Account of Stress Corrosion Crack Morphology on the Mechanical Situation at the Crack Tip

O.Z. Student and O.T. Tsyrulnyk

Karpenko Physico-Mechanical Institute of the National Academy of Sciences of Ukraine, Department of Corrosion-Hydrogen Degradation and Materials Protection, 5, Naukova Str., 79601 Lviv, UKRAINE, E-mail: student@ipm.lviv.ua

ABSTRACT. *It is difficult to evaluate the corrosion crack growth resistance parameters due to specific morphology of cracks (curvilinear propagation path, branching, corrosion and deformation blunting). In particular, the high-strength steels exhibit a curvilinear path of the cracks propagation and their intergranular branching, caused by the grain-boundary subcritical crack growth. For ductile materials the effect of deformation crack blunting due to active loading of a specimen and its sustained loading as well as corrosion blunting because of interaction of the specimen free surfaces with environment are very important. The experimental procedure for evaluation of peculiarities of the corrosion cracks growth is proposed. To take into account the corrosion crack branching,* K_{Ieff} *was evaluated, which was assumed to equal the maximum* K_I *value achieved at the tip of one of the crack branches. It has been shown that the account of the morphological specific features of the corrosion crack growth are very important for the correct evaluation of service characteristics of materials and determination of the environment influence mechanism. It has been shown that the precision of evaluating the* K_{Iscc} *level decreases and the usage of outer polarization for evaluation of mechanism of corrosion environment effect can lead to the wrong conclusion if the possible variation of the crack morphology is not taken into account. These peculiarities are very important for the correct evaluation of service characteristics of materials and for an examination of the rupture causes of the structure.*

INTRODUCTION

Curved crack trajectory and branching, corrosion blunting and sharpening are the main geometric features of the stress corrosion cracking (SCC), which undoubtedly decrease the intensity of the stress-strain field [1-3]. It is that change in the mechanical situation at the crack tip is dominating over the effect of the corrosion environment in a number of cases. In particular, curvilinear path of the cracks propagation and their intergranular branching are the effect of the grain-boundary SCC in the high-strength steels [1]. The deformation crack blunting during active and sustained loading of a specimen as well as its corrosion blunting as a consequence of interaction of the specimen free surfaces with environment is significant for ductile materials [2]. The role of anodic dissolution of the metal at the crack tip during sustained loading of a specimen is ambiguous for materials with low and high ductility. The crack blunting due to mechanical deformation is inessential for materials with low ductility, but in this case anodic dissolution becomes as an effective way of stress relaxation. The highly ductile materials reveal appreciable crack blunting due to mechanical deformation during loading and retarded yielding phenomenon at the crack tip under sustained static loading. Last phenomenon causes additional deformation blunting. It is difficult to evaluate the corrosion crack growth resistance parameters due to specific morphology of crack tip. In this case SCG by selective anodic dissolution would sharp the crack tip and intensify the stress concentration [3].

Thus corrosion environment affects not only crack growth resistance of material, but the stress-strain state at the crack tip. Usually the driving force of corrosion crack growth is considered as a result of strength decrease due to adsorption effect, hydrogen embrittlement, anodic dissolution, etc. The factors influencing on the mechanical situation near the crack tip are often ignored. From this it follows that method of evaluation of the effective stress intensity factor (SIF) K_{Ieff}, which takes into account just a change of the mechanical situation at the crack tip due to corrosion environment effect, is needed.

According to the fracture mechanics approach, the stress field at the crack tip can be described by SIF. The threshold SIF values obtain in various limiting stress states and its invariance in certain loading conditions is important for practice. In this case the crack resistance parameters can be used as important mechanical characteristics of structural materials. Under conditions of static delayed loading in aggressive environments the crack growth curves represent the dependence of the crack growth rate *da/dt* upon the SIF level K_I. The invariance of these diagrams is great importance, since they are often used in predicting the fracture kinetics of the structural components.

The chief aim of this article is creation the method of the effective kinetic diagrams building with taking to account a change of mechanical situation at the crack tip due to specific morphology of corrosion cracks. It enable explains of some kinetic effects at stress corrosion cracking of structural steels and verifies the assumptions about responsible mechanisms of corrosion environment influence on the crack growth.

EXPERIMENTAL DETAILS

The effective SIF K_{Ieff} was evaluate as the maximum SIF value, K_I, achieved at the tip of one of the corrosion crack branches. It enables to take into account the effect of corrosion cracks branching. To estimate K_{Ieff}, a procedure has been developed [1-4], which is based on the comparison of the fracture toughness of the specimens with a sharp fatigue (K_{Ic}) and a branched corrosion (K_{Ic}^c) cracks after interrupted corrosion tests. These values were determined at cryogenic temperature, which provided equality of the plastic zone dimensions at the corrosion crack tip before interrupted corrosion tests and during subsequent K_{Ic}^{c} tests. The factor of discrepancy between the values of K_{Ic} and K_{Ic}^{c} is accounted by the SIF relaxation factor, α:

$$\alpha = K_{Ieff} / K_{I} = K_{Ic} / K_{Ic}^{c}. \quad (1)$$

The K_{Ic}^{c} value is predetermined by the change of the corrosion crack geometry including its curvilinear path and corrosion tip blunting. Thus suggested procedure reflects integrally the variation of the mechanical situation at the crack tip caused by the corrosive environment effect because it allows taking into account the morphological differences between the corrosion and fatigue cracks.

However, the geometrical factor of deformation-induced crack blunting, which depends on the material structure, must be considered too. As a rule, such blunting is caused by material deformation in the vicinity of the crack under active loading and during subsequent holding of specimens under loading, due to retarded yielding. By analogy with $K_{Ic}(\rho) / \sqrt{\rho}$ and $K_{Iscc}(\rho) / \sqrt{\rho}$ parameters, which are independent from the notch radius [5, 6], the similar approach to estimation of the stress-strain state at the corrosion crack tip $K_{I} / \sqrt{\rho}$ parameter has been proposed. According to it, the actual crack is considered as a notch with a ρ radius. The value of ρ is obtained by metallographic investigations, as a half of crack tip opening displacement in the loading specimen. The branched and corrosion blunted crack was conventionally replaced by the notches of the same radius ρ_{eq}. When determining ρ_{eq}, it was assumed, that difference between fracture toughness levels in liquid nitrogen for the specimens with corrosion crack, which was grown to achieve a certain K_{I} level under stress corrosion cracking tests, and with fatigue crack blunted by a short-term loading in air to the same level of K_{I} (K_{Ic}^{c} and K_{Ic}^{b}, respectively) causes only crack geometry differences. Then ρ_{eq} is defined as:

$$\rho_{eq} = \rho \, (K_{Ic}^{c} / K_{Ic}^{b})^{2}, \quad (2)$$

where ρ is prefatigue crack tip radius metallographically determined under active loading to the level of K_{I}.

RESULTS AND COMMENTS

Taking into Account the Corrosion Cracks Morphology

From the dependencies crack growth rate da/dt vs. K_{I} and α vs. K_{I} for two “steel - environment” systems with distinctive micro- and macrobranching cracks, the corrected kinetic diagrams of fracture (KDF) were plotted in da/dt - K_{Ieff} coordinates (Fig. 1). There is a plateau in the KDF in nominal coordinates (da/dt - K_{I}), but this one is absent in the KDF in effective coordinates (da/dt - K_{Ieff}). This is evidence of the responsibility of crack branching for the seeming ambiguity of the correlations between crack growth rate and SIF.

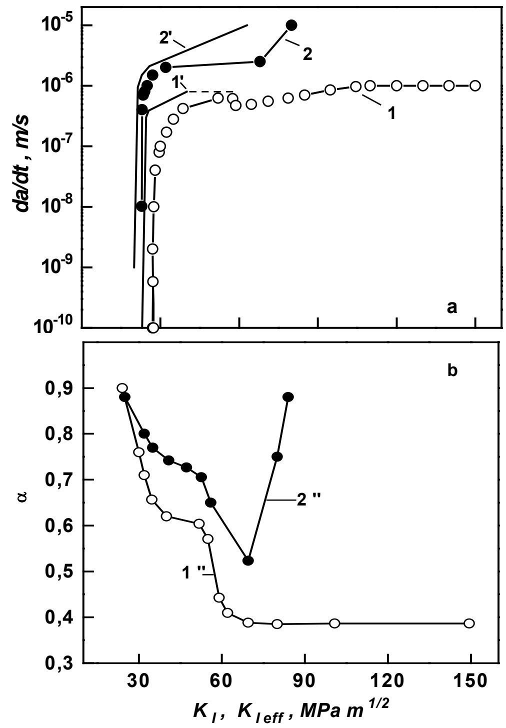

Figure 1. Dependencies *da*/*dt* - K_I (1, 2), *da*/*dt* - K_{Ieff} (1′, 2′) and α - K_I (1″, 2″) for tempered at 473 K 0.2C-13Cr steel in 3% NaCl solution (1, 1′, 1″) and tempered at 673 K 0.45C-Cr-2Ni-Mo-V steel in distilled water (2, 2′, 2″).

Crack branching causes a number of unexpected effects in corrosion fracture mechanics. For example, the lifetime curve for martensitic stainless steels is non-monotonic and consists of two parts (Fig. 2a): in the lower part the crack micro- and in the upper part macrobranching are observed.

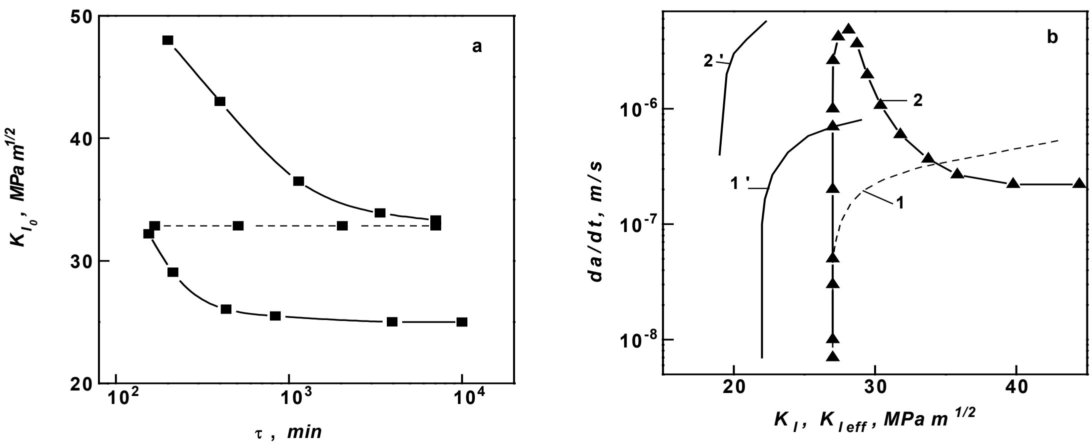

Figure 2. The life-time diagram (*a*) and KDF (*b*) in *da*/*dt* - K_I coordinates (1, 2) and *da*/*dt* - K_{Ieff} coordinates (1′, 2′) for 0.2C-13Cr steel (tempered at 473 K) in 3% NaCl solution at the corrosion potential (1, 1′) and cathodic potential φ = -1200 mV (2, 2′).

That's why by decreasing the testing base the precision of evaluating the K_{Iscc} level decreases. For the same system cathodic polarization initially accelerates SCG and then drastically retards it, as compared to the tests at corrosion potential (Fig. 2b). This can be considered as indication of the local anodic dissolution mechanism in the last case of SCG. However, metallographic investigations showed that similar kinetic effects appear also due to intensive crack branching. Consequently, if the possible variation of the crack morphology is not taken into account, usage of outer polarization for evaluation of the mechanism of the corrosion environment effect can lead to the wrong conclusions.

While investigating the structural sensitivity of the corrosion crack growth resistance characteristics of 0.45C-2Cr-Mo-V steel, the stress state at the crack tip , is proposed, to be evaluated using ratios $K_I/\sqrt{\rho}$, $K_I/\sqrt{\rho_{eq}}$, $K_{Iscc}/\sqrt{\rho_{scc}}$, (ρ_{scc} is the crack tip radius in the specimen after testing base at the level of K_{Iscc}). Thus, it is possible to consider the material structure-defined ability to stress relaxation by plastic deformation in the vicinity of the crack tip. Under active loading of the specimens, the stresses at the crack tip, characterised by $K_I/\sqrt{\rho}$ parameter, at first grow and later remain constant at a certain level. The following experimentally proved condition of realization of two alternative criteria of local fracture during K_{Ic} tests has been formulated: if under active loading up to critical SIF, the value of $K_I/\sqrt{\rho}$ steadily increases, the force fracture criteria and cleavage fracture mechanisms are realized; if stress stabilization precedes the K_{Ic} level, under increasing deformation in the vicinity of the crack tip, the deformation fracture criteria and microcleavage fracture mechanism are true.

The evolution of the structural sensitivity of $K_{Iscc}/\sqrt{\rho_{scc}}$ parameter, which characterizes the stress state at the crack tip at the threshold of the corrosion-static crack growth resistance, showed (Fig. 3) that in the temperature range of irreversible tempered embrittlement (573-673 K) a sharp decrease of fracture resistance is observed. For the low (473 K) and high (773 K) tempering, the value $K_{Iscc}/\sqrt{\rho_{scc}}$ is practically unchanged.

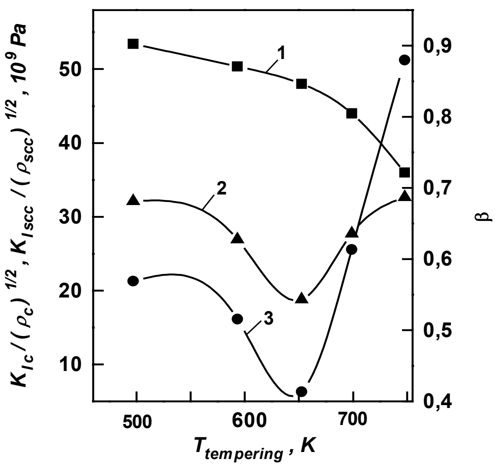

Figure 3. Dependence of parameters $K_{Ic}/\sqrt{\rho_c}$ (1), $K_{Iscc}/\sqrt{\rho_{scc}}$ (2) and β (3) vs. tempering temperature $T_{tempering}$ for 0.45C-2Cr-Mo-V steel in distilled water.

The decrease of coefficient β ($\beta = K_{Iscc}\cdot\sqrt{\rho_c}\ /\ K_{Ic}\cdot\sqrt{\rho_{scc}}$, where ρ_c is the fatigue crack tip radius at K_{Ic} level) characterized the degree of fracture stresses degreases. The influence of corrosive environment is maximum for the steel in the state of tempered embrittlement and minimum - for the high tempered steel.

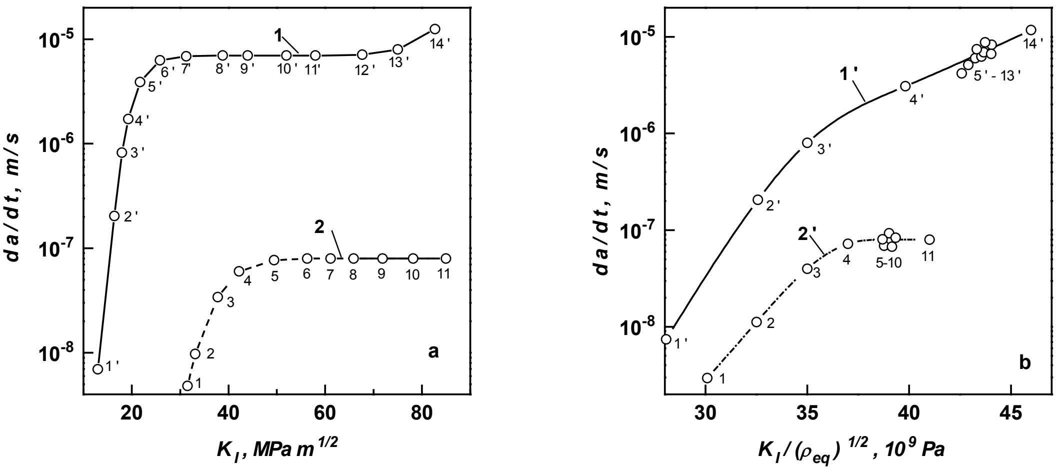

Figure 4. KDF *da/dt* - K_I (*a*, 1, 2) and *da/dt* - $K_I/\sqrt{\rho_{eq}}$ (*b*, 1′, 2′) in distilled water for 0.45C-2Cr-Mo-V steel tempered at 653 K (1, 1′) and 773 K (2, 2′). Identically numbered points at the curves correspond to same value of K_I.

Within the tempered embrittlement range (653 K) and after high tempering (773 K), the KDF for the 0.45C-2Cr-Mo-V steel is has a clear plane region (Fig. 4a). The metallographic analyses proved that in the first case, stabilization of *da/dt* in the wide range of nominal SIF is due to crack branching, and in the second case it is caused by the extensive crack tip blunting. When the KDF is replotted in *da/dt* - $K_I/\sqrt{\rho_{eq}}$ coordinates, there is a plane region for the high tempered steel, but not for the tempered embrittlement steel (Fig. 4b). Thus, the reploted KDF is an additional indicator what criteria (force or deformation) should predetermine fracture during SCC.

The Retarded Yielding Phenomenon

The crack tip gets blunted due to plastic deformation thus decreasing the stress concentration. This influences also the process of retarded yielding under sustained loading, especially in SCC tests. Thus, the retarded yielding of a material at the crack tip stretches this material on the one hand, and decreases the stress concentration at the crack tip on the other hand. Different ways exist to reveal the presence of retarded yielding of a material at the crack tip. Recording of the crack opening displacement or load line displacement, like it is performed in fracture toughness tests or during the measurement of the *J*-integral, can be used. However, in this case the recording of a force *F* vs. crack opening displacement δ (or deflection *f*) diagram is not restricted to ramp loading of pre-cracked specimen only, but it should be continued under sustained loading. The existence of a horizontal part on the diagram at maximum level of F indicates the occurrence of retarded yielding. SCC tests at constant loading structure steels in corrosion invironments show an increase of the value of deflection after loading. This is caused by retarded yielding of the material at the crack tip. The intensity of this process decreases with the time of exposition leading to a certain stabilisation. In-situ observation of the crack geometry can visualise the plastic deformation process during sustained loading. It is hardly possible to directly record the level of crack tip blunting; instead, it is easier to measure an increase in crack opening displacement. The retarded yielding phenomenon causes crack tip blunting and a decrease in stress concentration, a comparison of the fracture toughness of specimens showing different levels of crack blunting should reflect the change of the stress concentration. The decrease in stress concentration due to crack tip blunting was experimentally verified by determining the fracture toughness of Cr-Ni-Mo steel specimens in liquid nitrogen. These specimens were for different periods of time pre-exposed to a 3% NaCl solution at similar levels of J_I ($J_I > J_{Iscc}$) (Fig. 5), etc., which can substantially decrease the stress level in the vicinity of the corrosion crack tip.

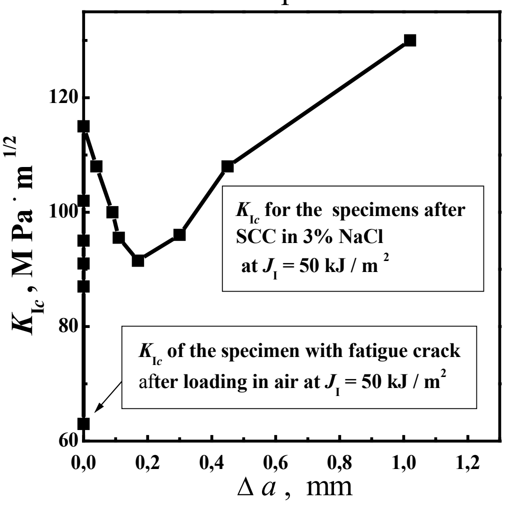

Figure 5. Influence of SCC increment Δa on K_{Ic} of Cr-Ni-Mo steel in liquid nitrogen.

At first, the fracture toughness increased (compared to precracked specimens which were subjected to the same level of J_I in air during the active loading). This confirms the assumption of crack tip blunting under the sustained loading. However, when the exposure time exceeded a certain level, the fracture toughness in liquid nitrogen decreased significantly. This is due to the initiation of a corrosion crack from the tip of the blunted fatigue crack. Since the corrosion crack is relatively sharp, it causes a high stress concentration. A further increase of the fracture toughness was observed when the crack extension exceeded 0.2 mm. This can be related to the corrosion crack branching.

Effect of Retarded Yielding on SCC Size Effect

Using the examples of engineering steels of different strength levels [4], it can be shown that the retarding yielding phenomenon can be responsible for size effects observed in SCC. For the 0,45C-2Cr-Mo-V steel it was shown that the parameter K_{scc} is more sensitive to b changes than K_c (Fig. 6*a*). A constant level of K_{Ic} for different b still does not guarantee a

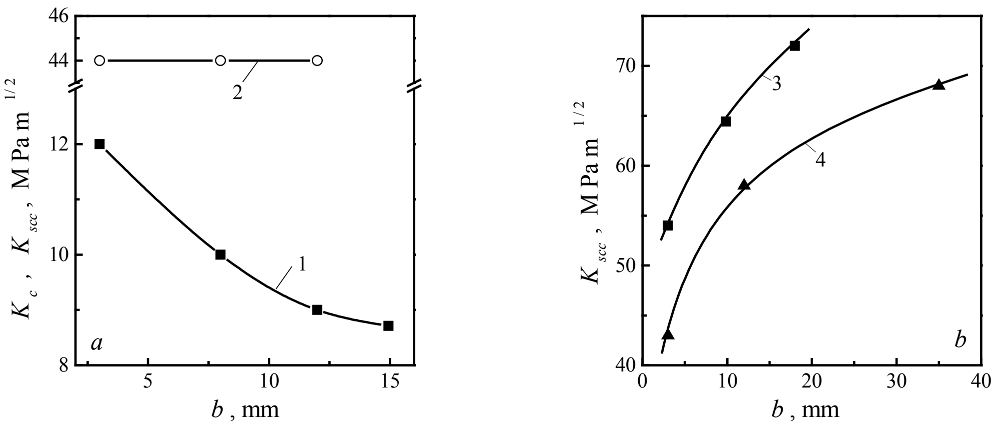

Figure 6. Dependences of $K_{scc} - b$ (1, 3 ,4) and $K_c - b$ (2) for 0,45C-2Cr-Mo-V (*a*), 20Cr (*b*, 3), and Cr-Ni-Mo (*b*, 4) steels with σ_{YS} =1790, 1150 and 1170 MPa correspondenly tested in air (2), water (1, 3) and in 3% NaCl solution (4).

constant value of K_{Iscc} which could be considered as a characteristic of the material/environment system. The test of the high-ductile steel lead to an inverse effect of the size factor: with increase of the *b*-factor, the parameter K_{scc} increases (Fig. 6*b*). These results can be related to the plastic deformation at the crack tip during the sustained loading. For steel of low ductility K_{Iscc} decreases with increasing specimen thickness, whereas for the more ductile steels it increases.

CONCLUSIONS

The procedure for evaluation of the curvilinear path of the SCC, their branching and blunting is proposed. It has been shown that the precision of evaluating the K_{Iscc} level decreases and the usage of outer polarization for evaluation of mechanism of corrosion environment effect can lead to the wrong conclusion if the possible variation of the crack morphology is not taken into account. Sustained loading of pre-cracked specimens is accompanied by the process of retarded yielding of the material at the crack tip. An inversion of the size effect on SCC for steels of different ductility levels in aqueous solutions has been observed as a result retarded yielding of the material at the crack tip.

REFERENCES

1. Student O.Z. Proc. 5th Polish Conf. Corrosion-96, Gdansk (1996), 575-578.
2. Student O.Z. Zeszyty Nauk. Politech. Swietokrzyskiej (1997) **62**, 439-445.
3. Nykyforchyn H., Student O. Proc. Conf.: Materials in Oceanic Environment - Euromat'98, Lisbon (1998), **1**, 569-576.
4. Nykyforchyn H., Tsyrulnyk O., Student O. Proc. Int.Conf.: Corrosion in Refinery Petrochemical and Power Generation Plants, Venezia, 2000. 83-92.
5. Malkin J., Tetelman A. *Eng. Fract. Mech.* (1971) **3**, 151-167.
6. Hirose Y., Tanaka K., Okabayashi K. *J. Soc. Mater. Sci., Jap.* (1978) **27**, 545-551.