

# ON THE INITIAL STAGES OF CORROSION FATIGUE EMANATING FROM SMOOTH SURFACE

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## ABSTRACT

The initial stage of corrosion fatigue was studied with take into account of the electrochemistry of the deformed smooth surface and its stress state. The main attention has been paid of electrochemical state variables of metal surface under cyclic deforming. This phenomenon was estimated by variation of the value of polarisation current  $I$ . It should be noted that under tests the maximum values of current  $I_{max}$  were recorded as well as variation of the polarisation current  $I_C$  during cycle of loading. It has been defined that synchronously to changing of load, there is change of polarisation current  $I_C$  within each cycle of loading. The parameter  $I_C$  increases under increasing of load and decreases under unloading. The analysis of the curves  $I_C = F(\sigma)$  showed on the next specificity. There is the some characteristic value of applied stress  $\sigma = \sigma_s$ , beginning from which the significant increasing of polarisation current  $I_C$  is observed. Under  $\sigma \leq \sigma_s$  the value of  $I_C$  is practically constant or its changing is negligible. The physical meaning of the parameter  $\sigma_s$  is discussed, in particular the possibility to reflect the beginning of the surface plasticity process under given testing conditions. As first approximation it has been postulated that parameter  $\sigma_s$  can be considered as the conventional surface yield stress limit  $\sigma_{YS}^*$ . Finally the some estimation of the corrosion fatigue cracks nucleation is given with relationship of the electrochemical conditions.

## INTRODUCTION

Corrosion fatigue of structural metals and alloys considers as process that is influenced by the number of factors, including stress level and strain-stress state, material microstructure and environment [1]. Developments in fracture mechanics approaches have provided the better understanding of fatigue failure as phenomenon of crack-like defect nucleation and growth to some critical size [2].

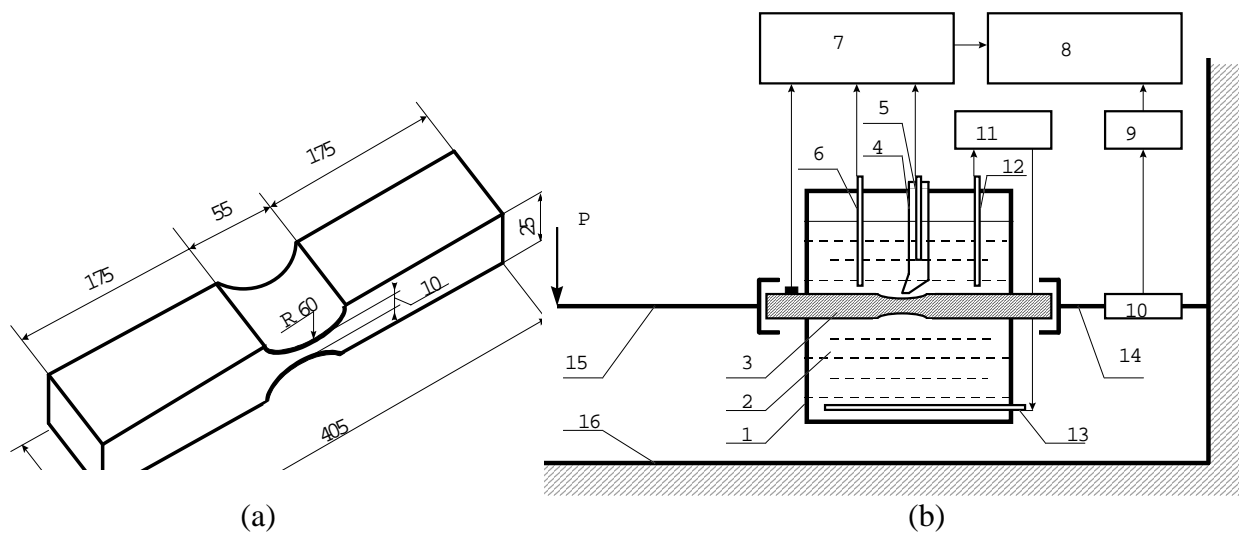
Now it is clearly that under certain circumstances corrosion fatigue lifetime may be controlled by the development and propagation of very small defects [3] The knowledge of initial stages of given processes become significantly important for prediction of total durability of structure components under operating conditions. Recently in framework of this problem the relationship between anodic dissolution process on a cyclically deformed smooth surface and short corrosion fatigue crack growth

behaviour has been established [4, 5]. As further developments of this direction the present work is focused on the initial stage of corrosion fatigue with take into account of detailed consideration of electrochemical state variables of metal surface under cyclic deforming.

## EXPERIMENTAL PROCEDURE

The low alloy steel *12Kh1MF* (yield stress for tension  $\sigma_{YS} = 260M Pa$ ) was used as investigation object. The nominal chemical composition of material was next (in weight percentage): C=0.08-0.15; Cr=0.9-1.2; Mo=0.25-0.35; V=0.15-0.30; Mn=0.40-0.70; Si=0.17-0.37; Ni<0.25; Cu<0.20; S<0.025; P<0.030; remainder Fe. The specimens have been made from the plate (thickness 40 mm) and their geometry is presented in Figure 1a.

The 3% NaCl aqueous solution under ambient temperature was taken as a basic corrosion environment. The tests were conducted in environments with different values of *pH*, namely 3.0; 6.5 and 9.0. For this purpose the small admixtures of *HCl* and *NaOH* were respectively used.



**Figure 1:** Specimen (a) and principal scheme of testing equipment (b): 1 - cell; 2 - corrosive environment; 3 - specimen; 4 - Haber-Luggin capillary; 5 - reference electrode; 6 - auxiliary electrode; 7 - potentiostat; 8 - XY-recorder; 9 - system for load regulation; 10 - system for load measurement; 11 - system for temperature regulation; 12 - electrocontact thermometer; 13 - heating element; 14 - fixed grip; 15 - active grip; 16 - base

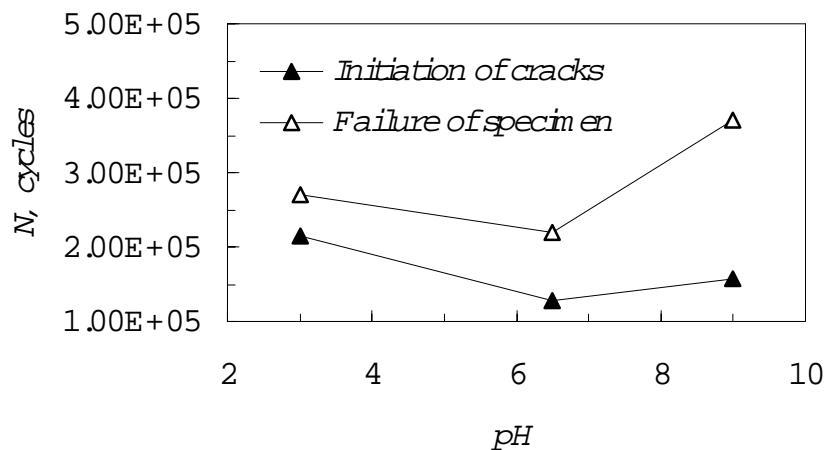
The specimens were tested under three points bending conditions and the scheme of corrosion fatigue tests is shown in Figure 1b. The tests were conducted under constant level of the cyclic stress and stress ratio  $R=0$ . The frequency of loading was equal  $\omega = 0.1 Hz$ . The values of cyclic stress were chosen with respect to the value of yield stress  $\sigma_{YS} (R_e)$  of the studying materials for providing the constant ratio  $\sigma_{max}/\sigma_{YS} = 1.0$ . Here  $\sigma_{max}$  is maximal stress per loading cycle.

The electrochemical tests were conducted according to the standard polarisation procedure and with using the special designed corrosion cell (see Figure 1b). For electrochemical measurements the potentiostat PI-50 with the *Ag/AgCl* reference electrode was applied. As auxiliary electrode, the special bar coated of platinum was used. 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.

For each tested specimen the surface was periodically observed and its corresponding images were fixed using a plastic replication technique [6]. The system used for receiving of these images from replicas involved a microscope with an attached television camera and a PC coupled to an image analysis software system.

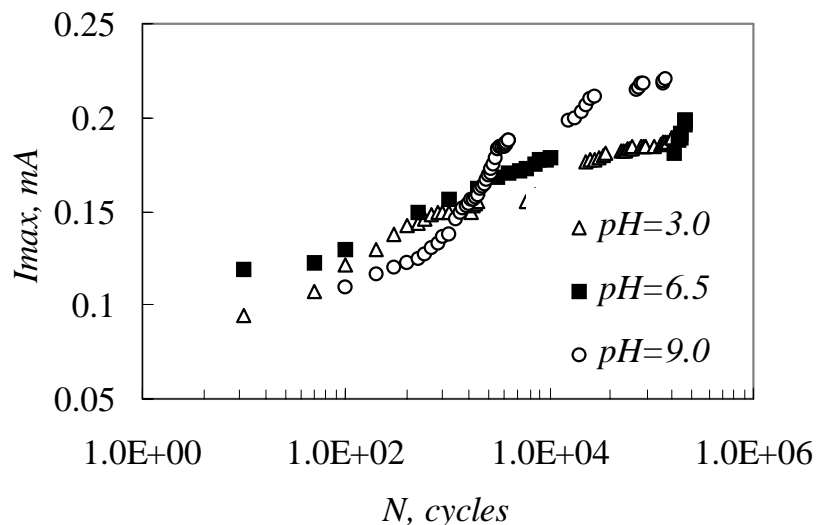
## RESULTS AND DISCUSSION

The general result of tests is presented as number of loading cycles to cracks initiation ( $N_i$ ) and to specimen failure ( $N_f$ ) versus value of  $pH$  (see Figure 2). These plots 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 process. This trend is observed for crack nucleation process as well as for total lifetime.

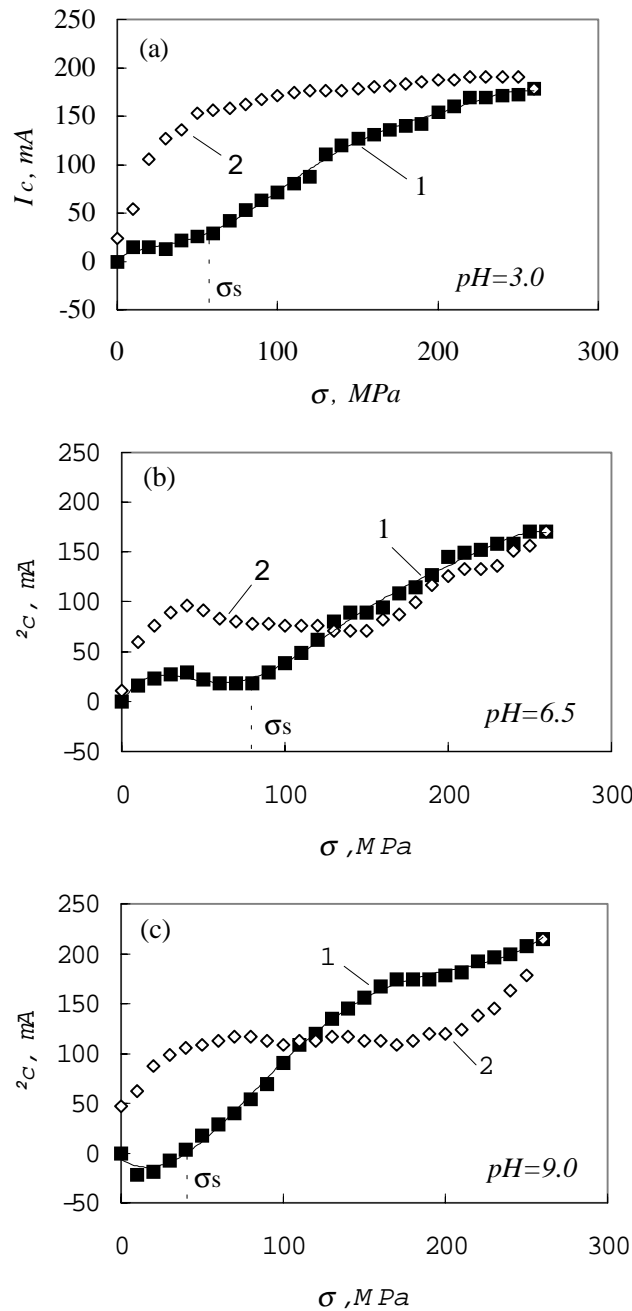


**Figure 2:** Number of loading cycles to cracks initiation and to specimen failure versus  $pH$

Besides that, the main attention has been paid of electrochemical state variables of metal surface under cyclic deforming. This process was estimated by variation of the value of polarisation current  $I$  under constant potential of specimen's surface. It should be noted that under tests the maximum values of current  $I_{max}$  were recorded as well as variation of the polarisation current  $I_c$  during cycle of loading. These dependencies and their combination were considered as basis for further analysing of the specificity of corrosion fatigue process for given testing conditions.



**Figure 3:** Dependencies of the maximum polarisation current  $I_{max}$  on number cycles of loading  $N$ . Dependence of the maximum polarisation current  $I_{max}$  on number cycles of loading  $N$  is shown in Figure 3 for corrosive environments with different  $pH$ . These plots have clear increasing tendency that reflects typical kinetics of corrosion damaging accumulation and nucleation and growth of crack-like defects.



**Figure 4:** Variation of the polarisation current  $I_c$  during cycle of loading under  $N=2000$  cycles:  
1 - loading; 2 - unloading

Investigation of variation of the polarisation current  $I_c$  during cycle of loading showed that synchronously to changing of load, there is change of polarisation current  $I_c$  within each cycle of loading (Figure 4). The parameter  $I_c$  increases under increasing of load and decreases under unloading. The analysis of the curves  $I_c = F(\sigma)$  indicated on the next specificity. There is the some characteristic value of applied stress  $\sigma = \sigma_s$ , beginning from which the significant increasing of

polarisation current  $I_C$  is observed. Under  $\sigma \leq \sigma_S$  the value of  $I_C$  is practically constant or its variation is negligible.

For determining of the values  $\sigma = \sigma_S$ , the next procedure was used. During each test the curves  $I_C = F(\sigma)$  were recorded versus number of loading cycles  $N$ . The loading part of these curves described by function:

$$I_C = A_0 + A_1\sigma + A_2\sigma^2 + A_3\sigma^3 + A_4\sigma^4 + A_5\sigma^5 + A_6\sigma^6; \quad (1)$$

where  $A_0 \dots A_6$  are constants. Using eqn. 1, the values  $\sigma = \sigma_S$  were determined analytically as point of inflection. Result of this calculation in dimensionless form is given in Table 1. Here  $N_i$  is the number of loading cycles to cracks initiation on cyclically deformed surface.

**TABLE 1**  
NUMERICAL VALUES OF PARAMETER  $(\sigma_S/\sigma_{YS})$  AS FUNCTION OF RATIO  $N/N_i$

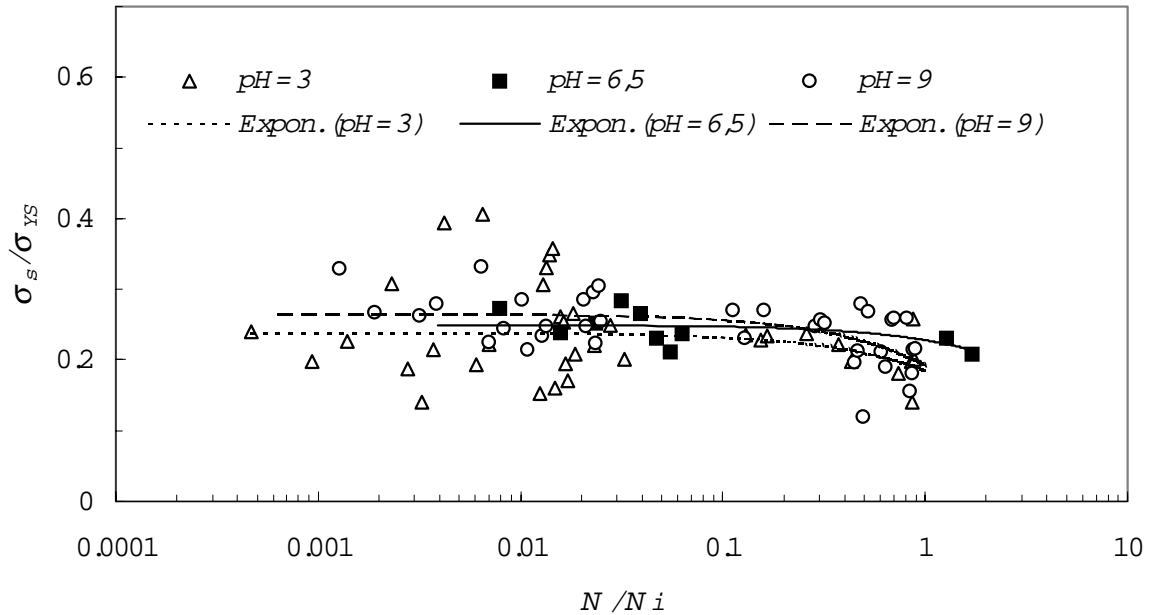
pH=3.0		pH=6.5		pH=9.0	
$N/N_i$	$\sigma_S/\sigma_{YS}$	$N/N_i$	$\sigma_S/\sigma_{YS}$	$N/N_i$	$\sigma_S/\sigma_{YS}$
0.0005	0.2401	0.0078	0.2724	0.0013	0.3289
0.0009	0.1975	0.0157	0.2390	0.0019	0.2675
0.0014	0.2264	0.0235	0.2519	0.0032	0.2629
0.0023	0.3080	0.0313	0.2829	0.0038	0.2793
0.0028	0.1866	0.0392	0.2662	0.0064	0.3319
0.0033	0.1396	0.0470	0.2314	0.0070	0.2246
0.0037	0.2140	0.0549	0.2111	0.0083	0.2448
0.0042	0.3930	0.0627	0.2374	0.0102	0.2857
0.0060	0.1935	1.0235	0.2309	0.0109	0.2144
0.0065	0.4062			0.0128	0.2338
0.0070	0.2221			0.0134	0.2477
0.0125	0.1518			0.0204	0.2850
0.0130	0.3061			0.0211	0.2469
0.0135	0.3307			0.0230	0.2959
0.0139	0.3479			0.0236	0.2228
0.0144	0.3573			0.0243	0.3054
0.0149	0.1604			0.0249	0.2548
0.0158	0.2605			0.1118	0.2701
0.0163	0.2527			0.1277	0.2315
0.0167	0.1950			0.1596	0.2703
0.0172	0.1710			0.2874	0.2470
0.0181	0.2652			0.3033	0.2565
0.0186	0.2081			0.3193	0.2517
0.0232	0.2198			0.4949	0.1197
0.0279	0.2489			0.5268	0.2686
0.0325	0.2014			0.6066	0.2108
0.1301	0.2346			0.6386	0.1902
0.1534	0.2276			0.6865	0.2559
0.1650	0.2332			0.7024	0.2593
0.2579	0.2369			0.8142	0.2599
0.3741	0.2218			0.8461	0.1554
0.4322	0.1976			0.8621	0.1809
0.7366	0.1813			0.8780	0.2137

0.8528	0.1973			0.8940	0.2155
0.8644	0.1402			1.0217	0.2765
0.8876	0.2012				

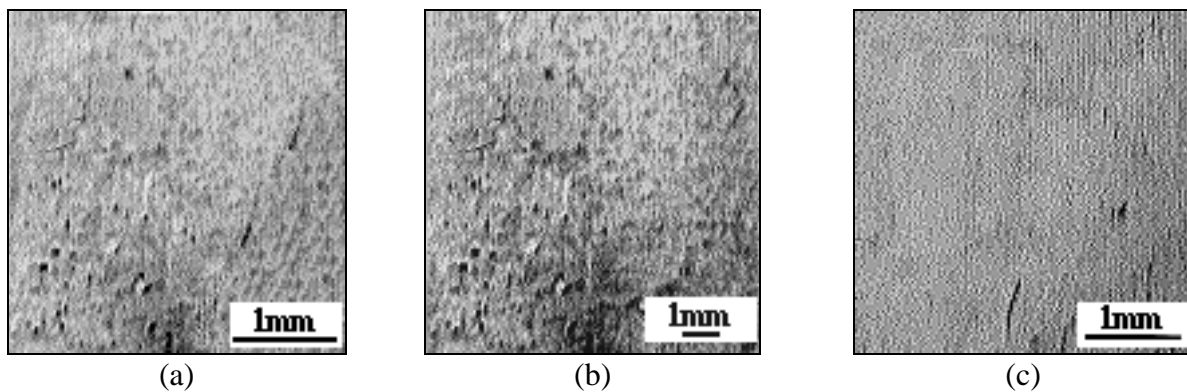
On base data from Table 1 the graphs of parameter  $(\sigma_s/\sigma_{YS})$  were plotted versus ratio  $N/N_i$  (Figure 5). These curves were also described by the next exponential function:

$$\frac{\sigma_s}{\sigma_{YS}} = B \cdot \exp[-C \cdot (N/N_i)]; \quad (2)$$

where  $B$  and  $C$  are constants.



**Figure 5:** Parameter  $(\sigma_s/\sigma_{YS})$  as function of ratio  $N/N_i$



**Figure 6:** Surface of specimens after corrosion fatigue tests ( $N/N_i \approx 0.8$ ) in corrosive environments with different value of  $pH$ : a - 3.0; b - 6.5; c - 9.0

From Figure 5 it can be seen that trend of parameter  $(\sigma_s/\sigma_{YS})$  on depends on duration of cyclic deforming. Under early stage of test its value is practically constant and has the tendency to decreasing with achieving of stage of surface corrosion fatigue crack nucleation. These results show that parameter  $\sigma_s$  is able to indicate on the corrosion fatigue process, i.e. corrosion damaging

accumulation and nucleation and further growing of crack-like defects (see Figure 6). This suggestion can be explained by the fact that for electrochemical activation of damaged metallic surface the lower value of applied stress than for undamaged is needed.

The physical meaning of the parameter  $\sigma_s$  may be different on different stages of corrosion fatigue process. In particular, we suppose that parameter  $\sigma_s$  can reflect the beginning of the surface plasticity process under given testing conditions. Basing on works [7-9], as first approximation it has been postulated that parameter  $\sigma_s$  may be considered as the conventional surface yield stress limit  $\sigma_{YS}^*$ . For confirmation of this statement the further investigations are needed for different material-environment systems.

## CONCLUSIONS

The results obtained in present study highlight the specificity of electrochemical state variables of metal surface under cyclic deforming and the initial stage of corrosion fatigue. For all considered cases it has been shown that within each cycle of loading there is the some characteristic value of applied stress  $\sigma = \sigma_s$ , beginning from which the significant electrochemical activation of deformed surface is observed.

The value  $\sigma_s$  can be accepted as some characteristic parameter for determination of specificity of corrosion fatigue process. The physical meaning of the parameter  $\sigma_s$  may be different on different stages of corrosion fatigue process and for early stage it has been postulated that parameter  $\sigma_s$  can be considered as the conventional surface yield stress limit  $\sigma_{YS}^*$ .

The received data give some basis for development of the experimental technique for detection of metallic surface under corrosion fatigue conditions by the electrochemical methods.

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