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THE DAMAGE MECHANICS ANALYSIS METHOD FOR METALLIC MATERIAL CORROSION FATIGUE PROBLEM

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ABSTRACT

Based on the theory of continuum damage mechanics, the prediction model of pre-corrosion fatigue life for metallic materials was established. Firstly, the damage evolution equation to estimate the metallic materials' pre-corrosion fatigue life was deducted according to the thermodynamics of damage, and additional initial damage extent was employed to describe the effects on the specimens' life at the different pre-corrosion level. Furthermore, the expression of the fatigue life about the stress and initial damage extent was gained under the conditions of constant amplitude loading. In this article, the pre-corrosion fatigue test data of LC4CS aluminum alloy plate in a manual were collected to fit the parameters of the damage evolution equation, the results showed that the additional initial damage extent increased as the corrosion level rose, the predicted life which came from the analysis model of damage mechanics were anastomosis well with experiment data.

Keyword: pre-corrosion; corrosion fatigue; damage mechanics analysis; Life prediction

1. INTRODUCTION

Corrosion problem throughout the various departments and industries, it has a serious harm on the national economy and national defense. In particular, the effect of corrosion will make a number of great accidents, the damage extent of structural corrosion is difficult to predict as well. According to the U.S. survey published in 2000, the loss caused by corrosion is about 4.7% of the total output value of its national economy. Moreover, our country up to 400 billion yuan approximately. In a variety of corrosive environments, the marine environment makes a non-ignored impact on the aircraft structure, because the life of aircraft structure is severe decreased in the marine salt spray environment. At the same time, the effect of corrosion and mechanical couping will accelerate the aircraft structure failure ahead of time, greatly reduces the fatigue limit and the damage threshould. Today, the service life of aircraft has a higher requirement, generally more than 25 years, which is a great trial for the aircraft design and life assessment, it needs to accurately predict the effects of corrosion on the aircraft structure. In addition, high temperature, great humidity and much of the coast in southern of our country, that are the very environment to corrode.

In the salt spray environment[1-5], pitting is the major corrosion at the metal surface, the accelerated destruction of metallic structure occurs under a force, which is named mechanical and chemical effects. Furthermore, corrosion is a kind of local behavior, pits on the metal surface can make the load-bearing area reduced and local stress concentration increased. So, the fatigue life of structure decreases quickly. Moreover, the fatigue crack usually occurs from the bigger corrosion pits. Therefore, it needs to study the corrosive effect on the metellic structural fatigue life.

There are many of methods to research the effects of corrosion on the fatigue life of structure. For example, the life of structure is divided into multiple stages first, and the next is to calculate each life of stages and superpose them, then the whole life of structure is got[6]. The probabilistic models of corroded fatigue for specimens were found in some articles[7,8]. There are also application the methods of damage mechanics and fracture mechanics to

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investigate it. Some articles [9,10] study from the experiments, accumulate a lot of test data for the model provided a strong basis.

The accelerated test of salt spray under the conditions of loading or not for high-strength aluminum alloy specimens was studied by Ling Wu[11]. Based on the thermodynamic theory, from the two sides of microscopic damage mechanics and continuum damage mechanics, the fatigue crack initiation lifes for high-strength aluminum alloy were researched. The Peterson's fatigue notch sensitivity theory was applied by D. T. Rusk *et al.*[12], the notch metric equation to estimate the peak stress concentration value was developed, and the corrosion fatigue life for high-strength steel was predicted. The fracture mechanics method was employed to predict the previous corrosion fatigue life for aluminum alloy by T. Ghidini and C. Dalle Donne[13]. To simulate the maximum corroded pit on the corrosive specimen's surface, an semi-elliptical surface crack was made at the center of non-corrosive specimen's surface. The two kinds of specimens which were pre-corrosion specimen and with center surface crack specimen were tested, and the notched specimen life was analyzed by using software. The fatigue lifes of 2024-T3 aluminum alloy which in the cases of different corrosive time, different corrosive position and different stress level were investigated by K. M. Gruenberg *et al.*[14]. In Youhong Zhang's[15] Ph.D dissertation, corrosion-induced damage extent on the structural life for aircraft aluminum alloy structure was researched. The two main forms of corrosion of aluminum structure—pitting corrosion and denudation corrosion—were discussed. A probability modeling of corrosive damage evolution was setted up, realizing that both different temperature and different corrosion time for specimens' damage extent obeyed Logistic distribution, then the local stress of pits were calculated with ANSYS software.

In this article, based on the continuum damage mechanics method, the damage evolution equation under the fatigue loading is established for pre-corrosive metallic structures. The pre-corrosion fatigue test data of the LC4CS aluminum alloy plate in the Mechanical Properties Handbook[16] were used to authenticate the model. The additional initial damage extent which caused by corrosion has been gained in different corrosive extent. By comparison of theoretical model's results and experimental data, the feasibility for damage mechanical model has been verified.

2. DAMAGE MECHANICS MODEL OF PRE-CORROSION FATIGUE ANALYSIS

2.1. In the Conditions of Pre-corrosion, the Damage Extent and Constitutive Relations

In the cycle load, the material deterioration reflects a decline in material stiffness. So, the damage extent is introduced to describe it as follows

$$D=\frac{E-E_D}{E},0\le D\le 1 \tag{1}$$

The E is Young's modulus without damage, and the E_D is defined for Young's modulus when the damage extent is D.

Considering the effect of corrosion, the Eq.(1) is changed into

$$D=D_j+D_f=\frac{E-E_D}{E},\ 0\le D\le 1 \tag{2}$$

In the Eq. (2), the damage extent D_j is caused by cycle load, the D_f describes the additional damage extent which comes from pre-corrosion. The D_f is a constant after pre-corrosion completion, it is not changed as the cycle load changes.

The linear elastic constitutive relation without damage is

$$\sigma_{ij}=\delta_{ij}\lambda\delta_{kl}\varepsilon_{kl}+2\mu\varepsilon_{ij} \tag{3}$$

in the Eq.(3), σ_{ij} and ε_{ij} express the stress component and strain component respectively, λ and μ are Lame constants

$$\lambda=\frac{E\nu}{(1+\nu)(1-2\nu)},\mu=G=\frac{E}{2(1+\nu)} \tag{4}$$

There, E is the Young's modulus without damage, ν is the Poisson's ratio and G is the Shear modulus without damage.

Based on the Eqs. (2), (3), the constitutive equation which considers the damage effect of pre-corrosion and cycle load can be gained as follows

$$\sigma_{ij} = (1 - \mathrm{D})\delta_{ij}\, \lambda\delta_{kl}\, \varepsilon_{ld} + 2(1 - \mathrm{D})\mu\varepsilon_{ij} \tag{5}$$

it reflects the the coupling between damage field and stress-strain fields.

2.2. The Damage Evolution Equation under the Conditions of Pre-corrosion

Fatigue failure is a process of irreversible thermodynamics, according to thermodynamic theory, under the uniaxial stress state, damage driving force is introduced

$$Y = -\frac{\partial W}{\partial D} = \frac{W}{1 - D} \tag{6}$$

where W is strain energy density at the damage evolution.

According to Eq. (6), the damage evolution rate can be expressed as the following forms:

(1) if $Y_{\max} > Y_{th,km}$ ($Y_{\max}$ is the damage driving force maximum, $Y_{th,km}$ is damage threshold.)

$$\frac{dD}{dN} = a\frac{\left(Y_{\max}^{\frac{1}{2}} - Y_{th,km}^{\frac{1}{2}}\right)^{m_k}}{(1 - D)^{m_k}} \tag{7}$$

(2) if $Y_{\max} < Y_{th,km}$

$$\frac{dD}{dN} = 0 \tag{8}$$

where a, m_k and $Y_{th,km}$ are undetermined parameters, they relate to the material property, state of stress concentration,initial damage extent and other factors.

2.3. Fatigue Life Prediction for Pre-corrosion Smooth Specimen

Using the $\sigma_{\max}$ represents the maximum stress which is caused by cycle load, the $\sigma_{\mathrm{th},1m}$ expresses the stress threshold when $K_T = 1$. From Eqs. (6), (7), the damage evolution equation at $K_T = 1$ is described as

$$\frac{dD}{dN} = \alpha_1 \frac{(\sigma_{\max} - \sigma_{th,1m})^{m_1}}{(1 - D)^{2m_1}} \tag{9}$$

in Eq.(9),

$$\alpha_1 = a\left(\frac{1}{2E}\right)^{\frac{m_1}{2}} \tag{10}$$

Assuming that the damage extent is 1 when the specimen failure. Integrate Eq. (9), the damage evolution equation is changed into

$$(\sigma_{\max} - \sigma_{th,1m})^{m_1} N_f = \frac{1}{\alpha_1(2m_1 + 1)}(1 - D_{0,1m})^{2m_1 + 1} \tag{11}$$

Using the notation

$$D_{0,1m} = D_{0,j} + D_f \tag{12}$$

in which, $D_{0,1m}$ is the material's total initial damage extent after pre-corrosion finished, $D_{0,j}$ is the damage extent which is caused by mechanical processing, heat treatment and other factors, D_f is the additional initial damage extent caused by pre-corrosion.

To separate variables of Eq. (11) and integrate it, the logarithmic form of the equation is

$$\lg N_f = \lg\left[\frac{1}{\alpha_1(2m_1+1)}(1-D_{0,1m})^{2m_1+1}\right] - m_1 \lg(\sigma_{\max} - \sigma_{th,1m}) \tag{13}$$

where, $\sigma_{th,1m} = \sigma_{th0}\,(1 - D_{0,1m})$, σ_{th0} indicates the threshold of material without damage, it is a material constant. The Eq. (13) is the relationship between fatigue crack initiation life N_f and maximal stress $\sigma_{\max}$ at the $K_T = 1$. It can be received the fatigue life curve in different initial damage extent from Eq. (13), which corresponds to commonly used median fatigue life curve, and the $D_{0,1m}$ in Eq. (13) corresponds to the initial damage extent of the median fatigue life curve.

2.4. Fatigue Life Prediction for Pre-corrosion Notched Specimen

From conservation integral principle of damage mechanics, in the small scale damage conditions, at the stress concentration point and its neighboring regions, the strain energy density W with damage is equal to the strain energy density W_0 without damage. Base on the above principle, an equal proportional assumption is introduced to describe the stress component relationship between the case of damaged and non-damaged. That is supposed that it is proportionally changed between axial stress with damage and axial stress without damage. Under the conditions of linear elastic, the strain component also proportionally changes. The relations of danger point stress at the state of non-damaged and damaged[17,18] are received

$$\sigma_{k,D,\max} = \sigma_{k,0,\max}\sqrt{1-D} \tag{14}$$

$$\sigma_{km,D,th} = \sigma_{km,th}\sqrt{1-D} \tag{15}$$

In which, $\sigma_{k,D,\max}$ and $\sigma_{k,0,\max}$ are the severe site's stress at damaged and non-damaged situation respectively when $K_T > 1$, while $\sigma_{km,D,th}$ and $\sigma_{km,th}$ represent the stress threshold under damaged and non-damaged situation respectively at $K_T > 1$.

Connecting Eqs. (6), (7), the damage evolution equation for pre-corrosion notched specimen is

$$\frac{dD}{dN} = \alpha_k \frac{(\sigma_{k,D,\max} - \sigma_{km,D,th})^{m_k}}{(1-D)^{2m_k}} \tag{16}$$

where α_k, m_k are damage evolution parameters, and $\alpha_k = a\left(\frac{1}{2E}\right)^{\frac{m_k}{2}}$, $\sigma_{km,D,th}$ is stress threshold as the damage extent is D at $K_T > 1$.

Substituting the Eqs. (14), (15) for the $\sigma_{km,D,th}$ and $\sigma_{km,th}$ in the Eq. (16) respectively, then integrates the Eq. (16)

$$(\sigma_{k,0,\max} - \sigma_{th,km})^{m_k} N_f = \frac{1}{\alpha_k\left(\frac{3}{2}m_k + 1\right)}(1-D_{0,km})^{\frac{3}{2}m_k+1} \tag{17}$$

In the Eq.(17)

$$D_{0,km} = D_{0,kj} + D_{kf} \tag{18}$$

where $D_{0,km}$ represents the total initial damage extent of material after pre-corrosion completed when $K_T > 1$, $D_{0,kj}$ is material initial damage extent caused by mechanical processing, heat treatment and other factors, D_{kf} denotes the additional initial damage extent comes from pre-corrosion.

In addition,

$$\sigma_{k,0,\max} = K_T \sigma_{n,\max} \tag{19}$$

here, $\sigma_{n,\max}$ is the critical point's nominal stress of non-damaged material at $K_T > 1$. Write the Eq. (17) for

$$(\sigma_{n,\max} - \bar{\sigma}_{th,km})^{m_k} N_f = \frac{1}{\alpha_k K_T^{m_k} \left(\frac{3}{2} m_k + 1\right)} (1 - D_{0,km})^{\frac{3}{2} m_k + 1} \tag{20}$$

Also, the another form of Eq. (20) is

$$\lg N_f = \lg[\frac{1}{\alpha_k K_T^{m_k} \left(\frac{3}{2} m_k + 1\right)} (1 - D_{0,km})^{\frac{3}{2} m_k + 1}] - m_k \lg(\sigma_{n,\max} - \bar{\sigma}_{th,km}) \tag{21}$$

In which, $\bar{\sigma}_{th,km} = \frac{\sigma_{th,km}}{K_t}$, $\sigma_{th,km} = \sigma_{th0}(1 - D_{0,km})$. The Eq. (21) is the final relation of notched specimen's stress and life. From Eq. (21), the fatigue life curve in different initial damage extent can be acquired, it corresponds to commonly used median fatigue life curve, then, the initial damage extent ($D_{0,km}$) in Eq. (21) corresponds to the median fatigue life curve's.

3. CALCULATION EXAMPLE

In this article, the collected data come from reference[16]. The fatigue test results in different pre-corrosion level for LC4CS aluminum plate are showed in Table 1.

Table 1
High-cycle Fatigue Property Data for LC4CS Plate with Corrosion Pits at Specimen Surfaces (in Laboratoty Air)

State/Heat Treatment	*Forma (mm)*	*Sampling Direction*	*Loading Way*	*Specimen Surfaces*	*Specimen Environment*	*Specimen Temperature*	σ_b *MPa*	$\sigma_{P0.2}$	*Test Frequency (Hz)*
CS	δ7plate	L	axial	Corrosion Pits	Laboratory Air	Normal Atmospheric Temperature	556	515	130~160

Corrosion level to specimen surfaces F	*Kt*	*R*	σ_{max} *MPa*	*Corrosion Fatigue Life N, Cycle*			*Specimen Numbers*
				Logarithmic Average $\overline{X}$	*Standard Deviation S*	N_{50} *(10^{30})*	
F = 0	2.5	0.1	160.0	5.1239		133.00	1
			150.0	5.0971	0.0993	125.06	3
			130.0	5.3530	0.0684	225.43	3
			100.0	5.6599	0.1237	457.00	3
			90.0	5.8831		764.00	1
			80.0	6.1375	0.1392	1372.56	5
			70.0	6.5426	0.4076	3488.04	3
F = 3	2.5	0.1	130.0	5.1921	0.0090	155.64	3
			110.0	5.4700	0.0405	295.13	3
			90.0	5.7324	0.0527	540.02	3
			80.0	6.0866	0.2819	1220.79	4
			70.0	6.3188		2083.46	2
			65.0	6.5239		3441.33	2
F = 5	2.5	0.1	130.0	5.1517	0.1077	141.81	3
			110.0	5.3684	0.0588	233.54	3
			90.0	5.6667	0.2363	464.15	5
			50.0	7.0002		10050.00	1

First, the data of corrosive level at $F = 0$ are choosed to decide σ_{th0}, a and m_k. Then, by fitting experiment data, it can be obtained

$$D_{0,km} = 0.0676,\ \sigma_{\mathrm{th0}} = 156.3717,\ a = 3.5994 \times 10^{-6},\ m_k = 1.5535.$$

Based on the least-squares method and σ_{th0}, a and m_k, the initial damage extents in different corrosion level are gained and exhibited in Table 2.

Table 2
The Initial Damage Extent for LC4CS Plate Specimen in Different Corrosion Level

Corrosion level	*Initial damage extent* $D_{0,kj}$	*Additional initial damage extent caused by pre-corrosive* D_{kf}	*Total initial damage extent after pre-corrosive* $D_{0,km}$
F = 0	0.0676	0	0.0676
F = 3	0.0676	0.0476	0.1152
F = 5	0.0676	0.0736	0.1412

Now, the other parameters have been obtained. Then, using the Eq.(21) and the data in table 2, the damage evolution equations can be established with different corrosion conditions.

Comparing the calculated results with test results in Fig. 1, it is showed that they are anastomosis well.

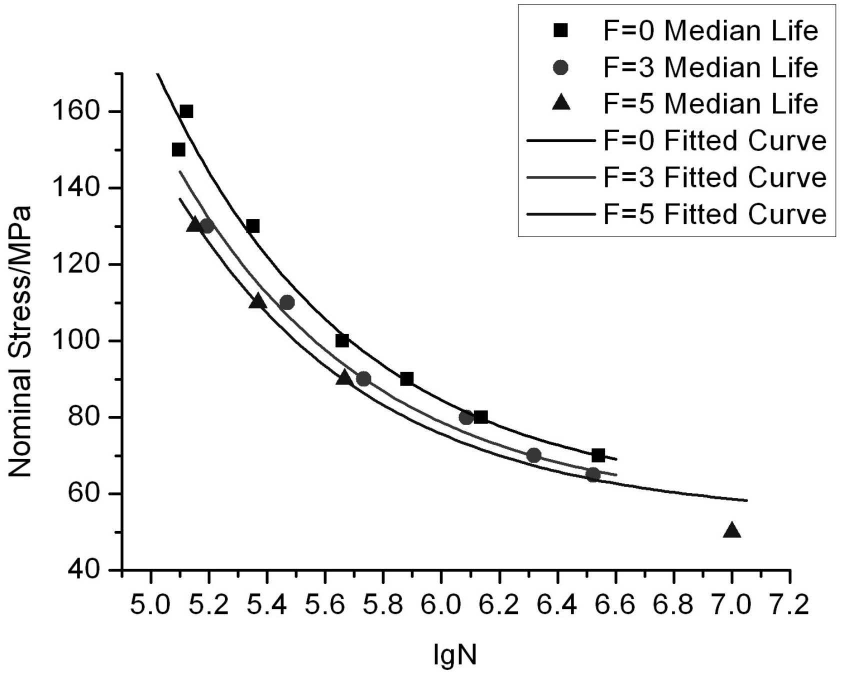

Figure 1: Median Fatigue Life and Fitted Stress-life Curve for LC4CS Aluminum Plate in Different Corrosion Level

4. CONCLUTIONS

- From the continuum damage mechanics method, the pre-corrosion damage evolution equation for smooth specimen and notched specimen are deduced. In this study, the total initial damage extent ($D_{0,km}$) is divided into two parts, one part is the material initial damage extent ($D_{0,kj}$) induced from mechanical processing,heat treatment and other factors, another is the additional initial damage extent ($D_{0,kf}$) caused by pre-corrosion. Simultaneously, after the pre-corrosion, the damage threshold will change as the corrosion of grade changes.
- Based on the fatigue test of standard specimen, the parameters of the damage evolution are obtained. Results exhibit that the additional initial damage extent caused by pre-corrosion rises as the corrosion level increases, and it takes up a great part of the total initial damage extent if the corrosion level is higher.

- It is coincided very well between the stress-life curves which come from the damage mechanics model and the experiment data in handbook in this study.

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