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Modeling for corrosion fatigue crack initiation life based on corrosion kinetics and equivalent initial flaw size theory

Tianliang Zhao[a], Zhiyong Liu[a,*], Cuiwei Du[a,*], Chao Liu[a], Xuexu Xu[a], Xiaogang Li[a,b]

[a] Corrosion and Protection Center, University of Science and Technology Beijing, Beijing, 100083, China
[b] Ningbo Institute of Material Technology & Engineering, Chinese Academy of Sciences, Ningbo, Zhejiang, 315201, China

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ABSTRACT

In present paper, a novel, effective and economical model based on corrosion kinetics and equivalent initial flaw size theory was proposed to predict the corrosion fatigue crack initiation (CFCI) life of E690 steel in simulated seawater. Comparison between the predicted *S-N* curves and the measured data showed that this model was of nice accuracy under high peak stresses, while non-negligible deviation existed under low peak stresses due to lack of enough measured data or consideration for the stress effect on corrosion rate. Despite of that, thought of this model still has a good practicability in predicting CFCI life of steels.

1. Introduction

Since the mechanism of fatigue crack initiation becomes much more complex in corrosive medium than in air, it is quite difficult to predict the life of corrosion fatigue crack initiation (CFCI) precisely [1,2]. The CFCI life was usually predicted by following the traditional method used in fatigue in air, such as using *S-N* curves of small-size specimens [3]. Traditionally, *S-N* curves are obtained by fitting the scatter data in several groups with some empirical equations and their theory modifications [4–6]. It often needs enormous amount of material, tests and time to obtain a reliable *S-N* curve. Moreover, a tiny bit environmental change may result in a great difference in *S-N* curve. Thus, it is of significance to find an effective and economical way to evaluate the CFCI life.

For fatigue in air, the equivalent initial flaw size (EIFS) theory was proposed and applied to evaluate the crack initiation life [7–10]. The EIFS theory assumes that flaws on actual sample surface can be equivalent to a crack with certain size on ideally smooth surface [11,12]. The crack nucleates as the stress intensity factor range (SIFR) of the equivalent crack is greater than the threshold value of short crack propagation. However, the EIFS theory is not suitable for the samples with an ever-changing surface, such as the samples under corrosion. Maybe it is applicable after addressing the corrosion effects on surface flaws.

In order to evaluate the critical crack size and crack initiation life under corrosion, Müller [13] proposed three corrosion kinetics-based models for three corrosion forms: the uniform corrosion, the localized corrosion and the passive corrosion, respectively. But he took the crack growth threshold (ΔK_{th}) as the only criterion for crack initiation. D. W. Hoeppner [14] indicated that the ΔK_{th} criterion was not sufficient for crack initiation at low frequencies. The crack couldn't nucleate if the corrosion rate was greater than the initial crack propagation rate [15]. Turnbull et al. [16] gave a model for CFCI life prediction based on the statistical distribution of pit depth at different immersion duration. However, the prediction needed plenty of tests and time and was only suitable for pitting corrosion. M.A. Daeubler [17] and predicted the CFCI life and behavior of an iron-base superalloy through combining readily measureable electrochemical and mechanical properties. M. E. May [18] also applied the similar methods on the CFCI life prediction of a martensitic stainless steel. Their premise was both the passive electrochemical conditions which could ensure the availability of those properties but limits the application on other corrosion forms. Moreover, many empirical models or methods based on fracture mechanics were also proposed and developed due to their simplicity and practicability in engineering [3,19–26]. For example, S. I. Rokhlin [3] established an empirical relation between the depth of the corrosion pit and the fatigue life based on experimental data. X. Zheng [20,21] developed a formula for the fatigue crack initiation life by introducing the fracture mechanics analysis of corroded specimens into the Coffin formula. D. T. Rusk et al. [25] utilized an empirical approach based on large amounts of fatigue tests on corroded specimens to assess the residual fatigue life. However, those empirical models or methods were short of intrinsic relationship with corrosion mechanism. That usually induced a big distribution range of the predicted result. Therefore, we believe that our

* Corresponding authors at: 30 Xueyuan Rd., Beijing, 100083, China.
E-mail addresses: liuzhiyong7804@126.com (Z. Liu), dcw@ustb.edu.cn (C. Du).

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work can make a contribution to modeling the CFCI life by combining corrosion mechanism with fracture mechanics.

Based on the corrosion kinetics and EIFS theory, the present paper has successfully proposed a model for predicting CFCI life in efficient and economical way. Afterwards, the model was applied on E690 steel in simulated seawater and the predicted S-N curves were compared with the experimental data reported in our previous work [27,28]. At last, the accuracy and practicability of the model was discussed.

2. The theoretical basis and model description

2.1. Corrosion kinetics basis

Our previous studies had revealed that E690 steel showed different CFCI mechanisms at different peak stress ranges [27]. Under cyclic loadings with low peak stress (peak stresses below 0.8 $\sigma_{p0.2}$), anodic dissolution goes much faster at the grain boundaries than at grain interiors, resulting in localized corrosion along the grain boundaries prior to crack initiation. Under cyclic loadings with high peak stress (peak stresses above 0.8 $\sigma_{p0.2}$), broad pitting occurs on the surface instead of the intergranular corrosion, leading to crack initiation from the corrosion pits. The corrosion rates of both the two modes are the function of elapsed time, which can be expressed as follows [29].

$$a_{corr} = \mathrm{F}(t) = At^B + Ct + D \tag{1}$$

where a_{corr} is depth of the intergranular corrosion crevice or the corrosion pit, t the elapsed time and A, B, C, D the undetermined parameters. Since corrosion depth prior to crack initiation is a very small quantity, the relationship between a_{corr} and t is approximately linear. Thus, Eq. (1) is simplified as follows.

$$a_{corr} = A\cdot t + D \tag{2}$$

Moreover, previous studies [30–32] indicated that corrosion rate was quite affected by the suffered stress close to or above the proof stress ($\sigma_{p0.2}$) (here, we define "peak stress close to the proof stress" as "0.8 $\sigma_{p0.2} \leq \sigma_{max} < \sigma_{p0.2}$" for E690 steel). Therefore, we introduce the effect of stress on corrosion rate under high stress levels into Eq. (2).

$$a_{corr} = A'\cdot e^{\alpha\Delta\sigma}\cdot t + D \tag{3}$$

Thus, the expression of corrosion rate under high and low stress levels is as follows.

$$\left(\frac{da}{dt}\right)_{corr} = \begin{cases} A,\ \sigma_{max} < 0.8\sigma_{p0.2} \\ A\cdot e^{\alpha\Delta\sigma},\ \sigma_{max} \geq 0.8\sigma_{p0.2} \end{cases} \tag{4}$$

2.2. Equivalent initial flaw size theory

As to the prediction of fatigue life, the key is how to determine the crack initiation. For small-scale specimens, their crack propagation lives can be ignored compared with the whole fatigue lives. The whole fatigue life is approximately equivalent to the crack initiation life. For large-scale specimens, their crack initiation lives are just part of the whole lives. The crack initiation life in this situation is closely related to the critical size of crack nucleation. Currently, the critical size is determined mainly with three methods. One is the empirically defined crack size as the critical size, usually 0.25 ~ 1 mm for metals [33]. Another one is detecting the crack nucleation size by nondestructive testing methods [34]. Actually, the current nondestructive testing methods cannot truly detect the crack nucleation size. The prediction results would be usually overoptimistic if the empirically defined or nondestructively detected crack nucleation size was adopted. Thus, EIFS theory was introduced into the determination of the critical size of crack nucleation as the third method. As mentioned in the introduction, EIFS theory has been proved to be a practicable approach to evaluate the crack initiation and fatigue life. However, EIFS theory was mainly applied in the fatigue in air so far and barely adopted in corrosion fatigue [35].

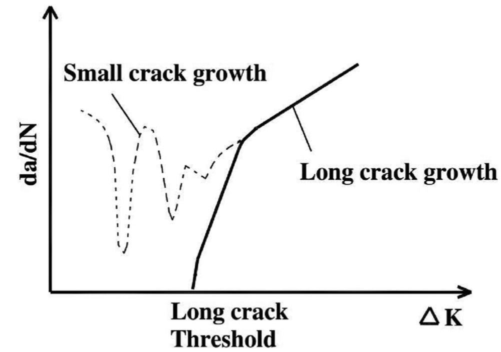

Fig. 1. Schematic diagram of short-crack and long-crack propagation in near-threshold regnion [7].

The concept of EIFS was first invented to address the problem of fatigue life prediction models based on fracture mechanics. As is known, any specimen surface cannot be absolutely smooth and always has defects including manufactured defects, corrosion defects and unexpected scratching and striking defects. All these defects on one surface can be equivalent to a hypothetical crack of an initial size on the surface, namely the EIFS. Then the next problem is how to determine the EIFS. Generally, cracks nucleating on surface are of typical short-crack features. As is well known, short cracks have propagation behaviors much different from those of long cracks [36–39]. Fig. 1 [7] shows the propagation behaviors of short crack and long-crack in near-threshold region. It is seen that the fluctuant small crack growth curve is quite deviated from the long crack growth curve in near-threshold region. Therefore, it is unreasonable to calculate the EIFS with long-crack propagation threshold. As the small-crack growth curve can hardly be measured, the EIFS theory adopts the back extension of Paris linear section to substitute the short-crack propagation curve. Generally, the SIFR obtained through back-extending Paris section to 10^{-10} mm/cycle is adopted as the short-crack propagation threshold. The literatures [8] had proved its feasibility.

2.3. Criterions for crack nucleation and fracture mechanics analysis

It is generally accepted that crack would not nucleate until corrosion trace, including the intergranular corrosion crevice and broad pit, reach a critical size. However, it can still be assumed that an imaginary crack, which is of size equivalent to the corrosion traces, exists before the real crack nucleation. The real crack nucleation must meet two critical conditions [40,41]:

$$\Delta K_{max} \geq \Delta K_{th} \tag{5}$$

$$\left(\frac{da}{dt}\right)_{crack} \geq \left(\frac{da}{dt}\right)_{corr} \tag{6}$$

where ΔK_{max} is the maximum SIFR of the imaginary crack, ΔK_{th} the critical SIFR of short crack propagation, $(da/dt)_{crack}$ the propagation rate in terms of time of the imaginary crack and $(da/dt)_{corr}$ the growth rate in terms of time of corrosion traces.

Figs. 2 and 3 show structural sketch of the imaginary crack corresponding to intergranular corrosion crevice under low peak stresses and corrosion pit under high peak stresses, respectively. Both the intergranular corrosion crevice and corrosion pit are seen as a semielliptical surface crack in an elastomer. The SIFR at crack tip is expressed as follows [42,43]:

$$\Delta K_{corr} = \frac{1.12\Delta\sigma\sqrt{\pi a}}{\phi}\left[\sin^2\theta + \left(\frac{a}{c}\right)^2\cos^2\theta\right]^{1/4} \tag{7}$$