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MODELLING AND PREDICTION IN FAILURE PROCESSES BY MECHANICAL STRESSES IN CORROSIVE ENVIRONMENT

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ABSTRACT

The complex interaction effect of mechanical stress- mechanical systems and aggressive environment, leads, at dramatic decreasing of their durability and reliability. The analyze of physical-chemical processes such as: electrode potential evolution, anodic current density evolution, size evolution and growing speed of cracks, allow finding common characteristics of failure due to mechanical stress combined with aggressive environment. Based on the analyze of failure mechanisms by stress cracking corrosion (monotonic mechanical loading), fatigue corrosion (cyclic mechanical loading) and tribocorrosion the paper authors suggest a global model of this kind of failure, based on degradation process of stress cracking corrosion with capability to realize a prediction of damage by these processes

KEYWORDS: corrosion pit, crack, stress cracking corrosion, fatigue corrosion, tribocorrosion.

1. Introduction

Due to permanent presence of corrosive environment in all human activities, the study of its influence on engineering structures mechanical loaded is necessary in order to establish their durability.

In the same time with corrosive environment, on engineering structures act different kind of mechanical stresses. Their action, combined, lead to: stress corrosion, fatigue corrosion, tribocorrosion. The evolution speed of these compound failure processes is higher than each and every situation considered separately, and the effect is not added, but, by overlapping of individual effects, much more complex, there is a synergetic process.

The aim of this paper is to analyze processes that occur at the interface metallic loaded structure-corrosive environment. There will be studied three types of stresses: monotonic stresses, cyclic stresses, wear stresses under relative sliding conditions of metallic surfaces.

Failure under mechanical stresses in corrosive environment is connected mainly by the initiation and growth of cracks which involves the following stages:

- initiation of corrosion pit;
- pit-crack transition;
- crack development under aforementioned stresses: monotonic stress leads to failure by stress corrosion; cyclic stress leads to failure by fatigue corrosion; cyclic stress at low loading and low frequency and close to flow limit leads to failure by tribocorrosion.

2. Initiation of failure processes by corrosion and mechanical stresses

2.1. Modelling of pit corrosion initiation process

According to previous studies, the first stage of failure by mechanical stress in corrosive environment is mainly connected with electrochemical processes that occur during corrosion process, [1], and the result is corrosion nucleation [2].

The number of pit corrosions at a certain moment in time, *t*, may be described by the distribution function *P(x,t),* where *x* is the dimension (usually the pit depth). This way the number of pits with the depth of $x+\delta_x$ with be $P(x,t)\delta_x$.

Depending on environment aggressively pit corrosions will grow in time. It may be assumed that the growth in time of the pit corrosion can be expressed by the relationship:

$$\frac{dx}{dt} = g(x) \qquad (1)$$

where g is a function depending of pit size, which, in its turn, depends of other parameters such as applied stress and temperature [3].

It was shown that the pit depth distribution function evolution $P(x,t)$ is ruled by a differential equation as:

$$\frac{\partial P(x,t)}{\partial t} = -\frac{\partial}{\partial x}\left[g(x)P(x,t)\right] + S(x,t), \qquad (2)$$

where $g(x)$ is the pit growing speed with depth x, and $S(x,t)$ is the number of pits between x and $x+\delta x$, which trigger at the studied surface within the time δt.

The term $S(x,t)$ means a more general situation, but when a stabile distribution for pit depth is considered, this member may be neglected, and the depth may be described by:

$$x = \alpha \cdot t^{\beta}, \qquad (3)$$

and the growing speed of the crack will be:

$$\frac{dx}{dt} = g(x) = \beta\alpha^{1/\beta} \cdot x^{(1-1/\beta)} \qquad (4)$$

β is a constant that must be determined and α is unknown with a normal distribution.

2.2. Pit to crack transition

According to Kondo criterion [6] transition occurs when the crack depth is bigger than a critical depth, which is an opening force threshold for the crack or the growing speed of crack is higher than the growing speed of pit. The depth threshold at which will be triggered the growth of crack depends of applied stress, σ, and the environment conditions. Thus the growing speed of crack can be described by the relationship:

$$\frac{dx}{dt} = c \cdot \sigma^{p} \cdot x^{q}, \qquad (5)$$

where x is the crack depth.

This relationship has a similar configuration as the one for stress intensity factor [7]:

$$K = Y\sigma\sqrt{\pi l}$$

where Y - dimensional factor, σ- applied stress, l- crack length.

Considering a statistical distribution of pit growing speed, it means that the crack growing speed can also be statistically interpreted. In the equation that gives the grow speed of pit, the factor that can offer this character is parameter C that may be random determined in a normal distribution.

Finally, the critical depth at which the failure evolution speed is higher than the necessary crack evolution speed is:

$$x_{crt} = \left(\frac{\beta\alpha^{1/\beta}}{e\alpha^{p}}\right)^{\beta/1-\beta(q-1)} \qquad (6)$$

3. Modelling of failure process by stress cracking corrosion

Anodic failure process at the crack tip depends of anodic dissolution mechanisms and brittleness by hydrogen which combine together or, at some moment one of them may be more important than the other [8]. Processes intensity evaluation at the crack tip may be done, taking in account both mechanisms contribution:

$$\Delta V_c = \Delta V_a + \Delta V_n, \qquad (7)$$

where: ΔV_c is the growing evolution speed of crack due to anodic dissolution, and ΔV_n is the growing evolution speed of crack due to brittleness by hydrogen [8], [9].

Knowing that in the case of anodic dissolution the crack tip is anodic and metal surface is cathode [10], the difference in potential between the crack tip (τ_v) and the metal surface (τ_s), $\Delta\tau_s = \tau_v - \tau_s$, will determine the size of anodic dissolution current $I_a(\Delta\tau_a)$ [11]. The size of this current determines the dissolution speed at the crack tip and thus the growing evolution speed of crack due to this process. If the growing evolution speed of crack is controlled only by this process, based on Faraday law, it can be written:

$$\Delta V_a = \frac{i_a}{z \cdot F \cdot \rho}, \qquad (8)$$

where: i_a is the anodic dissolution current intensity at the crack tip; M- atomic mass of metal; Z- electrical load of negative ions in the solution; F- Faraday's constant; ρ- metal density.

If the crack is considered like a V cut, with the tip angle α (fig. 1) and if it is assumed that the anodic dissolution happens only on the height h situated at x_1 distance from the crossing point of crack faces and at $x_1 - x_2$ distance from the specimen surface, the anodic dissolution current intensity at the tip of the crack will be:

$$i_a = \frac{\alpha\chi\Delta\varphi_a}{h\ln\left(\frac{x_2}{x_1}\right)}, \qquad (9)$$

where χ is the electro-conductivity of the electrolyte.

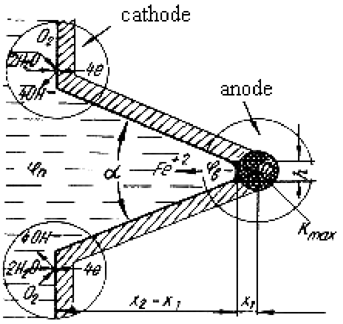

***Fig. 1** Electrochemical processes at crack tip.*

After replacement:

$$\Delta V_a = \beta_a \Delta\varphi_a , \qquad (10)$$

where:

$$\beta_a = \frac{\alpha M \chi}{ZF\rho h \ln\left(\frac{x_2}{x_1}\right)} , \qquad (11)$$

For a system metal-watery environment the growth of corrosion crack speed under stress is determined at some point by the jump in potential in the crack. The size of speed growth for crack evolution may be used for quantitative determination of anodic metal dissolution using an average value of S_a parameter.

$$S_a = \frac{\beta_0}{\tau_0} \int_0^{\tau_0} \left[\Delta\varphi_a(\tau)\right] d\tau , \qquad (12)$$

where τ_0 is the process evolution time.

For cyclic loading this parameter may be determined in a similar way. Thus,

$$S_a = \frac{\beta_0}{N_0} \int_0^{N_0} \left[\Delta\varphi_a(N)\right] dN \qquad (13)$$

where N_0 is the number of cyclic loading.

Generally speaking, every system material-corrosive environment has its own characteristic failure diagram. Thus, the kinetically diagram for stress corrosion is a curve with three distinct areas between two characteristic values of stress intensity factor (fig. 2): K_{ISCC}, the corresponds to stress intensity factor under which the crack in corrosive environment at monotonic loading doesn’t develop; $K_{I_c}(K_c)$ - value of stress intensity factor that characterises materials strength at brittle fracture [15], [16], [17].

The threshold value K_{ISCC} is an essential characteristic of cracking process. Depending of the nature of material-environment system, the value of this factor may vary in a wide range, and for corrosion resistance is close to K_{I_c}. Some materials, such as aluminum alloys don’t have a physical limit K_{ISCC}. That is why for this value is adopted the value at which the evolution rate of crack on the flat portion of the curve may be considered as a characteristic of stress corrosion failure.

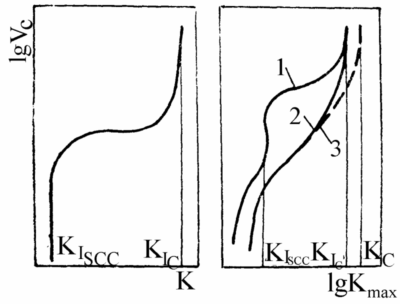

***Fig.2.2**. Kinetic diagrams of failure in corrosive environment.*

For this particular reason, in the case of monotonic loading in corrosive environment it is important finding this type of relationships. These would allow a comparative analyze of experimental data for different types of material-environment couples and would appreciate both qualitative and quantitative influence of various factors on failure kinetic diagram. Besides, with little experimental data, based on analytical relationships, can be established conventional values for K_{ISCC}, values than could be very hard to be found out on experimental ways [18], [19].

In a first approximation the diagram for evolution speed of stress corrosion crack may be described with relationships similar to the ones for fatigue crack evolution:

$$v = v_0 \left(K_I - K_{ISCC}\right)^n \left(K_{I_C} - K_I\right)^m , \qquad (14)$$

where v_0, *n*, *m* material depending constants.

In this relationship, for K_I values close to K_{ISCC}, evolution rate of crack goes to zero. And for $K_I \to K_{I_C}$, this will grow unlimited. If *n* and *m* go to zero, in the mean zone of K_I, the diagram will be merely horizontal.

4. Modelling of failure process by fatigue corrosion

Most of research papers regarding fatigue corrosion suggest a failure process starting from pit-crack transition. After this, failure may continue under several mechanisms: small cracks growth,

transition from short crack to long crack, big cracks growth and their reunion to a main crack.
From rupture mechanics point of view [20] the transition from pit to crack trigger occurs when stress intensity factor reaches the threshold K_{th} necessary to fatigue crack appearance.

$$(\Delta K)_{pit} = (\Delta K)_{th}, \qquad (15)$$

where

$$(\Delta K)_{th} = \beta \Delta \sigma \sqrt{a}, \qquad (16)$$

and β is a geometric parameter.

The growth speed of small cracks may be described with Paris law:

$$\frac{da}{dN} = C_{sc} (\Delta K)^{m_{sc}}, \qquad (17)$$

where C_{sc} and m_{sc} are material parameters.

The transition from small cracks to long ones is modelled by specialists in two ways:

1. surface crack followed by through crack and
2. short crack followed by a long crack [21], [22],[23].

Long crack growth may be described by a Paris relationship as well:

$$\frac{da}{dN} = C_{1c} (\Delta K)^{m_{1c}}, \qquad (18)$$

where C_{1c} and m_{1c} are material parameters.

In the case of fatigue stress in corrosive environment it is characteristic that cracks get reunited in a main crack that leads to rupture.

5. Modeling of failure process by tribocorrosion

In tribological contacts that work in corrosive environment, failure appears by removing the material from both surfaces, simultaneously, both by wear processes and corrosion reactions. The two mechanisms interact [24], [25], [26]. Material removing by abrasion lead to the local removal of the passive layer resulted after pure material is exposed to aggressive action of environment, and further acceleration of corrosion process (tribocorrosion) [27]. Usually the term abrasive wear may be interpreted as material loss due to hard particle action. Material removal may be done by several mechanisms, such as micro-ruptures, loss of individual particles, or fatigue mechanism by repeated deformation [28], [29].

If failure by tribocorrosion is analyzed based on material loss, the total loss by tribocorrosion V_{cw} is higher than by cumulating material loss by pure corrosion V_c and material loss by wear in the absence of corrosion V_w,:

$$V_{cw} = V_c + V_w + \Delta V_s \qquad (19)$$

where ΔV_s is the corrosion process effect that leads to wear intensification ΔV_w and of wear process that leads to corrosion intensification ΔV_c.

Consequently

$$\Delta V_s = \Delta V_w + \Delta V_c \qquad (20)$$

Generally writing

$$W_{cw} = V_{wc} + V_{cc} \qquad (21)$$

where

$$W_{cw} = V_w + \Delta V_w \text{ and } V_{cc} = V_c + \Delta V_c, \qquad (22)$$

From crack evolution by tribocorrosion point of view, [30], [31], the process is similar to fatigue corrosion process, and may be given by the relationship

$$\left(\frac{da}{dN}\right)_t = \left(\frac{da}{dN}\right)_R + \left(\frac{da}{dN}\right)_{cf} + \left(\frac{da}{dN}\right)_{scc}, \qquad (23)$$

where, $\left(\frac{da}{dN}\right)_R$ is pure mechanical fatigue of the superficial layer contribution; $\left(\frac{da}{dN}\right)_{cf}$ is the component of crack evolution speed growth as a result of cyclic loading and corrosive environment; $\left(\frac{da}{dN}\right)_{scc}$ crack evolution speed growth as a result of static loading under residual stresses and of static stress when crack sides are not in contact, at higher levels of stress intensity factor K_{ISCC}.

It was shown that material loss may be expressed by [32], [33]

$$V_c = \frac{M \cdot t}{ZF\rho} A_a i_p \qquad (24)$$

and

$$\Delta V_c = \frac{M \cdot t}{ZF\rho} K_w l \left(\frac{W}{H}\right)^{1/2} \left(i_0 - i_p\right) f \tau_0 \left[1 - \exp\left(\frac{-1}{f\tau_0}\right)\right] \qquad (25)$$

where A_a- apparent contact area; i_p- passive current intensity through the contact area; t- time; K_w- constant; l- friction trace widening; W- normal load; H- fragility; i_0- maximum density of the current on the fresh material surface in the begging of the passive process; f- contact frequency between the two surfaces; τ_0- initial time.

The V_w and ΔV_w components may be written

$$V_w = \frac{\pi D^2 N_c A_a f \cdot t}{6}\left[\left(\frac{da}{dN}\right)_r + \left(\frac{da}{dN}\right)_{cf} + \left(\frac{da}{dN}\right)_{css}\right] \quad (26)$$

and

$$\Delta V_w = \frac{\pi D^2 N_c A_a f \cdot t}{6}\left[\left(\frac{da}{dN}\right)_{cf} + \left(\frac{da}{dN}\right)_{css}\right], \quad (27)$$

where D – worn particle diameter; N_c- number of active zones with micro-cracks.

These relationships show that the main influence of cyclic mechanical stresses on V_w component, and the main influence of chemical factor on V_c component. The analyze of chemical and physical aspects of tribocorrosion processes shows that, at this kind of process as well, there are two essential mechanisms: the cyclic mechanical one- as a result of fatigue process at high level of stress, close to low cycle fatigue, and the electrochemical mechanisms un stress corrosion conditions.

6. Suggested models for failure by mechanical stresses in corrosive environment

In conditions of mechanical stresses in corrosive environment there are several models of failure due to static loading, dynamic loading and tribocorrosion.

The objectives of this project are to set up new models for failure by corrosion fatigue and tribocorrosion based on experimental analyze that govern these processes. In the same time, the project aims the set up of an integrated model of failure by mechanical stresses in corrosive environment where to initial source of failure is the stress corrosion.

6.1. Suggested model for corrosion fatigue

The authors of this project suggest as a model for failure by corrosion fatigue, a model similar to the one that describes fatigue stress, with a static component determined by the mean value of stress, σ_m and a variable component σ_a.

$$\sigma_{(t)} = \sigma_m + \sigma \sin\left(2\pi f t + \varphi\right), \quad (28)$$

where $f = 1/T$ is the fundamental frequency.

Extending to cyclic stresses in corrosive environment, the static component may be described by stress corrosion process (*SCC*) overlapping the cyclic component which may be described with Paris relationship $\Delta K = Y \Delta\sigma_a \sqrt{\pi a}$, where Y- geometric factor and $\Delta\sigma$ - variation of the second term in the loading general equation.

6.2. Suggested model for tribocorrosion

Analyzing the failure process in the superficial layer shows that this is a result of overlapping several simple failure processes and has a evolutionary character.

An elastic plastic surface subjected to alternative movements of sliding, in contact with a hard object, has an elastic cyclic strain with two components:
a cyclic plastic strain where the number of cycles up to the braking moment can be determined with Coffin-Manson relationship [35]:

$$\frac{\Delta\varepsilon_p}{2}\varepsilon'_f\left(2N_f\right)^c, \quad (29)$$

where ε'_f- fatigue ductility factor; ε_p- plastic deformation, c- fatigue ductility exponent or Coffin exponent, $2N_f$- number of total cycles until rupture and a plastic monotonic component. For most of materials ε'_f is identical with breaking elongation, and for many metals has values between 0.5 and 0.7.

When the plastic reversible strain is accompanied by the accumulation of unidirectional plastic strain (ratcheting process) and when this value reaches a critical level ε_c, than the crack is triggered. The number of cycles at breaking moment is

$$N_r = \frac{\varepsilon_c}{\Delta\varepsilon_r}, \quad (30)$$

where $\Delta\varepsilon_r$ is the necessary stain for ratcheting process appearance on a loading cycle.

The two processes compete and as a result material fails either by oligocyclic fatigue or by cumulating plastic excessive flows (ratcheting). According to the two competing processes the failure in corrosive environment continues similarly to fatigue process when the corrosive environment may lead to the increase of number of possible crack triggering areas.

The second mechanism is related with wear debris appearance by weakening the connections between atoms at the crack tip under the influence of active products of corrosive wear.

Knowing the number of cycles under the final break N_f and the correspondent time t_f the speed of generating wear debris v_g may found out:

$$v_g = \frac{N_c}{t_f}, \quad (31)$$

Where N_c is the number of crack starting centers on the surface unit.

When the ratcheting process is dominant in corrosive environment conditions the failure may go on similarly to a stress corrosion process.

6.3. The global model regarding failure by mechanical stress in corrosive environment

Analyzing the failure by mechanical stress in corrosive environment, such as failure by stress corrosion, by corrosion fatigue and by tribocorrosion, shown a few common characteristics of all these processes.

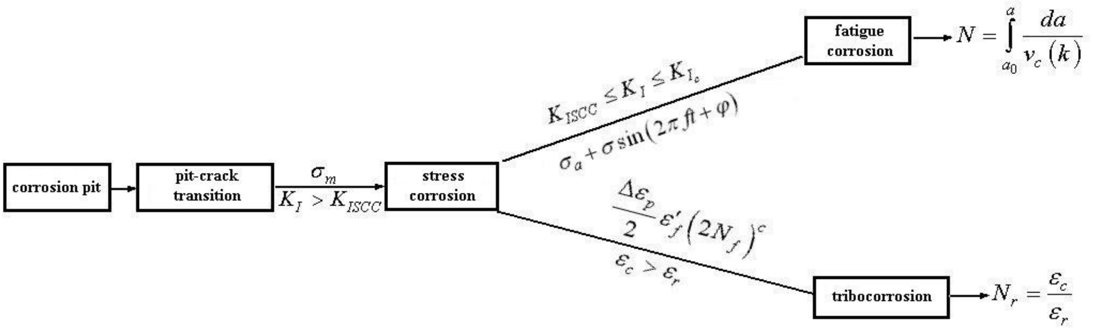

Fig.3. *The stress evolution by mechanical damage in corrosive environment*

The authors of this paper consider that the central mechanism governing failure by mechanical stress in corrosive environment is the one of stress corrosion by electrochemical processes of anodic dissolution and mechanical processes of oxide layers rupture.

Overlapping a cyclic component of stress over the failure by stress corrosion leads to corrosion fatigue. The stress evolution is described by a Paris like relationship with more intense physical mechanisms than stress corrosion.

Overlapping a cyclic component of low frequency stress close to flow limit leads to tribocorrosion. The speed of stress evolution is described by a Coffin-Manson like relationship or by cyclic plastic strain values (fig. 3).

From the point of view of rupture mechanics, stress corrosion processes appear when stress intensity factor goes above the threshold value $K_I > K_{JSCC}$. Furthermore corrosion fatigue appears when $K_{ISCC} < K < K_c$.

Tribocorrosion appears when the durability is: $N < N_t$ (N_t- number of loading cycles at the bound elastic-plastic).

In the same time the number of rupture cycles N_r is determined by rate between critical values of unidirectional plastic strain (ratcheting process) and the plastic strain ε_r at which the process starts (fig. 4).

$$N_r = \frac{\varepsilon_c}{\varepsilon_r}, \qquad (32)$$

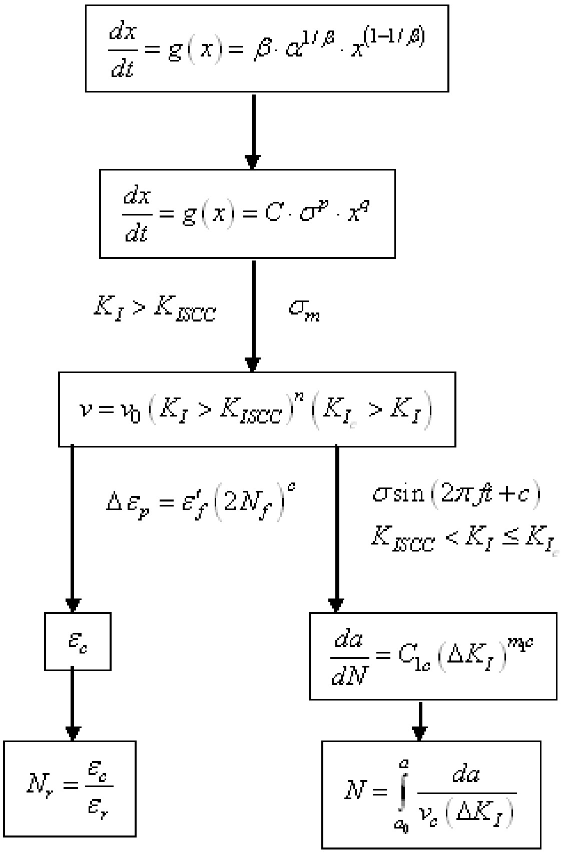

Fig.4. *Logical scheme of damage rate by mechanical stresses in corrosive environment.*

7. Conclusions

This paper suggests a model for failure due to mechanical stresses in corrosive environment.

Analyzing the failure by mechanical stress in corrosive environment, such as failure by stress corrosion, by corrosion fatigue and by tribocorrosion, shown a few common characteristics of all these processes like: anodic dissolution, brittleness by hydrogen, oxide layers rupture.

The authors of this paper consider that the central mechanism governing failure by mechanical stress in corrosive environment is the one of stress cracking corrosion and these processes are manifesting by a synergetic mechanism.

Overlapping a cyclic component of stress over the failure by stress corrosion leads to corrosion fatigue. Overlapping a cyclic component of low frequency stress close to yield limit leads to tribocorrosion.

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