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A nonlinear cumulative evolution model for corrosion fatigue damage*

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Abstract: A nonlinear cumulative evolution model for corrosion fatigue damage was proposed. Corrosion fatigue damage was considered as a nonlinear cumulative result of stress corrosion damage and fatigue damage. The influences of stress corrosion damage and fatigue damage on corrosion fatigue damage and damage evolution life were studied from a phenomenological point of view. The relevant damage parameters were determined by the experimental results of the LY12CZ aluminum alloy, and the corrosion fatigue life evaluation model based on damage evolution law was established. The corrosion fatigue life predicted by evaluation model agrees well with the experimental result. The damage evolution model in this study can provide a new method for theoretical research and life prediction of corrosion fatigue.

Key words: Corrosion fatigue, Stress corrosion, Nonlinear accumulation, Damage evolution
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1 Introduction

Corrosion fatigue is recognized as one of the significant degradation mechanisms that affect the reliability and durability of metal components and structures (Tang and Li, 2007; Bhuiyan *et al.*, 2008; Ishihara *et al.*, 2008; Zhao *et al.*, 2012; Huang and Xu, 2013; Misak *et al.*, 2013). Corrosion fatigue phenomenon is very common in marine and aerospace engineering, but there are many other issues which still do not have good solutions to this problem. With the flourish of damage mechanics (Lemaitre, 1985; Lemaitre and Chaboche, 1990; Fatemi and Vangt, 1998; Jain and Ghosh, 2008; Besson, 2010; Ohata *et al.*, 2010), some researchers tried to study corrosion fatigue behavior of metals from the perspective of damage evolution, and proposed some corrosion fatigue damage evaluation methods (Kotsikos *et al.*, 1999; Kermanidis *et al.*, 2005).

Corrosion fatigue damage is the property degradation process of materials caused by the constant initiation, propagation and merger of internal defects, under the interaction of cyclic loads and a corrosive environment, which can obviously accelerate the corrosion fatigue damage evolution, which is caused by the coupling effect of stress corrosion damage and fatigue damage. In general, the evolution of fatigue damage is cycle-dependent, while the accumulation of stress corrosion damage is time-dependent, so the meso-mechanism of this coupling is very complex. To simplify the characterization of corrosion fatigue damage, a nonlinear cumulative model of corrosion fatigue damage is proposed in this paper. Based on Miner's linear cumulative damage theory, the corrosion fatigue damage is dealt as the nonlinear

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accumulation of stress corrosion damage controlled by the average stress and fatigue damage controlled by the stress amplitude. The corrosion fatigue experiments of the LY12CZ aluminum alloy are designed to determine the relative damage parameters and establish the corrosion fatigue damage evolution law. Such an approach is practical and useful for the simulation of the entire corrosion fatigue damage process and the remaining life assessment in aging aircraft and ocean structures.

2 Theoretical model

2.1 Stress corrosion damage

The researches related to stress corrosion damage at present mainly adopt the continuum damage mechanics methods. These methods do not consider the variation of the internal microstructure of the material, but instead construct the damage constitutive equations and evolution equation by introducing the damage variables in different forms from a macro perspective to achieve the harmony of theoretical predictions and experimental results.

Generally, stress corrosion damage and its evolution are controlled by the mechanical properties of material and external factors such as static load, temperature, and corrosive environments. Therefore, the stress corrosion damage variable D_c is expressed as the formula of effective stress σ, stress corrosion threshold stress σ_{th}, time t, temperature T, and the pH value of solution, i.e.,

$$D_c = F_c(\sigma, \sigma_{th}, t, T, \text{pH}, \cdots), \tag{1}$$

where the effective stress is shown as $\sigma=P/A$, P is the load, and A is the effective bearing area.

In a specific experimental environment, the variation of temperature and pH value can be ignored, so the stress corrosion damage law is simplified as

$$\frac{\mathrm{d}D_c}{\mathrm{d}t} = f_c(\sigma, \sigma_{th}, D_c), \tag{2}$$

where $f_c(\,)$ is the derivative of $F_c(\,)$ with time.

When the effective stress of the specimen is less than threshold stress, tensile stress corrosion damage does not happen. Therefore, the stress corrosion damage evolution model can be simplified as (Chaboche, 1988a; 1988b; Wu *et al.*, 2004; Alamilla *et al.*, 2009; Raykar *et al.*, 2011)

$$\frac{\mathrm{d}D_c}{\mathrm{d}t} = \begin{cases} \kappa \dfrac{(\sigma - \sigma_{th})^p}{(1-D_c)^q}, & \sigma > \sigma_{th}, \\ 0, \ \sigma \le \sigma_{th}, \end{cases} \tag{3}$$

where κ, p, and q are material constants related to environment.

2.2 Corrosion fatigue damage model

In the conventional damage theory, time is always used as the reference variable for damage evolution. However, for fatigue caused by cyclic loading, the damage accumulates with load cycles, so the form of the fatigue damage evolution equation is often written as

$$\frac{\mathrm{d}D_f}{\mathrm{d}N} = F_f(\sigma_{max}, \sigma_0, D_f, T, \cdots), \tag{4}$$

where D_f is the fatigue damage variable, N is the load cycle, σ_{max} is the maximum stress, and σ_0 is the average stress.

If only the influence of cyclic stress amplitude σ_a is considered in the above fatigue damage model, fatigue damage per cycle can be simplified as (Chaboche, 1981; Fatemi and Vangt, 1998; Zhang *et al.*, 2011)

$$\frac{\mathrm{d}D_f}{\mathrm{d}N} = (1-D)^{-\mu} \left(\frac{\sigma_a}{M(\sigma_0)} \right)^B, \tag{5}$$

where D is the corrosion fatigue damage variable, μ and B are experimental constants, and $M(\sigma_0)$ is a material parameter relative to average stress.

The corrosion fatigue damage is caused by the interactions of corrosive environment and cyclic loading, but it is essentially different from stress corrosion damage and fatigue damage. In this study, the idea is proposed that stress corrosion damage and fatigue damage occur during the corrosion fatigue process and mutually reinforce the damage evolution.

Consequently, corrosion fatigue damage is dealt with as the accumulation of stress corrosion damage and fatigue damage.

If the stress corrosion damage and fatigue damage accumulate linearly, the corrosion fatigue damage increment can be written as

$$\mathrm{d}D = f_{\mathrm{c}}\mathrm{d}t + F_{\mathrm{f}}\mathrm{d}N. \tag{6}$$

The linear damage accumulation model is simple, but its prediction is too inaccurate to be adopted. In contrast, the nonlinear cumulative damage evolution law is more acceptable for most materials, namely,

$$\mathrm{d}D = (1-D)^{-\omega} f_{\mathrm{c}}\mathrm{d}t + F_{\mathrm{f}}\mathrm{d}N, \tag{7}$$

where ω is the non-negative damage cumulative exponent.

Combined with the nonlinear accumulation method, the corrosion fatigue damage evolution law can be rewritten as

$$\frac{\mathrm{d}D}{\mathrm{d}N} = \kappa f(\sigma-\sigma_{\mathrm{th}})^{p}(1-D)^{-\psi} + (1-D)^{-\mu}\left(\frac{\sigma_{\mathrm{a}}}{M(\sigma_0)}\right)^{B}, \tag{8}$$

where f is the cyclic load frequency, and $\psi=q+\omega$.

Introducing N_{f} to characterize the load cycles of fatigue failure and modifying the stress corrosion failure life in the form of a cycle number, denoted as N_{c}, according to the respective damage evolution law, we have

$$N_{\mathrm{f}} = \frac{1}{(\mu+1)}\left(\frac{\sigma_{\mathrm{a}}}{M(\sigma_0)}\right)^{-B}, \tag{9}$$

$$N_{\mathrm{c}} = \frac{1}{\kappa f(1+\psi)(\sigma-\sigma_{\mathrm{th}})^{p}}. \tag{10}$$

Substituting Eqs. (9) and (10) into Eq. (8), the corrosion fatigue damage evolution law equation is rewritten as

$$\frac{\mathrm{d}D}{\mathrm{d}N} = \frac{(1-D)^{-\psi}}{(1+\psi)N_{\mathrm{c}}} + \frac{(1-D)^{-\mu}}{(1+\mu)N_{\mathrm{f}}}. \tag{11}$$

Integrating Eq. (11), the corrosion fatigue life based on the damage evolution law is obtained as

$$\frac{N}{N_{\mathrm{c}}} = \int_0^1 \left(\frac{(1-D)^{-\psi}}{(1+\psi)} + \frac{N_{\mathrm{c}}(1-D)^{-\mu}}{N_{\mathrm{f}}(1+\mu)}\right)^{-1}\mathrm{d}D. \tag{12}$$

3 Experiments on damage parameters determination

3.1 Materials and specimens

To determine the damage parameters of the above corrosion fatigue damage evolution model, experiments for corrosion fatigue and stress corrosion are designed. The sample material is the LY12CZ aluminum alloy and taken from the same sheet, and the related mechanical properties are shown in Table 1. The sample is a funnel-shaped design shown in Fig. 1.

Table 1 Mechanical property for the LY12CZ aluminum alloy

Young's Modulus, E (GPa)	Yield limit, $\sigma_{0.2}$ (MPa)	Ultimate strength, σ_{b} (MPa)	Elongation, δ
72	320	460	0.174

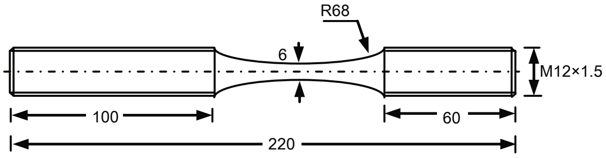

Fig. 1 Schematic diagram of funnel-shaped specimen (unit: mm)

3.2 Damage parameters of stress corrosion

Stress corrosion experiments of the LY12CZ aluminum alloy exposed in 3.5% NaCl (in weight) solution (pH=7.0) at room temperature (20 °C) are carried out on the slow strain-rate stress corrosion testing machine (GB/T 15970.4–2000; G49-85–2011). According to the actual experimental conditions, the testing strain-rate is taken as 1×10^{-6}/s (Li *et al.*, 2010; Kim *et al.*, 2010; Nakano *et al.*, 2012). The stress corrosion life curve declining with effective stress is shown in Fig. 2. As can be seen, the stress corrosion life is constantly decreasing with the increase of the effective stress. Through numerical regression of the experimental data, the stress corrosion life model of LY12CZ in 3.5% NaCl (in weight) solution is determined, and the stress corrosion threshold stress is shown to approach 172 MPa.

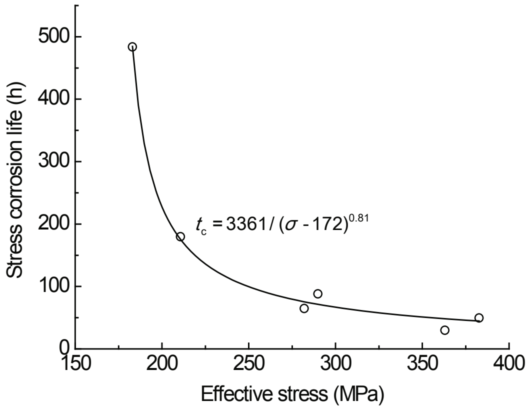

Fig. 2 Stress corrosion life curve of LY12CZ aluminum

3.3 *S-N* data of corrosion fatigue

Corrosion fatigue experiments of the LY12CZ aluminum alloy are carried out on the MTS809 servo fatigue testing machine, with the loading equipment of samples as shown in Fig. 3. The experiments are done at 10 cycles per second using cyclic stress fluctuations in the form of a sinusoidal wave controlled through a constant stress amplitude (GB/T 20120.1–2006; E466-07–2007). The maximum stress of the two groups of samples (6 samples per group) is set to 400 MPa and 360 MPa, respectively, with the load ratio of 0.1.

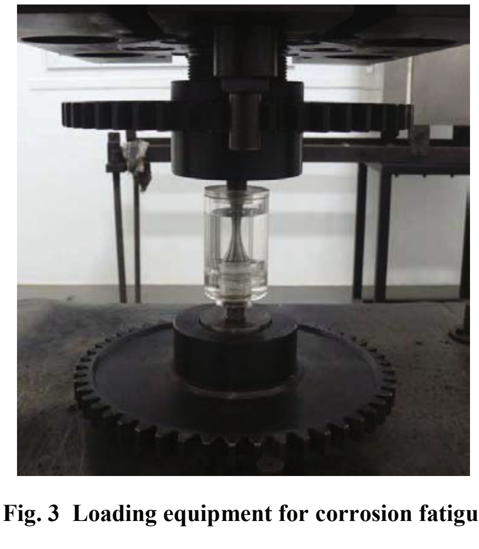

Fig. 3 Loading equipment for corrosion fatigue

The corrosion fatigue *S-N* data of the LY12CZ aluminum alloy in 3.5% (in weight) NaCl solution are shown in Fig. 4. Because of the processing of the samples and the operation factors during testing, the experimental results had certain dispersions. After being averaged, the corrosion fatigue life of the samples at the maximum stress of 400 MPa (average stress σ_0=220 MPa, stress amplitude σ_a=180 MPa) is 10084 cycles, and the corrosion fatigue life at the maximum stress of 360 MPa (average stress σ_0= 198 MPa, stress amplitude σ_a=162 MPa) is 13460 cycles.

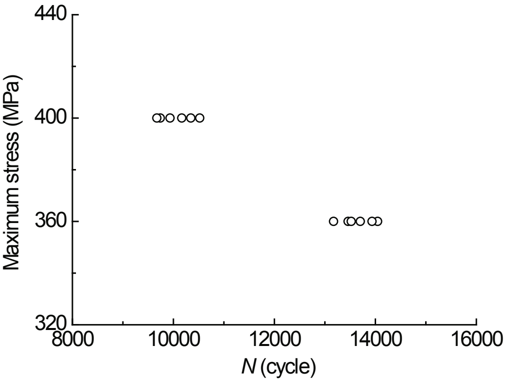

Fig. 4 The *S-N* data of corrosion fatigue

4 Damage evolution model of corrosion fatigue

According to the stress corrosion and corrosion fatigue life data of the LY12CZ aluminum alloy, the corrosion fatigue damage evolution model is established and the relative damage parameters are determined. On the basis of the considerable experimental data for LY12CZ smooth specimens, Gao *et al.* (1999) summarized the fatigue life formula, i.e.,

$$N_{\mathrm{f}} = 1.634\times10^{9}\left(\frac{466^4}{466^4-\sigma_0^4}\sigma_{\mathrm{a}}-43\right)^{-2.1319}. \quad (13)$$

When only the influence of stress amplitude to fatigue life is considered, the fatigue damage evolution parameters can be determined by fitting the fatigue experimental results under different stress amplitudes with average stress unchanged. Combined with Eq. (5), the formula for fatigue life based on damage evolution can be modified as

$$\lg\sigma_{\mathrm{a}} = \lg M(\sigma_0) - \frac{1}{B}\left[\lg N_{\mathrm{f}} + \lg(\mu+1)\right]. \tag{14}$$

The fatigue damage parameters at σ_0=220 MPa are regressed as

$$M(\sigma_0)=3762.3,\ B=2.969,\ \mu=-0.809, \tag{15}$$

and at σ_0=198 MPa,

$$M(\sigma_0)=3324.6,\ B=2.942,\ \mu=-0.874. \tag{16}$$

Consequently, the corrosion fatigue damage evolution formulas at σ_0=220 MPa and σ_0=198 MPa are rewritten as

$$\frac{N}{N_{\mathrm{c}}} = \int_0^1 \left(\frac{(1-D)^{-\psi}}{1+\psi} + \frac{(1-D)^{0.809} N_{\mathrm{c}}}{0.191 N_{\mathrm{f}}} \right)^{-1} \mathrm{d}D, \tag{17}$$

and

$$\frac{N}{N_{\mathrm{c}}} = \int_0^1 \left(\frac{(1-D)^{-\psi}}{1+\psi} + \frac{(1-D)^{0.874} N_{\mathrm{c}}}{0.126 N_{\mathrm{f}}} \right)^{-1} \mathrm{d}D. \tag{18}$$

Since Eqs. (17) and (18) cannot be explicity integrated, the Gaussian integration method is adopted for computing the corrosion fatigue damage evolution life (ΔD=0.001). Corrosion fatigue lives based on damage evolution theory vary with the corrosion fatigue damage index ψ (Figs. 5 and 6). As can be seen, the theoretical curve fits quite well with the experimental data when the damage index ψ valued 0.0002 at σ_0=220 MPa, and the theoretical one fits well with the experimental data when ψ valued 0.001 at σ_0=198 MPa. In short, all the corrosion fatigue damage parameters can be determined by fitting the experimental results of the relative materials, and thus a complete corrosion fatigue life prediction model based on damage evolution theory is formed.

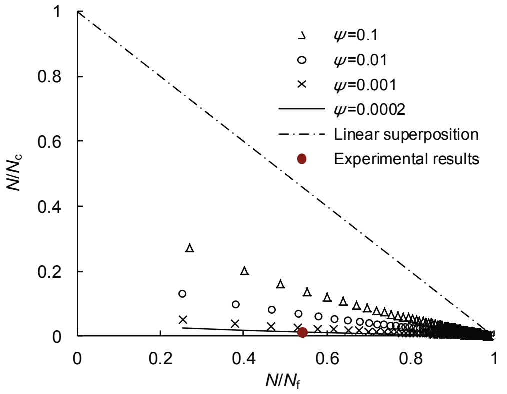

Fig. 5 Corrosion fatigue damage life of the LY12CZ aluminum alloy at σ_0=220 MPa

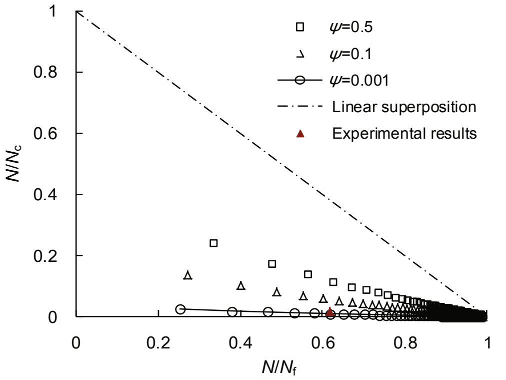

Fig. 6 Corrosion fatigue damage life of the LY12CZ aluminum alloy at σ_0=198 MPa

5 Conclusions

Based on the theory of damage mechanics, a corrosion fatigue damage evolution model is proposed. Corrosion fatigue damage is treated as the nonlinear accumulation of stress corrosion damage and fatigue damage. Combined with the experimental results of the LY12CZ aluminum alloy, the corrosion fatigue damage parameters are determined and the theoretical corrosion fatigue life prediction model of the LY12CZ aluminum alloy is established. This model can provide a new method for the theoretical study of corrosion fatigue and its life prediction.

However, to reduce the number of damage parameters and to determine these damage evolution parameters in convenience, only the influence of alternating stress amplitude on the damage evolution is considered in this paper, recognizing the uncertainty of the physical meaning of these parameters and the poor application of the corrosion fatigue damage model. At the same time, the corrosion fatigue damage evolution parameters may have certain differences for different materials. So the determination of the relative damage parameters should rely on the experimental data of the corresponding material. Thus, the corrosion fatigue damage evolution model will be improved gradually.

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中文概要：

本文题目：一种腐蚀疲劳损伤的非线性累加演化模型

A nonlinear cumulative evolution model for corrosion fatigue damage

研究目的：提出一种新的腐蚀疲劳损伤演化模型，建立基于损伤演化的腐蚀疲劳寿命预测模型。

创新要点：将应力腐蚀损伤与疲劳损伤非线性耦合，建立腐蚀疲劳损伤演化律，依托实验确定腐蚀疲劳损伤演化参数，形成基于损伤演化律的腐蚀疲劳寿命预测模型。

研究方法：采用理论研究与实验验证相结合的研究方法。选取特定材料设计应力腐蚀实验，回归应力腐蚀门槛值应力和损伤参数（图 2）；查阅疲劳实验数据建立变幅疲劳损伤模型，将应力腐蚀损伤与变幅疲劳损伤非线性累加形成腐蚀疲劳损伤非线性演化模型。根据腐蚀疲劳实验结果，验证腐蚀疲劳损伤演化模型并确定非线性损伤累加参数（图 5 和 6），形成基于损伤演化律的腐蚀疲劳寿命预测模型。

重要结论：从损伤力学角度，将材料的腐蚀疲劳损伤处理成应力腐蚀损伤与疲劳损伤的非线性累加，形成腐蚀疲劳损伤演化模型。结合 LY12CZ 铝合金的试验结果，验证了损伤演化模型的可行性。该方法可以为材料腐蚀疲劳的寿命评价研究提供新的思路。