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Validity of three engineering models for fatigue crack growth rate affected by compressive loading in LY12M aluminum alloy

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Abstract: Based on the crack propagation mechanism of elastic-plastic fracture, a finite element analysis was performed upon the effect of compressive loading on fatigue crack tip stress field in LY12M aluminum alloy. By the validation of test data, two actual engineering models and a published double-parameter crack growth model, called Zhang-model, are all suitable in the case of negative stress ratio, and are used to describe the test data in the corresponding coordinate system. By comparing the degrees of linear correlation, R^2, of each fitting line, it shows that Zhang-model is a better engineering method for life prediction of fatigue crack growth under negative stress ratio of aluminum alloy, some factors can be obtained from elastic-plastic finite element computation, and it will save a lot of funds in the new materials research.
Key words: fatigue life prediction; fatigue crack growth rate; compressive loading; aluminum alloy

1 Introduction

New materials, such as Al−Li alloy [1], Al−Mg alloy [2,3], conventional titanium alloy [4] and aluminum alloy [5] with new processing technic, were applied on civil aircraft structure more and more. Fatigue performance of materials is an important thing which should be considered in the structure design. Fatigue life prediction and damage tolerance design of aeroplane structure are related closely to the calculation of fatigue crack growth rate da/dN. Because huge expense of material parameter test is determined by the model of crack growth rate, it needs to consider carefully in choosing a reasonable model.

In recent decades, it becomes a common view that compressive loading in the tension—compression fatigue spectrum can accelerate the fatigue crack growth rate of aluminum alloy. The affect of pressure has been omitted for a long time in the life prediction research of the fatigue crack propagation. In a tension—compression loading, the stress intensity factor range, ΔK, is usually calculated on the stress range in the tensile load part, as prescribed in the previous version of ASTM E-647. In the revised version since E647-00, when stress ratio, R, is negative, the increases in fatigue crack growth rates, da/dN, have been mentioned. For predicting crack-growth lives generated under various R conditions, the life prediction methodology must be consistent with the data reporting methodology [6].

Traditionally, the valid model for fatigue crack growth is described in the range from initial crack length of 2−3 mm to failure, in which the crack growth rate is stable, and the influence of microstructure, mean stress, ductility, environment and thickness are small. When R>0, famous Paris law is used extensively to describe the linear phenomenon between lg(da/dN) to lg(ΔK). SILVA found that for several materials the compressive part of the fatigue load cycle plays a significant role on fatigue crack propagation and the concept of fatigue crack closure is not adequate to describe fatigue crack growth rate at R<0 properly [7, 8]. Recently, FONTE et al found that for 7049 aluminum alloy there is a significant difference in fatigue crack propagation rate between R=0 and R=−1 [9].

Comparing data developed under $R\leq 0$ with data

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developed under $R>0$, it may be beneficial to plot the da/dN data versus effective stress intensity factor, K_{eff}, to include the acceleration effect due to compressive stress. In this work, finite element analysis illustrates that the compressive loading part of a tension—compression loading cycle make a positive contribution to fatigue crack growth. Moreover, by means of a set of fatigue crack propagation test data of LY12M aluminum alloy under R ratio varying from 0 to −2, two actual engineering models and a published double-parameter crack growth model, called Zhang-model, which all can be used in the case of negative stress ratio, were used to describe the test data in the corresponding coordinate system. In this work, some factors of Zhang-model obtained from elastic-plastic finite element computation, by comparing the degrees of linear correlation, R^2, of each fitting line, good agreements of Zhang-model were obtained.

2 Engineering model in full range of stress ratio *R*

For the relationship between stress intensity factor range ΔK and maximum stress intensity factor $K_{\max}$, $\Delta K=(1-R)K_{\max}$, the differential equation used to describe the data is often in the form of $\mathrm{d}a/\mathrm{d}N=f(\Delta K, R)$ or $\mathrm{d}a/\mathrm{d}N=f(K_{\max}, R)$ according to which one is convenient. It describes the relationship between fatigue crack growth rate da/dN and appointed loading parameters. The function f usually contains several empirical parameters derived from fitting curves of test data. As results, the fatigue crack growth model parameters have no physical significance, but are representative of the curve fitting technique used to describe the da/dN versus ΔK (or $K_{\max}$) curve. So, there are many valid models which can be used to describe particular sets of fatigue test data and to predict crack growth rates in some specified conditions [10].

Nowadays, the comprehension of fatigue phenomenon in many structures and materials is still limited. It is difficult to obtain an accurate fatigue life prediction by theoretical analysis or fatigue design rules. Fatigue life estimation procedures are available, but they are generally based on extrapolations of available fatigue data for the similar case to fatigue test condition [11]. For the damage tolerance evaluation of aeroplane structure, it is allowed to get only one curve for all R ratios in so-called Paris domain. Boeing and Airbus have different models described below as Eq. (1) and Eq. (3), respectively [12].

Boeing model,

$$\mathrm{d}a/\mathrm{d}N=n\cdot 10^{-4}\left(\frac{Z\cdot K_{\max}}{C}\right)^{p}=C'\cdot(Z\cdot K_{\max})^{p} \tag{1}$$

where n is the amount of growing crack tip; Z is the minimum stress factor, defined as:

$$Z=\begin{cases}(1-R)^{q},\ 0<R<1.0\\ 1-uR,\ R\le 0\\ 1.1,\ R\le -1.0,\ u=0.1\\ 0,\ R\ge 1.0\end{cases} \tag{2}$$

where C, p, q and u are the materials parameters derived from the experimental data of constant amplitude crack propagation test. In the case of n=1, then, $C'=10^{-4-p}$.

Airbus model,

$$\mathrm{d}a/\mathrm{d}N=C_{\mathrm{eff}}\cdot(\Delta K_{\mathrm{eff}})^{m} \tag{3}$$

where C_{eff} is material parameter which is independent of R-ratio, and ΔK_{eff} is the effective stress intensity factor range, which is defined as Eq. (4) depending on the loading conditions.

$$\Delta K_{\mathrm{eff}}=\begin{cases}U(R)\cdot\Delta K,\ \ \sigma_{\min}\ge 0\ \text{ and}\\ \quad U(R)=(A+BR),\ \ (A+B)=1\\ U'(R)\cdot K_{\max},\ \sigma_{\min}<0\ \text{ and}\\ \quad U'(R)=A\cdot\left(1+\alpha\cdot\dfrac{2\cdot|\sigma_{\min}|}{R_m+R_{0.2}}\right)\end{cases} \tag{4}$$

where A and B are Elber constants; $\alpha=(1-A)/A$; R_m and $R_{0.2}$ are ultimate strength and yield strength of structure materials, respectively.

3 Elastic-plastic finite element analysis and introduction to Zhang-model

The elastic-plastic finite element analysis in this work was performed by ABAQUS software. The geometry of CCP (Central Crack Panel) specimen is shown in Fig. 1(a)). In order to ensure the accuracy of computation at crack tip, the minimum size of element around crack tip is smaller than 1 μm. Because of the symmetry of the specimen, a quarter of CCP specimen was used to decrease the amount of elements, as shown in Fig. 1(b). To simulate the contact of the crack face and to prevent the nodes of the crack face from penetrating through the symmetric surface, a rigid body was used as a symmetric surface. Because of the severe deformation near the crack tip, the model was built in large deformation nonlinear geometry condition. The von Mises yield criterion and Prandtl-Ruess flaw rule were used, with kinematic hardening law considering the influence of Bauschinger effect. The loading procedure type is quasi-static loading. The loading history is shown in Figs. 2(a) and (b), at the stress ratio R=0 and R=−1, respectively.

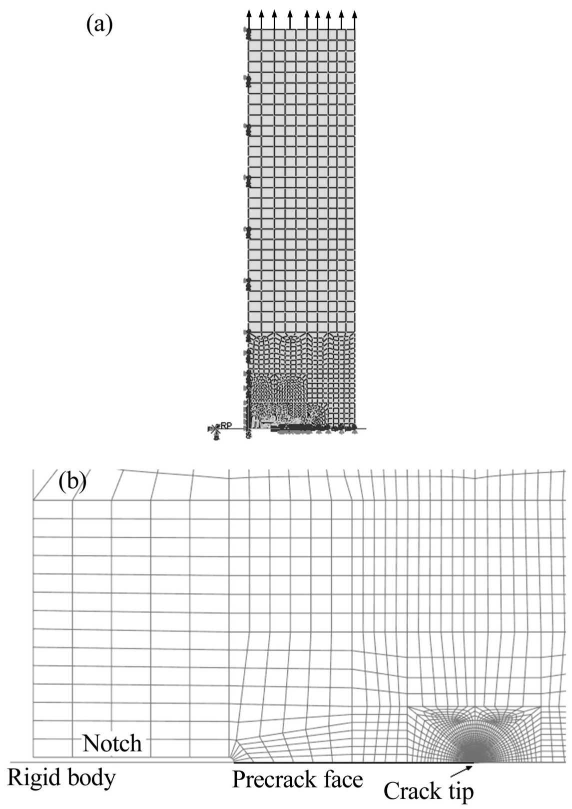

Fig. 1 Geometry of specimen (a) and finite element model (b)

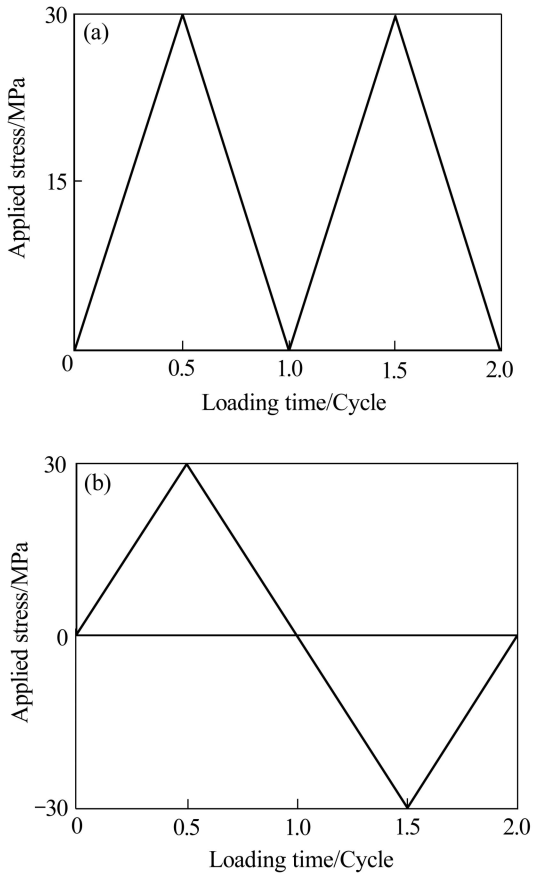

Fig. 2 Applied loading vs loading time of R =0 (a), R=−1 (b), and $\sigma_{\max}$=30 MPa

The material of finite element model was defined identically with the specimen used in the fatigue tests, LY12M aluminum alloy. Elastic modulus is 70 GPa, and Poisson ratio is 0.3. The 0.2% yield stress and the ultimate stress used in this analysis are 120 MPa and 214 MPa, correspondingly, and the failure plastic strain is 0.21 [13].

Figure 3(a) shows that for the case R=0, after a loading cycle, the applied force corresponding to the

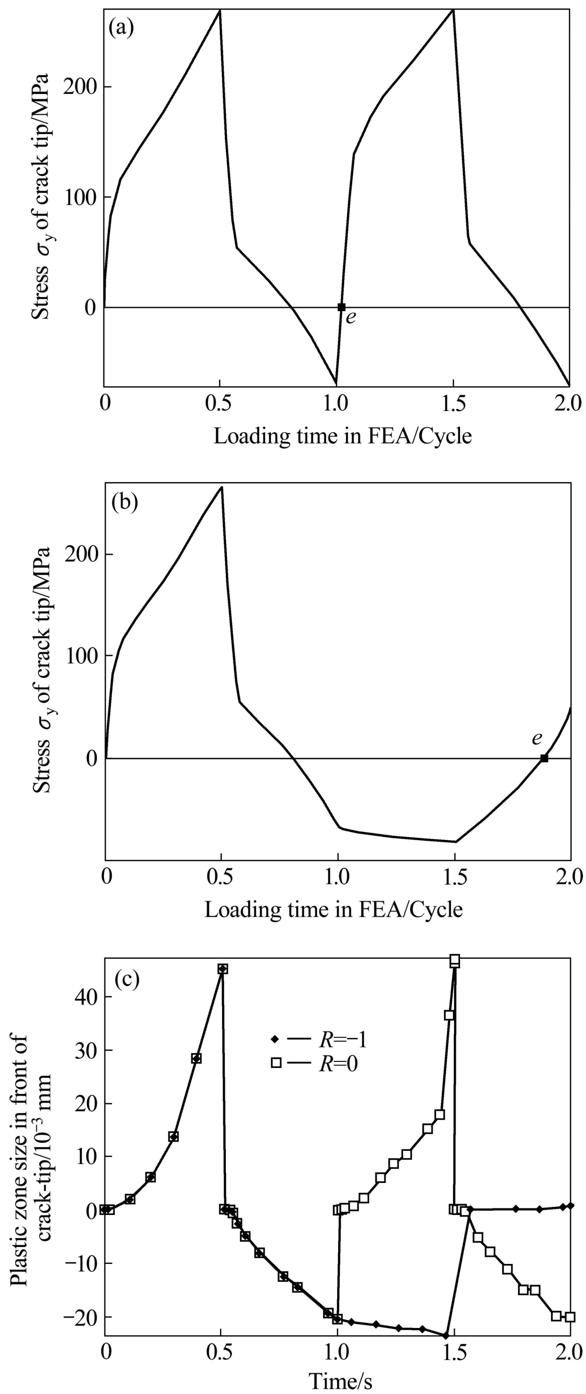

Fig. 3 Analysis results of stress curve of crack tip along Y axis (applied stress orientation) during a lading cycle: (a) R=0; (b) R=−1; (c) Plastic zone size in front of crack tip

time ‘*e*’ is tensile while the stress σ_y at crack tip is zero. Figure 3(b) shows that for the case R=−1, during a loading cycle, although the applied force corresponding to the time ‘*e*’ is still compressive, the reverse stress (tensile stress) occurred after the time ‘*e*’ due to the effect of plastic zone deformation in the front of the crack tip. This indicates that the part of compressive load has a positive contribution to the crack growth. The size of plastic zone can be calculated by the elastic-plastic FEA model. The results are showed in Fig. 3(c).

Zhang-model, a new model of fatigue crack propagation research under negative stress ratio, was presented subsequently. Detailed description can be seen in Refs. [14−16]. The equations are presented directly here.

$$\mathrm{d}a/\mathrm{d}N = C\cdot(\rho_\lambda \cdot K_{\max})^m \tag{5}$$

where C and m are the materials parameters derived from the experimental data of constant amplitude crack propagation test; ρ_λ is a correction factor representing the influence of reverse plastic zone size generated during the unloading part of the previous stress cycle, and is defined as:

$$\rho_\lambda = (1-\gamma\sigma_{\max-\mathrm{com}})^{\beta/m} \tag{6}$$

where β, γ are the factors which reflect the impact of reverse plastic zone ahead of crack tip on the crack growth. They can be calculated by elastic-plastic finite element model, and are independent of the maximum compressive stress, $\sigma_{\text{max-com}}$.

4 Verification by experimental data

Fatigue crack propagation rate test have been done according to ASTM E-647. Schematic illustration of a LY12M aluminum alloy specimen is shown in Fig. 4(a). Precracking and fatigue crack propagation test were implemented by a PLG−100C high-cycle fatigue-testing machine. Crack propagation data were acquired from the specimen photographs after assigned loading cycle, as shown in Fig. 4(b), measured by an image processing software programmed in Adobe Flash.

From Eqs. (1), (3) and (5), it is found that da/dN can be described as the function of ΔK or $K_{\max}$ with modified parameters, similar as the form of Paris law. Thus, it is easy to compare the results obtained from three models with the same experimental data. When the linear fitting curve used to describe the relationship of lg(da/dN) vs lg(ΔK), and ΔK is calculated by the method specified in the ASTM E-647, it can be seen in Fig. 5(a) that the data are dispersed in different lines of different R ratio for the

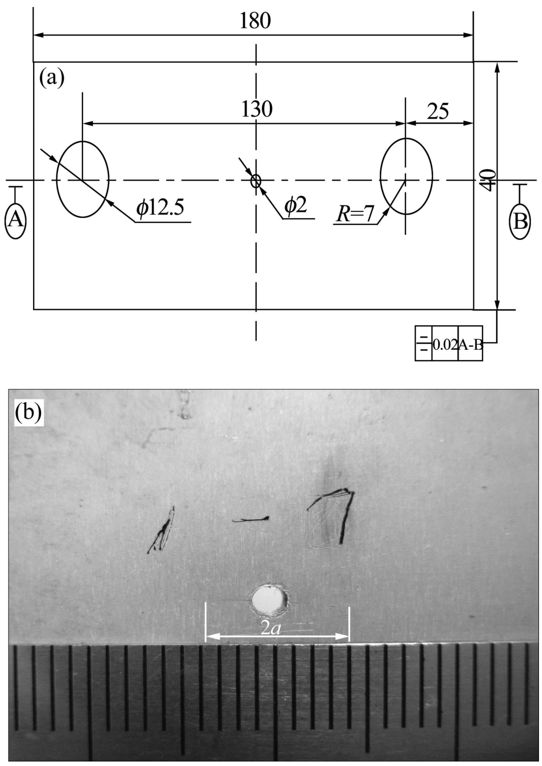

Fig. 4 LY12M aluminum alloy specimen: (a) Configuration (unit: mm); (b) Fatigue crack length measuremen

same materials. The material parameters C and m in Paris law of the same material are different when the R ratio varies from 0 to −2. For this reason, it is not a good method to use in the engineering application.

Using other method shown as Eqs. (1), (3) and (5) to describe the relationship between lg(da/dN) vs lg(ΔK or $K_{\max}$) with modified parameters, only one curve in good accordance can be presented, as shown in Figs. 5(b), (c) and (d). The degrees of linear correlation, R^2, of each fitting line are listed in Table 1. It is obviously found that the method of Zhang is more efficient to describe the fatigue crack growth of one material in complex loading conditions.

The materials parameters, C, β and m, of Eq. (5), are defined by the test data. Factor γ can be determined by the FEA results as shown in Fig. 3(c).

Table 1 Degree of linear correlation of fitting lines in Fig. 5

Model	R^2
Paris, lg(da/dN) vs lg(ΔK)	0.6035
Boeing, lg(da/dN) vs lg($ZK_{\max}$)	0.6827
Airbus, lg(da/dN) vs lg(ΔK_{eff})	0.8679
Zhang, lg(da/dN) vs lg($\rho_\lambda K_{\max}$)	0.9387

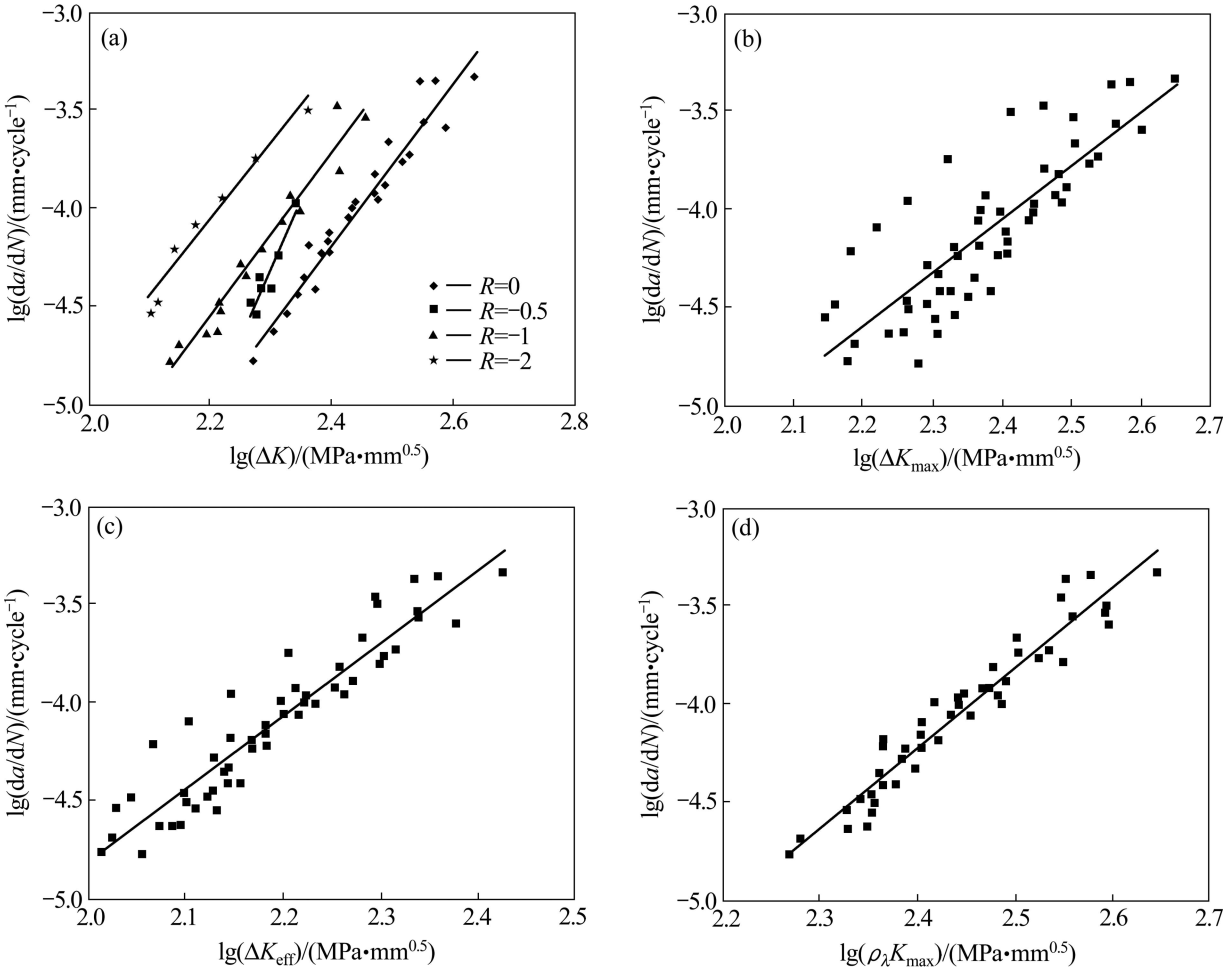

Fig. 5 Fitting results of same fatigue test data under $R \le 0$ by different methods: (a) Paris law; (b) Method of Boeing shown as Eq. (1); (c) Method of Airbus shown as Eq. (3); (d) Method of Zhang shown as Eq. (5)

5 Conclusions

1) The elastic-plastic finite element analysis shows that the part of compressive load has a positive contribution to the crack growth. For LY12M aluminum alloy, compressive stress accelerates the crack propagation rate.

2) By means of test data validation, comparison results of three double-parameter crack growth models show that Zhang-model is a better engineering method for life prediction of fatigue crack propagation under negative stress ratio of LY12M aluminum alloy. For the reason that some factors can be obtained from elastic-plastic finite element computation, it will save a lot of funds in the new materials research.

3) To be an actual engineering model in the future, there are considerable work should be done to validate the feasibility of Zhang-model.

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压载荷对LY12M铝合金中疲劳裂纹扩展速率影响的三种工程模型的验证

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摘　要：基于弹塑性断裂力学的裂纹扩展机理，用弹塑性有限元分析压载荷对LY12M铝合金疲劳裂尖应力场的影响。介绍了可用于负应力比试验数据描述的两种实际应用的工程模型和一种已发表的称作“张模型”的双参数裂纹扩展模型，通过在相应坐标系下描述试验数据，并比较各自拟合线的线性相关度R^2。结果验证“张模型”的拟合效果较好，是一种负应力比下预测铝合金疲劳裂纹扩展寿命的较好的工程方法，同时，由于部分参数可用弹塑性有限元计算获得，所以可节省大量新材料研究的经费。

关键词：疲劳寿命预报；疲劳裂纹扩展速率；压载荷；铝合金

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