TWO-PARAMETER DRIVING FORCE MODEL FOR FATIGUE CRACK GROWTH UNDER THE EFFECT OF STRESS RATIO

Chen Bo a, Yan Fangfang b and Wang Yun c
Xinxiang University, Henan 453000, China
a baiifpl@163.com, b xxy413@163.com, c xw430@126.com

ABSTRACT: Elber and Walker’s effective stress intensity factor range model and Kujawski’s two-parameter driving model were used for the normalization of the Crack growth curves under different stress ratios(R). These two models were applied under the condition that the stress ratio only affected the position of crack growth rate curves, but not their shapes. When crack growth curves under different stress ratio were normalized, these two models were only applicable to the intermediate-regions of crack growth threshold. A new improved two-parameter driving model was proposed, which is appropriate for intermediate-region and accelerated region of crack growth curves. In this model, the exponents are a function of these parameters: stress ratio, fracture toughness, stress intensity and the parameter calculated from the two-parameter driving model, when fatigue crack growth rate tends to infinity. The crack growth curves under different R can be normalized into one curve by using this new improved two-parameter driving model, which has different shape in the intermediate-region and accelerated region. The modified two-parameter model was verified by the fatigue crack growth data of PMMA (YB-MD-11 and YB-MD-3) and titanium alloy (Ti-1023).

KEYWORDS: Crack Growth Rate; Stress Intensity Factor; R-Ratio Effect; Two-Parameter Model; Improved Model

1 INTRODUCTION

In the study of fatigue crack propagation, the stress field intensity factor range $\Delta K$ proposed by Paris-Erdogan (P.C. Paris and F. Erdogan, 1963) is usually used as the variable of the crack growth rate function $da/dN$ to quantitatively calculate the fatigue crack growth rate, and thus estimate the crack propagation life. But the $da/dN-\Delta K$ curve is also affected by the loading frequency (Rebecca M. et al, 2019, F. V. Antunes, et al, 2018, F. Iacoviello, et al, 2018, T. Fischer and B. Kuhn. 2019, T. Fischer and B. Kuhn. 2018), temperature ( Dawei Huang, 2018, A. Evangelou, et al, 2019, Keisuke Tanaka, et al, 2016, V. N. Shlyannikov, et al, 2018), environment (Victor Igwemzie, et al, 2019, J. L. Jones, et al, 2018, V. Giorgetti, E. A. et al, 2019), and stress ratio $R$ ($P_{min}/P_{max}$) ( K. S. Ravi. 2019, Karthik Rajan et al, 2018, K.S. Ravi Chandran. 2017, A. Roiko, J. Solin. 2017). Since the actual components are usually affected by variable amplitude cyclic loads, it is necessary to find a new crack propagation dynamic parameter $\Delta K_{drive}$, so that the $da/dN-\Delta K_{drive}$ curves at different stress ratios can be normalized to one crack growth rate curve corresponding to a special stress ratio. In this condition, it is only necessary to test the crack growth rate constant at a certain stress ratio, besides that the crack growth rate curves at other stress ratios can be predicted. And this work has important practical value.

In 1970, the effective stress field intensity factors based on different theories were proposed by (W. Elber.1970) and (K. Walker. 1970) respectively. And recently the local crack closure model (D.L. Chen, B. Weiss and R. Stickler.1996) and two-parameter dynamic model (D. Kujawski. 2001) were proposed. These dynamic crack growth models all normalized the $da/dN-\Delta K$ curves corresponding to different stresses to one crack growth rate curve. In this study, it is found that the Elber model, Walker model and Kujawski’s two-parameter dynamic model all normalized different $da/dN-\Delta K$ curves to one specific crack growth curve (or strip) without changing the original shape characteristics of crack growth rate curves. These formulas were applied in the case that the stress only had the effect on the position of the fatigue crack growth rate curve (intercept of the middle region, threshold and $(1-R)K_c$) and less effect on the slope of the crack growth middle region. If the stress ratio has both effect on the slope and intercept of the middle region, the above models are not applicable in theory (Marcu, T., Todea, M., Maines, L., et al. 2012).

At present, for the normalization of the crack
growth rate curves in the near threshold region and the middle region, there are the $K_{op}$ model of Elber crack opening stress field intensity factor and the modified model of exponential in Kujiawski's two-parameter dynamic model. However, these two models cannot be applied to the crack growth rate curves including the middle region and the accelerated region. In this study, the two-parameter dynamic model is further modified so that the two-parameter dynamic model can be suitable for such special situations.

2 FATIGUE CRACK GROWTH RATE MODEL

In the famous fatigue crack growth formula given by Paris-Erdogan (P.C. Paris and F. Erdogan, 1963), the stress intensity factor $\Delta K$ was taken as the driving force of crack propagation and the $da/dN\cdot \Delta K$ curve in double logarithmic coordinates was obtained. Meanwhile, a formula was given to describe the fatigue crack growth rate curve in the middle region, as shown in the following formula.

$$\frac{da}{dN} = C (\Delta K)^m$$  \hspace{1cm} (1)

In formula (1), the coefficient $C$ and exponent $m$ are affected by the material and stress ratio. The effect of stress ratio on fatigue crack growth rate curves containing near threshold region, middle region and accelerated propagation region are shown in Fig.1.

![Fig. 1 Crack growth rate curves under different R-ratio](image)

From Fig.1, it can be seen that the stress ratio has more effect on the near-threshold region and the accelerated region, but it has less effect on the middle region, and the $da/dN\cdot \Delta K$ curves under specific stress ratios are different from each other.

In order to describe the crack growth rate curves in the middle region and accelerated propagation, Forman (Forman, R.G., Kearney, V.E. and Engle, R.W.1967) proposed a fatigue crack growth rate formula containing the stress ratio $R$ on the basis of formula(1), which is shown in the following formula.

$$\frac{da}{dN} = \frac{C (\Delta K)^n}{(1 - R) K_C - \Delta K}$$  \hspace{1cm} (2)

In formula (2), the coefficient $C$ and exponent $m$ are the same as those in formula (1); $R$ is the stress ratio and $K_C$ is the fracture toughness.

For $\Delta K$ is the driving force of fatigue crack propagation, the correlation coefficient $C$ (intercept of middle region) and index $m$ (slope of middle region) in formula (1) and (2) will change when the stress ratio is different for the same material. The improved Elber model, the Walker model and the two-parameter dynamic model of Kujiawski can normalize the $da/dN\cdot \Delta K$ curves at different stresses to one curve. In these formulas the fitting parameters will not change with the stress ratio. In this case, the fitting parameters obtained from a certain crack growth rate curve under one stress condition can be used to estimate the crack growth life under other stress conditions.

2.1 Crack closure model

In (W. Elber.1970) proposed the concept of effective stress field intensity factor $\Delta K_{eff}$, which is taken as the crack propagation driving force and the expression is:

$$\Delta K_{eff} = K_{max} - K_{op}$$  \hspace{1cm} (3)

In formula (3), $K_{op}$ is the field intensity factor when crack is open, and $K_{max}$ is the maximum stress field intensity factor. The relationship between $\Delta K_{eff}$ and $\Delta K$ is given as follows.

$$\Delta K_{eff} = U \Delta K$$  \hspace{1cm} (4)

The parameter $U$ in formula (4) is related to the stress ratio $R$, i.e. $U=U (R)$. When the stress ratio was in the range of $(-1, 1)$, $U$ can be expressed as follows according to (Schijve, J.1981):

$$U = 0.55 + 0.33 + 0.12 R^2$$  \hspace{1cm} (5)

However, for the same material, $K_{op}$ value is a variable value due to the different measurement location and technique (Macha DE, et al, 1979, Shin CS, 1985). (Sadananda, 1993, Sadananda K, 1997) considered that the effect of crack closure on crack propagation was overstated. While (Kujiawski D. 2001) considered that the relationship between $\Delta K_{eff}$ and $\Delta K$ satisfied the formula (4), and a modified function for $K_{op}$ was given. For the crack propagation rate from the near threshold region to the central region, $K_{op}$ gradually increases with the increase of $K_{max}$ from $K_{maxTH}$ to $K_C$ and tends to the original measured $K_{op}$ value. The effective stress field intensity factor range is calculated as follows:
\[ \Delta K_{\text{eff}} = K_{\max} - K_{p} \left[ 1 + \left( \frac{2}{\pi} - 1 \right) g \right] \]

\[ g = \exp \left[ - \left( \frac{K_{\max}}{K_{\max \text{TH}}} - 1 \right) \right] \quad (6) \]

In formula (6), the crack propagation rate approaches zero in the condition of \( K_{\max} \leq K_{\max \text{TH}} \). It can be seen from formula (6) that for the same material, the calculated parameter \( U \) value will increase with the increase of \( K_{\max} \) from \( K_{\max \text{TH}} \) to \( K_{\text{C}} \), even if the stress ratio is constant.

There’s a global translation for \( da/dN-\Delta K \) curves under different stress ratios by using Formula (4), while the shape of the \( da/dN-\Delta K \) curves was changed except the translation of the curves by using Formula (6).

### 2.2 Walker model

In 1970, Walker (K. Walker.1970) proposed an empirical model of crack propagation dynamics based on the experimental data. It is considered that the effective stress field intensity factor is related to the maximum stress field intensity factor and the range of stress field intensity factor.

\[ \Delta K = (K_{\max})^{1-p} (\Delta K)^{p} = (1-R)^{p-1} \Delta K \quad (7) \]

The exponential \( p \) in formula (7) is a material constant, and the crack propagation dynamics is only suitable for the case of stress ratio greater than zero \((R>0)\), but for the normalization in the case of \( R<0 \) it is not clear (A.H. Noroozi, G. Glinka and S. Lambert.2005).

For the effective stress field intensity factor range proposed by Walker, formula (7) is equivalent to the following formula.

\[ \Delta K = f (R) g \Delta K \quad (8) \]

For a given stress ratio \( R \), \( f(R) \) is a fixed value, so the different \( da/dN-\Delta K \) curves can be translated into a curve (or band) by using formula (7) without changing the \( da/dN-\Delta K \) curve.

### 2.3 Kujawski model

In (D. Kujawski.2001) proposed a two-parameter dynamic model in crack propagation of aluminum alloy. It is assumed that the stress field intensity factor range related with the pressure has no effect on the crack propagation rate, so it is considered that the crack propagation dynamics is the geometric mean of the maximum stress field intensity factor \( K_{\max} \) and the stress field intensity factor corresponding to the tensile stress.

\[ K_{1}^{*} = \left( K_{\max} \Delta K^{*} \right)^{0.5} \quad (9) \]

In equation (9), \( \Delta K \) is the range of force field intensity factor corresponding to the normal stress, when \( R > 0 \), \( \Delta K = \Delta K \); when \( R \leq 0 \), \( \Delta K = K_{\max} \).

Later on, Kujawski (D. Kujawski.2001) extended the two-parameter dynamic model and considered that the crack propagation dynamics is as follows:

\[ K^{*} = (K_{\max})^{a} (\Delta K^{*})^{1-a} \quad (10) \]

Noroozi (A.H. Noroozi, G. Glinka and S. Lambert,2005) found that it had better normalization effect for the \( da/dN-\Delta K \) curves under different stress ratios in the case of \( 0 \leq R < 1 \) than in the case of \(-1 \leq R < 0 \) by using the two-parameter dynamic model shown in Formula (10). (Hunag X. P. 2007) used the Formula (10) to normalize the crack growth rate curve for Ti-6Al-4V. It was found that the normalization effect is not good in the condition of \( R>0.7 \), and an improved two-parameter dynamic model is proposed. The formula is as follows:

\[ K_{1}^{*} = \left( K_{\max} \right)^{a} \left( \Delta K^{*} \right)^{1-a} \]

\[ \begin{align*}
& \left( 1 - R \right)^{2} \Delta K, -5 \leq R < 0 \\
& \left( 1 - R \right)^{2} \Delta K, \quad 0 \leq R < 0.5 \\
& \left( 1.05 - 1.4 + 0.6 R \right)^{2} \Delta K, \quad 0.5 \leq R < 1
\end{align*} \quad (11) \]

In Formula (11), \( \beta \) and \( \beta_{1} \) are material constants, and \( \beta \leq \beta_{1} \leq 1 \). Then the Formula was verified by using Ti-6Al-4V with the stress ratio \( 0.1 \leq R \leq 0.8 \), Aluminum alloy Al7075-T6(-1 \leq R \leq 0.5), Al 2024-T351(-2 \leq R \leq 0.5) and other materials.

Sudip Dinda (Dinda S., Kujawski D.2004) adopted Formula (10) to normalize crack growth rate curves in the near threshold and middle extension zones of nodular cast iron. It was found that the stress ratio not only affects the intercept in the middle part of the crack growth rate curve, but also affects the slope of the middle region. And with the increase of the stress ratio, the slope of the middle region increases, so it has different shape of the \( da/dN-\Delta K \) curve under different stress ratio. It is impossible to normalize the \( da/dN-\Delta K \) curve under different stresses to a curve (or strip) only by the translation of Formula (10). According to the Formula (6), the author considered that the value of exponent \( a \) in Formula (10) is not a fixed value, but a function of the threshold value of maximum stress field intensity factor \( K_{\max} \), which is the threshold value of maximum stress field intensity factor \( K_{\max \text{TH}} \) and the calculated exponential \( a \) in Formula (10) in the condition of \( \Delta K \rightarrow \Delta K_{\text{th}} \). The expression is as follows:

\[ a = a_{0} \exp \left[ \left( \frac{K_{\max} - 1}{K_{\max \text{TH}}} \right) \right] \quad (12) \]

According to the Formula (12), the value of exponent \( a \) in formula (10) is a variable value for the same stress. By operation, the \( da/dN-\Delta K \) curves under different stress ratios were not simply translated, at the same time the curves with different
shapes are transformed into curves with the same shape.

In the Formula (10), when the stress ratio $R$ is greater than 0, then $\Delta K^*$ is equal to $\Delta K$. If the parameter $\alpha$ is set to $(1-p)$, then there is:

$$K^* = (K_{max})^*(\Delta K^*)^{1-x}$$

$$= (K_{max})^{1-x}(\Delta K)^{1-x} = (K_{max})^{1-x}(\Delta K)^x$$  \hspace{1cm} (13)

Formula (13) is the same as Formula (7). Formula (9) can be considered as the case that the exponent $\alpha$ of Formula (10) or the exponent $p$ in formula (7) is 0.5. In this situation, the two-parameter dynamic model proposed by Kujawski is equivalent to the effective stress field intensity factor model proposed by Walker, only the representation is different.

The Formula (4), (7), (9), (10) and (11) are crack propagation driving force models with different expression form, and they all can be expressed as formulas in the following form.

$$\Delta K_{drive} = f(R)g\Delta K$$ \hspace{1cm} (14)

The function $f(R)$ in formula (14) is a function of stress ratio. Through the operation of the above formula, the crack growth rate $dalpha$/d$N$-$\Delta K$ curve with different stress ratios were normalized to a crack growth rate curve. By this operation, the $dalpha$/d$N$-$\Delta K$ curve was only translated without changing its shape feature. Therefore, the application premise is that: the stress ratio only affects the upper limit of the crack growth rate curve $\Delta K_{th}$; the lower threshold of the crack growth rate curve $(1-R)K_C$ and the central intercept $C$ described by the Paris formula, while it has little effect on the slope $m$ for the central region of curve described by the Paris formula. Only in this way, the $dalpha$/d$N$-$\Delta K$ curves corresponding to different stress ratios can be normalized to a crack growth rate curve (or strip) by translation operation.

The modification of the crack opening force by formula (6) and the exponent in the two-parameter dynamic model by formula (12) can be summarized as the following calculation formula.

$$\Delta K_{drive} = f(K_{max}, K_{maxTH})g\Delta K$$ \hspace{1cm} (15)

The function $f(K_{max}, K_{maxTH})$ in formula (15) is not only the function of stress ratio, but also related to the threshold value of maximum stress field $K_{maxTH}$ and changed with $K_{max}$.

The application condition of Formula (6) and formula (12) are different from that of formula (4), (7), (10), (11). They can be applied in the case that stress ratio not only affects the lower threshold $\Delta K_{th}$, the upper limit $(1-R)K_C$ of crack growth rate curve, and the intercept $C$ of the middle region described by Paris formula, but also affects the slope for the central region of the curve described by the Paris formula. Finally, the fatigue crack growth rate curves under different stress ratios were normalized to a crack growth rate curve (or strip) by translating and changing the shape of the curves.

### 3 IMPROVED TWO-PARAMETER DYNAMIC MODEL

Obviously, the fatigue crack propagation rate curves corresponding to different stress ratios have different shapes in the central and accelerated propagation regions, so it is not suitable to adopt the translation operations of Formula (4), (7), (9), (10) and (11) for normalization. The formulas (6) and (12) are only valid for the the normalization of near threshold region and the central extension region, so they are also invalid for the normalization of central region and the acceleration region.

(Sadananda K., Vasudevan A.K. 2004) proposed that the dynamic force of crack propagation is $K_{max}$ and $\Delta K$, which play a dominant role at different stages. The size of monotone plastic deformation zone at crack tip is mainly controlled by $K_{max}$, and the size of cyclic plastic zone is controlled by $\Delta K$ parameter. The $dalpha$/d$N$-$\Delta K$ curve corresponding to stress ratio $R_t$ was shown in Figure 1. It was shown that with the increase of stress intensity factor range, the tendency of monotone fracture will increase with the increase of stress field intensity factor range $(1-R)KC$. In this case, $K_{max}$ is the main dynamic force of crack propagation, while the influence of $\Delta K$ can be ignored. Compared with the accelerated growth zone, the tendency of monotone fracture for the crack propagation rate in the middle zone is small. In this case $\Delta K$ is the main crack propagation dynamics, and the value of exponent $\alpha$ in the two-parameter dynamic model increases with the increase of $\Delta K$. For the same $\Delta K$, if there is $R_t>R_t>R_t$, then the fatigue crack propagation rate curve with stress ratio being $R_t$ will enter the accelerated expansion region earlier, that means the value of exponent $\alpha$ in the two-parameter dynamic model corresponding to the same $\Delta K$ will increase with the increase of the stress ratio.

Therefore, the value of exponential $\alpha$ in the two-parameter dynamic model increases with the increase of stress field intensity factor $\Delta K$ during the transition of the crack growth rate from the middle region to the acceleration region. For the same stress field intensity factor $\Delta K$ value, different stress ratio corresponds to different crack growth rate. And the larger the stress ratio is, the larger the corresponding crack growth rate and the value of exponential $\alpha$ in the two-parameter dynamic model is. Due to this effect, when $\Delta K$ approaches $(1-R)K_C$, $K_{max}$ is the main dynamic force of crack propagation, and the value of exponent $\alpha$ in the two-parameter
dynamic model tends to be a constant value, which was denoted as \( a_t \).

In combination with the above analysis and formula (14), when the stress ratio has a great effect on the slope \( m \) of the central region described by the Paris formula, the calculation formula of the exponential in the two-parameter dynamic model for the crack propagation rate changes from the middle region to the accelerated region is as follows:

\[
a_m = a_t \exp \left[ -\frac{(1-R)K_C}{\Delta K} \right]
\]

(16)

In formula (16), \( K_C \) is the fracture toughness. With the increase of \( \Delta K \), the exponential parameter \( a_m \) increases gradually. When \( \Delta K \) approaches \((1-R)K_C\), and \( a_m \) approaches \( a_t \) which is a material constant, then the corresponding modified two-parameter dynamics is denoted as \( K_C \).

4 TEST DATA VERIFICATION

4.1 Perspex experiment

Aeronautical PMMA plate specimens with two kinds of materials were used in the test. And the materials were oriented YB-DM-11 and YB-DM-3 respectively. The sizes of the samples are 320mm(length)\times100mm(width)\times16mm(thickness). The central crack was prefabricated with the size of \( 2a_0 = 10-15mm \). The crack propagation test was carried out on an electro-hydraulic servo fatigue testing machine with the temperature of 23±2°C, the frequency of 2.5 Hz and the stress ratio of \( R = 0.4, 0.1 \) as well as 0.4.

For the sample with material of directional YB-DM-11, the \( \frac{da}{dn} / \text{cycle} \) curve of the sample with the Forman formula, as shown in figure 2 and the fitting results by using Forman formula are shown in Table 1. It can be seen from the result that the stress ratio not only affects the upper limit value \( (1-R)K_C \) and intercept \( C \) for the middle region of the crack growth rate curve, but also affects the intercept \( m \) for the middle region of the curve. Although the parameter \( m \) corresponding to \( R = 0.4 \) and 0.1 respectively is close, the parameter \( m \) corresponding to \( R = 0.4 \) varies greatly. It means that the stress ratio has a great influence on the central region of the curve. Therefore, the crack growth rate curves corresponding to different stress ratios are not only different in position, but also in shape. It is impossible to normalize the crack growth rate curves under different stress ratios to a crack growth rate curve (or strip) by simply translating the crack growth rate curve with Formula (9) and Formula (10). The curve with Formula (9) was shown in Figure 3 and the curve corresponding to \( \alpha = 1.1 \) with Formula (10) was shown in Figure 4.

![Table 1 Fitting results of fatigue crack growth rate curve with the Forman formula](image)

<table>
<thead>
<tr>
<th>( R )-ratio</th>
<th>( C )</th>
<th>( m )</th>
<th>( (1-R)K_C )</th>
<th>( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R = 0.4 )</td>
<td>5.61E-7</td>
<td>3.205</td>
<td>2.1201</td>
<td>0.9884</td>
</tr>
<tr>
<td>( R = 0.1 )</td>
<td>5.75E-7</td>
<td>3.664</td>
<td>1.9458</td>
<td>0.9881</td>
</tr>
<tr>
<td>( R = 0.4 )</td>
<td>8.44E-7</td>
<td>3.901</td>
<td>1.2469</td>
<td>0.9870</td>
</tr>
</tbody>
</table>

![Fig.2 Fatigue crack growth data defined by \( \Delta K \) with Forman formula](image)

![Fig. 3 Fatigue crack growth data defined by \( K \) with the Forman formula](image)

By the comparison of Fig. 3 and Fig. 4 with Fig. 2, it is found that the crack growth rate curves under different stress ratios are merely translated by using the Formula (9) and Formula (10). Because the
shape of the fatigue crack growth rate curves under different stress ratios is different, it is impossible to translate the fatigue crack growth rate curves under different stress ratios to a crack growth rate curve (or strip). As shown in Fig.4, when \( \alpha \) is set to be 1.1 and the two-parameter dynamic model corresponding to Formula (10) is used as the driving force for crack propagation, the latter half of the accelerated propagation zone can be overlapped. So, by applying Formula (16) and taking the \( \alpha_1 \) as 1.1, the corresponding crack growth rate curve was shown in Fig.5.

As can be seen from Fig.5, Formula (16) not only translates the crack growth rate curves under different stresses, but also changes the shape of the curves, and thus the crack growth rate curves under different stress ratios are normalized to one curve.

![Fig. 4 Fatigue crack growth data defined by \( K^1 \) (YB-DM-11)](image)

![Fig. 5 Fatigue crack growth data defined by \( K^4 \) (YB-DM-11)](image)

Fig. 6 Fatigue crack growth data defined by \( \Delta K \) (YB-DM-3)

![Fig. 7 Fatigue crack growth data defined by \( \Delta K \) (YB-DM-3)](image)

Similarly, for the specimen with the material of directional YB-DM-3, the \( da/dN-\Delta K \) curve is shown in Figure 6. And the \( da/dN-\Delta K \) curve obtained by applying Formula (15) with the parameter \( \alpha_1 \) also being 1.1 is shown in Figure 7.

4.2 Ti-1023 experiment

The data of fatigue crack growth rate for Ti-1023 derived from reference, and the \( da/dN-\Delta K \) curve was shown in Figure 8. It can be seen from the Figure that the curves corresponding to different stress ratio have different shapes in the middle region and the accelerated expansion zone.

Using the two-parameter dynamic model expressed by the formula (10) and taking the exponent \( \alpha \) in the formula as 0.8, the crack growth rate curves corresponding to different stress ratio which were simply translated was shown in Fig.9. Although there is a better normalization for a part of the accelerated growth zone, it is obviously unreasonable for the crack growth rate curve in the middle zone because the fatigue crack propagation life was found to increase with the stress increasing.
5 CONCLUSION

1. The Elber model, the Walker model, the Kujawski two-parameter dynamic model and the modified Formula (11) all can be applied to translate the da/dN-ΔK curve under different stress ratios to the same da/dN-ΔKdrive curve by the ΔKdrive=f(R)ΔK operation. The applicable condition for these models is that the fatigue crack growth rate curves corresponding to different stresses have the same shape and different positions. The modification of Kdrive is by the modification of exponential α in two-parameter dynamic model.

2. Formula (4) made a modification of Kα and Formula (12) made a modification of exponential α in two-parameter dynamic model. Both Formula (4) and Formula (12) can translate the da/dN-ΔK fatigue crack growth rate curves under different stress, which have different shape and position to a curve while changing the shape of the curves. But they are only applicable for the crack growth rate curve in the near threshold and middle zone.

3. For the da/dN-ΔK curves in the middle and accelerated regions of fatigue crack propagation, the position and shape of the curves are different with the stress ratio, such as the da/dN-ΔK curves for plexiglass and titanium alloys. By modifying the exponents in the two-parameter dynamic model with Formula (14), the shape of the da/dN-ΔK curve is modified and thus the da/dN-ΔK curves under different stress ratio are normalized to the da/dN curve.

6 REFERENCES


