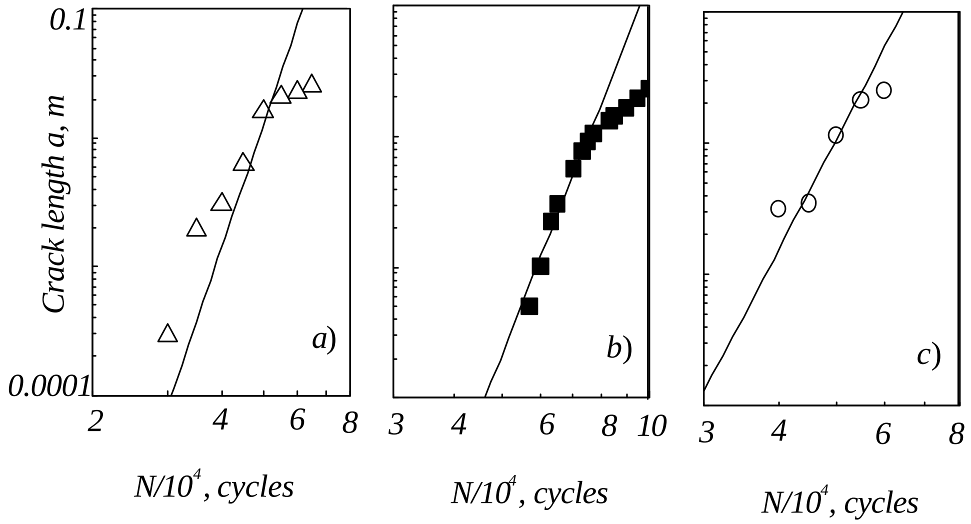

Figure 5: Comparison experimental (points) and predicted (lines) values of corrosion fatigue surface crack length *a* with respect to number cycles of loading *N* for tests in environments with different *pH*: a – *pH=3.0*; b – *pH=6.5*; c – *pH=9.0*.

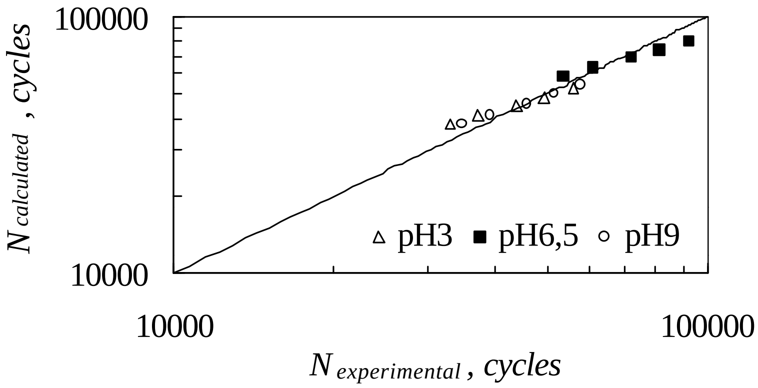

Figure 6: Experimental and predicted according to formula (7) values of number cycles of loading *N* for corrosion fatigue surface crack of different length.

On the base of equation (6) the formula for prediction of the number of loading cycles *N* for corrosion fatigue crack nucleation of length *a* is proposed:

$$N_i = \left[\frac{A \cdot a^n}{(s_s)^m \cdot \frac{M}{z \cdot F \cdot r} \cdot \frac{1}{f} \cdot \frac{I_0}{u+1}} \right]^{\frac{1}{u+1}} . \qquad (7)$$

Assessment of required number cycles of loading N with using of relation (7) gives satisfied correlation with experiment (Figure 6) that shows on engineering applicability of the proposed model.

CONCLUSIONS

The criterion of surface corrosion fatigue crack nucleation by length a as function of the number of loading cycles N for crack nucleation, maximum corrosion current per loading cycle I_{corr}, constants of electrochemical dissolution of metal surface and the characteristic stress s_S is developed. On this base the expression for assessment of the needed number of loading cycles N is proposed and that was verified for engineering applicability.

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