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A Study on the Relation Between Threshold Effective Stress Intensity Factor Range and Load Ratio

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Abstract: The threshold effective stress intensity factor range, $\Delta K_{eff,th}$ is normally viewed as a constant under different load ratios. However, the fatigue crack growth data always collapse into a relatively narrow band rather than a single curve as expected.On the other hand, sensitivity analyses for $\Delta K_{eff,th}$ based on the extended McEvily model show that $\Delta K_{eff,th}$ has significant effect on the fatigue crack growth rate especially near the threshold region where most of the fatigue life is consumed. Therefore,$\Delta K_{eff,th}$ is regarded as a variable for different load ratios in this paper and the relation between $\Delta K_{eff,th}$ and load ratio, R is further studied mainly based on the following three aspects: (a) the simple model of $\Delta K_{eff,th}$ proposed by Schmidt and Paris and the corresponding experimental data; (b) the direct experimental data of $\Delta K_{eff,th}$ with the conventional full crack closure concept; (c) the experimental results of modified $\Delta K_{eff,th}$ with the partial crack closure model. Results show that $\Delta K_{eff,th}$ will firstly increase with increasing load ratio below the critical load ratio,R_c and then decease above R_c. Besides, the function of $\Delta K_{eff,th}$ against load ratio, R is further studied through the curve fitting method according to the experimental data.It is found that Lorentz distribution is in reasonably good agreement with the employed experimental data.

Key words: fatigue crack growth; sensitivity analysis; crack closure; threshold effective stress intensity factor range; load ratio
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Nomenclature

- a　crack length (m)
- A　material- and environmentally-sensitive constant ($MPa^{-m}m^{1-m/2}$)
- B　material constants
- k　material constant reflecting the rate of crack closure development (m^{1})
- K　stress intensity factor ($MPa\sqrt{m}$)
- K_c　fracture toughness of the material ($MPa\sqrt{m}$)

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K_{max} maximum stress intensity factor ($MPa\sqrt{m}$)
$K_{max,th}$ maximum stress intensity factor at the threshold level ($MPa\sqrt{m}$)
$K_{min,th}$ minimum stress intensity factor at the threshold level ($MPa\sqrt{m}$)
K_{op} crack opening stress intensity factor ($MPa\sqrt{m}$)
$K_{op,max}$ maximum stress intensity factor at the crack opening level ($MPa\sqrt{m}$)
ΔK_{eff} effective stress intensity factor range ($MPa\sqrt{m}$)
$\Delta K_{eff,P}$ effective stress intensity factor range with partial crack closure concept ($MPa\sqrt{m}$)
$\Delta K_{eff,th}$ threshold effective stress intensity factor range ($MPa\sqrt{m}$)
$\Delta K_{eff,th,P}$ threshold effective stress intensity factor range with partial crack closure concept ($MPa\sqrt{m}$)
ΔK_{th} threshold stress intensity factor range ($MPa\sqrt{m}$)
$\Delta K_{th,R0}$ threshold stress intensity factor range corresponding to R=0 ($MPa\sqrt{m}$)
m constant representing the slope of the fatigue crack growth rate curve
n parameter reflecting the effect of K_{max}/K_c
r_e size of an inherent flaw (m)
R load ratio
R_c critical load ratio
Y(a) geometrical factor
γ material constants
σ_{max} maximum stress (MPa)
σ_V virtual strength (MPa)
da/dN fatigue crack growth rate (m/cycle)

1 Introduction

It was a milestone that the stress intensity factor, K, was adopted to describe the fatigue crack growth rate which was proposed by Paris[1]. However, later, it was found that the Paris law could not account for the load ratio effect and then the crack closure concept was suggested by Elber[2] to explain this phenomenon. The effective stress intensity factor range is accordingly defined as:

$$\Delta K_{eff}=K_{max}-K_{op} \tag{1}$$

where K_{max} is the maximum stress intensity factor in a loading cycle and K_{op} is the crack opening stress intensity factor. Much progress has been made since ΔK_{eff} is employed to represent the fatigue crack growth rate. A large number of fatigue crack propagation models including the partial crack closure model[3-8] and the two-parameter driving force model[9,10] have been proposed in order to condense fatigue crack growth data under different load ratios to a single curve.However,in fact,the predicted results always collapse into a relatively narrow band rather than a single curve. So, as pointed out by McEvily et al[11], the effective stress intensity factor range at the threshold level, $\Delta K_{eff,th}$ maybe is a function of load ratio, R. In this paper, a sensitivity analysis for $\Delta K_{eff,th}$ will be conducted, followed by a discussion on the simple model of $\Delta K_{eff,th}$ proposed by Schmidt and Paris[12],and then the experimental results of $\Delta K_{eff,th}$ in the published literature will be presented with a discussion on the relation between $\Delta K_{eff,th}$ and load ratio, R. Finally, the function of $\Delta K_{eff,th}$ against load ratio, R is proposed through the curve fitting method according to the presented experimental data.

2 Sensitivity analysis for $\Delta K_{eff,th}$

As one of the fatigue crack growth models, McEvily model[11,13] can not only account for the effects of initial crack size and load sequence,but also explain various other phenomena of metal fatigue observed in tests. Furthermore, the model is valid for both physically short crack and macroscopically long crack[14]. The model shows promising capability and is further extended to a general relation for fatigue crack growth analysis by the authors[15,16] which can be described as follows:

$$\frac{da}{dN}=\frac{AM^m}{1-\left(\frac{K_{max}}{K_c}\right)^n} \tag{2}$$

$$M=K_{max}(1-R)-(1-e^{-ka})(K_{op,max}-RK_{max})-\Delta K_{eff,th} \tag{3}$$

$$K_{max}=\sqrt{\pi r_e\left(\sec\frac{\pi}{2}\frac{\sigma_{max}}{\sigma_V}+1\right)}\left(1+Y(a)\sqrt{\frac{a}{2r_e}}\right)\sigma_{max} \tag{4}$$

where da/dN is the fatigue crack growth rate, m/cycle; a is the crack length, m; A is a material- and environmentally-sensitive constant, $MPa^{-m}m^{1-m/2}$; m is a constant representing the slope of the fatigue crack growth rate curve; $K_{op,max}$ is the maximum stress intensity factor at the crack opening level, $MPa\sqrt{m}$; K_c is the fracture toughness of the material, $MPa\sqrt{m}$; n is a parameter reflecting the effect of K_{max}/K_c; k is a material constant which reflects the rate of crack closure development with crack advance, m^{1}; r_e is the size of an inherent flaw, a parameter whose magnitude is of the order of several microns in length[11], m; σ_{max} is the maximum stress in a loading cycle,MPa; σ_V is the virtual strength of the material which is defined in Ref.[15], MPa; Y(a) is a geometrical factor. K_{max} and $\Delta K_{eff,th}$ are parameters as mentioned above.

The above extended McEvily model[16] is employed to perform the sensitivity analysis for $\Delta K_{eff,th}$. The parameters adopted for two load ratios R=0.1 and R=0.7 are listed in Tab.1. It is normally assumed that at high load ratios the fatigue experimental data are closure free. Then for load ratio R=0.7 parameters k and $K_{op,max}$ related to crack closure are equal to zero.For two load ratios, the geometrical factor, Y(a) is set to 0.65 and the maximum stress, σ_{max} is set to 150MPa.Effect of $\Delta K_{eff,th}$ on the fatigue crack growth rate under load ratios R=0.1 and R=0.7 is shown in Fig.1 and Fig.2 respectively.It can be seen that for both load ratios $\Delta K_{eff,th}$ has significant effect on the fatigue crack growth rate especially near the threshold region. For load ratio R=0.7 where crack closure does not exist the fatigue crack propagation is even influenced in a certain degree by $\Delta K_{eff,th}$ in the so- called Paris region. Furthermore, Paris et al[6] pointed out that fatigue crack growth life accumulated most of its cycles at or near the lowest propagation rates.Then it can be concluded that it may be more reasonable to regard parameter $\Delta K_{eff,th}$ as a variable for different load ratios as suggested by McEvily et al[11]. In the following sections the relation between $\Delta K_{eff,th}$ and load ratio,R will be discussed based on the simple model of $\Delta K_{eff,th}$ proposed by Schmidt and Paris[12] and the experimental results of $\Delta K_{eff,th}$ in the published literature.

Tab.1 The parameter values adopted to perform the sensitivity analysis for $\Delta K_{eff,th}$

R	A	m	n	k	K_c	r_e	σ_V	$K_{op,max}$
	$MPa^{-m}m^{1-m/2}$	-	-	m^1	$MPa\sqrt{m}$	m	MPa	$MPa\sqrt{m}$
0.1	4.242 3E- 10	2.50	6.08	9 673	58.90	3.05E- 07	423	2.70
0.7	4.242 3E- 10	2.50	6.08	0	58.90	3.05E- 07	423	0.00

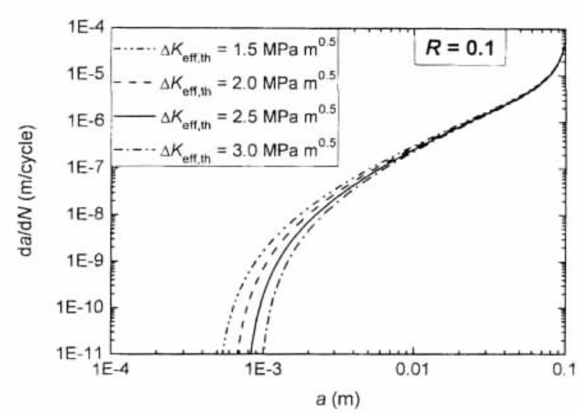

Fig.1 Effect of $\Delta K_{eff,th}$ on the fatigue crack growth rate under load ratio R=0.1

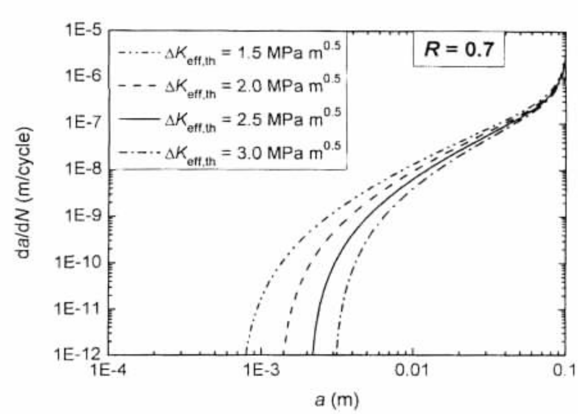

Fig.2 Effect of $\Delta K_{eff,th}$ on the fatigue crack growth rate under load ratio R=0.7

3 The simple model of $\Delta K_{eff,th}$ proposed by Schmidt and Paris[12]

Assuming that both $\Delta K_{eff,th}$ and K_{op} are constant and independent of load ratio, R, Schmidt and paris[12,17] proposed the following equation

$$\Delta K_{eff,th}=\begin{cases}K_{max,th}-K_{op} & R<R_c\ (K_{min,th}<K_{op})\\ K_{max,th}-K_{min,th}=\Delta K_{th} & R>R_c\ (K_{min,th}>K_{op})\end{cases} \tag{5}$$

where $K_{max,th}$ and $K_{min,th}$ are the maximum and minimum stress intensity factors at the threshold level respectively; ΔK_{th} is the stress intensity factor range at the threshold level; R_c is the critical load ratio at which $K_{min,th}=K_{op}$. Under above conditions, $K_{max,th}$ is independent of load ratio, R below R_c and ΔK_{th} is also independent of load ratio, R above R_c. Plotted as ΔK_{th} versus $K_{max,th}$, the transition exhibits itself as a dramatic 'L' shape, as shown in Fig.3. However, many experimental results indicate that the value of ΔK_{th} is not invariant at $R>R_c$ and ΔK_{th} continues to decrease with increasing load ratio, R as pointed out by Boyce and Ritchie[17]. At the same time, the following equations are largely adopted to represent the effect of load ratio R on ΔK_{th}[10,18,19]:

$$\Delta K_{th}=\Delta K_{th,R0}-BR \tag{6}$$

$$\Delta K_{th}=\Delta K_{th,R0}(1-R)^{\gamma} \tag{7}$$

where $\Delta K_{th,R0}$ is the threshold stress intensity factor range value corresponding to R=0 and B and γ are material constants. According to Schijve[20], γ is between 0.5 and 1.0. Both Eq.(6) and Eq.(7) reveal that ΔK_{th} tends to decrease as load ratio increases.

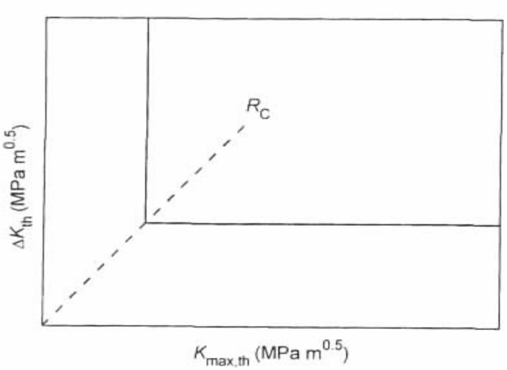

Fig.3 Schematic illustration of ΔK_{th} versus $K_{max,th}$ proposed by Schmidt and Paris[12]

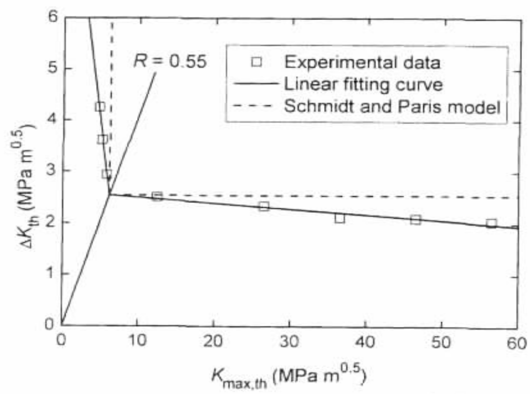

Fig.4 Experimental data of ΔK_{th} and $K_{max,th}$ of Ti-6A1-4V alloy with eight load ratios ranging from 0.1 to 0.964 in Ref.[17]

The experimental data of ΔK_{th} and $K_{max,th}$ at crack growth rate,da/dN=1.0E-10 m/cycle reported in Ref.[17] with eight load ratios ranging from 0.1 to 0.964 are shown in Fig.4. The material under investigation is a Ti-6A1-4V alloy.It can be seen that the experimental results are distinctly different from the simple model suggested by Schmidt and Paris[12]. $K_{max,th}$ is not constant any more at $R<R_c$ and tends to increase as load ratio increases.ΔK_{th} is also not constant any more at $R>R_c$ and continues to decrease with increasing load ratio R. It was also reported in Ref.[17] that at low load ratios, R<0.5, K_{op} values were found to be approximately constant and no crack closure was detected at R>0.5, i.e. R=0.8, R=0.91, R=0.94, R=0.955

and R=0.964, Then $\Delta K_{eff,th}$ has to increase as $K_{max,th}$ increases at load ratios, R<0.5 according to Eq.(5).It has been widely reported[6,17,21-24] that crack closure will disappear at load ratios exceeding a certain value. Beyond the certain load ratio $\Delta K_{eff,th}$ will apparently be equal to ΔK_{th} as at load ratios $R>R_c$. The critical load ratio, R_c is about 0.55 as shown in Fig.4. It is clear that the certain load ratio will be higher than the critical load ratio R_c and the fatigue crack propagation at $R>R_c$ will accordingly include the cases where crack closure disappears.As discussed above, $\Delta K_{eff,th}$ at $R>R_c$, i.e. ΔK_{th} will decrease with increasing load ratio R. Then it can be concluded that $\Delta K_{eff,th}$ will firstly increase as load ratio increases at $R<R_c$ and then decrease at $R>R_c$.

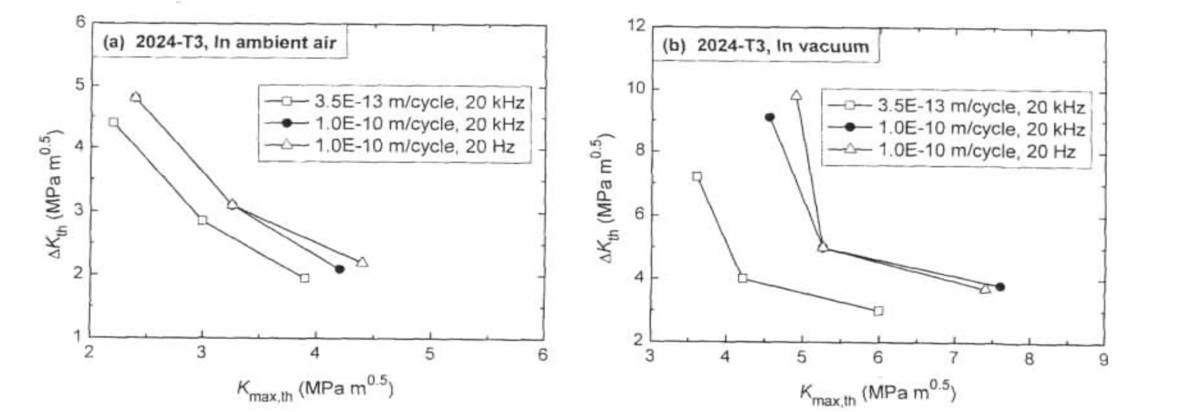

Fig.5 Experimental data of ΔK_{th} and $K_{max,th}$ of aluminum alloy 2024–T3 with load ratio ranging from –1 to 0.5 under different conditions: (a) In ambient air; (b) In vacuum

Fig.5 shows the experimental results of ΔK_{th} and $K_{max,th}$ of aluminum alloy 2024- T3[25] at 3.5E- 13 m/cycle and 1.0E- 10 m/cycle determined with servo- hydraulic (20Hz) and ultrasonic (20kHz) equipment in ambient air and in vacuum. Three points in each line represent the corresponding experimental results with three load ratios R=- 1,R=0.05 and R=0.5 under the same condition.All results under different conditions indicate that ΔK_{th} tends to decrease and $K_{max,th}$ continues to increase with load ratio increasing from - 1 to 0.5.Commonly, the critical load ratio,R_c ,approaches 0.5.Then the results of $K_{max,th}$ are evidently different from the simple model suggested by Schmidt and Paris[12] which demonstrates that $K_{max,th}$ is invariable at $R<R_c$ .Furthermore, it can be expected that $\Delta K_{eff,th}$ at $R>R_c$, i.e. ΔK_{th} will continue to decrease with increasing load ratio, R. According to the experimental results and above discussion, the conclusion can be made that $\Delta K_{eff,th}$ will firstly increase as load ratio increases at $R<R_c$ and then decrease at $R>R_c$.

Fig.6 shows the experimental results of ΔK_{th} and $K_{max,th}$ of aluminum alloy 7075- OA[25] at 3.5E- 13 m/cycle and 1.0E- 10 m/cycle under cycling frequencies of 20Hz and 20kHz in ambient air and in vacuum. The similar results can be found and then the similar conclusion can be drawn as above aluminum alloy 2024- T3.

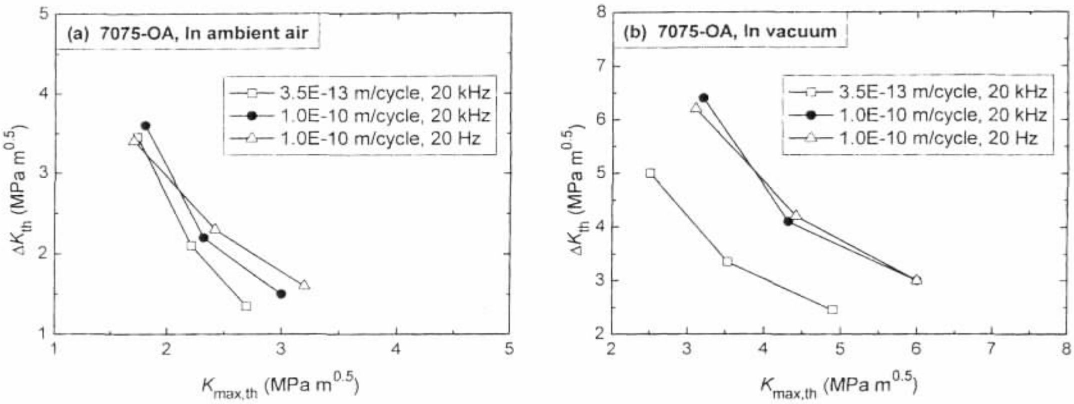

Fig.6 Experimental data of ΔK_{th} and $K_{max,th}$ of aluminum alloy 7075–OA with load ratio ranging from −1 to 0.5 under different conditions: (a) In ambient air; (b) In vacuum

Based on the previous discussion,the conclusion is obvious that $\Delta K_{eff,th}$ will firstly increase as load ratio increases at $R<R_c$ and then decrease at $R>R_c$ which is clearly different from the simple model suggested by Schmidt and Paris[12].

4 Experimental results of $\Delta K_{eff,th}$

Fig.7 shows the experimental results of ΔK_{th} and $\Delta K_{eff,th}$ under different load ratios for four materials: (a) Ti-8A1-1Mo-1V[26]; (b) Cold-worked Copper[3]; (c) Pure Copper[27,28]; (d) Aluminum alloy 2024-T3[29]. It can be obviously seen that for all cases ΔK_{th} continues to decrease with increasing load ratio which is consistent with the results revealed by Eq.(6) and Eq.(7). The $\Delta K_{eff,th}$ values were estimated based on Eq.(1) by measuring the crack opening stress intensity factor, K_{op}, in tests. It is clear that for each case the $\Delta K_{eff,th}$ values are much lower than the corresponding ΔK_{th} values particularly at low load ratios.

Fig.7(a) gives the experimental results of Ti-8A1-1Mo-1V alloy at load ratios R=0.1, R=0.5 and R=0.7 at the same temperature.Each data point is determined by averaging the two specimen results. It can be seen that $\Delta K_{eff,th}$ is equal to ΔK_{th} at R=0.7. This implies that at R=0.7 $K_{min,th}$ is larger than the corresponding K_{op} or the crack closure does not exist any more. Normally, the critical load ratio, R_c, is about 0.5 at which $\Delta K_{eff,th}$ is equal to ΔK_{th}. In this case $\Delta K_{eff,th}$ is lower than ΔK_{th} at R=0.5 and then the critical load ratio,R_c ,should lie between load ratios R=0.5 and R=0.7 and be much closer to R=0.5.It is clear that $\Delta K_{eff,th}$ tends to increase below R_c and continues to decrease above R_c .

In Fig.7(b) the experimental results of cold-worked Copper at load ratios R=-1, R=0 and R=0.4 are shown. $\Delta K_{eff,th}$ is lower than ΔK_{th} at the largest load ratio R=0.4. Then load ratio R=0.4 is below the critical load ratio, R_c . So from Fig.7(b) we can see that $\Delta K_{eff,th}$ continues to increase below R_c as expected.

In Fig.7(c) the experimental data of pure Copper at load ratios R=0.1, R=0.3, R=0.5 and R=0.7 are illustrated. At load ratio R=0.7 $\Delta K_{eff,th}$ is nearly equal to the average value of ΔK_{th} under two conditions and at load ratio R=0.5 $\Delta K_{eff,th}$ is still lower than ΔK_{th} .Then it is fairly easy to judge that the critical load ratio R_c is between 0.5 and 0.7 and is approximately 0.6. It is also apparent that $\Delta K_{eff,th}$ exhibits consistent increase below R_c and reversed decrease above R_c.

In Fig.7(d) the experimental data of aluminum alloy 2024-T3 at load ratios R=0.05, R=0.2, R=0.25, R=0.4, R=0.5, R=0.6 and R=0.7 are shown. Even at load ratio R=0.7 $\Delta K_{eff,th}$ is still lower than the corresponding ΔK_{th} .Then the critical load ratio R_c should exceed 0.7 and be a larger value.$\Delta K_{eff,th}$ totally tends to increase below R_c though $\Delta K_{eff,th}$ almost keeps constant for load ratios from R=0.05 to R=0.4.

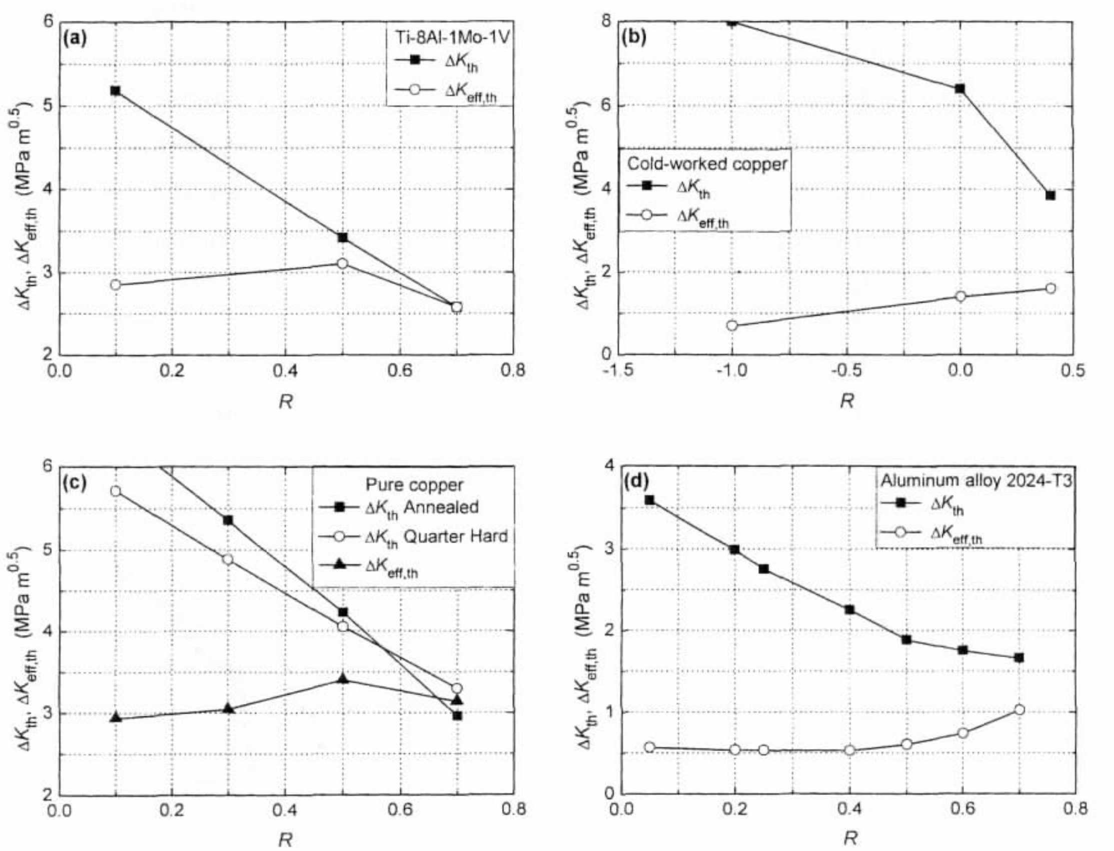

Fig.7 Experimental results of ΔK_{th} and $\Delta K_{eff,th}$ under different load ratios for different materials: (a) Ti–8A1–1Mo–1V; (b) Cold–worked Copper; (c) Pure Copper; (d) Aluminum alloy 2024–T3

It is evident that for four materials the variation of $\Delta K_{eff,th}$ is much smaller than the corresponding ΔK_{th} which is contributed to by crack closure. The variation of $\Delta K_{eff,th}$ for Ti-8A1-1Mo-1V alloy,pure Copper and aluminum alloy 2024-T3 is about 0.5 and for cold-worked Copper is almost 1.0 respectively. The previous sensitivity analyses indicate that $\Delta K_{eff,th}$ has great effect on the fatigue crack growth rate though $\Delta K_{eff,th}$ varies in a limited range. Based on the above discussion, it is clear that for four materials $\Delta K_{eff,th}$ tends to increase below R_c and decrease above R_c in a certain degree.

5 Modified $\Delta K_{eff,th}$ with the partial crack closure concept

As mentioned in the above sections, $\Delta K_{eff,th}$ is commonly much lower than the corresponding ΔK_{th} where ΔK_{eff} is given by Eq.(1). At the same time, Donald[22] has observed a lack of correlation of fatigue crack growth rate using the traditional definition of ΔK_{eff} which is also given by Eq.(1). It is found in plots of da/dN against ΔK_{eff} that significant scatter exists only in the near threshold region and ΔK_{th} and $\Delta K_{eff,th}$ of the presented experimental data exhibit a fully reverse order, i.e. ΔK_{th} data decrease and $\Delta K_{eff,th}$ data increase respectively as load ratio increases. Kujawski[30] has pointed out that the effect of crack closure on the crack driving force given by Eq.(1) might be greatly exaggerated. Chen[4,5] found in tests that the cyclic loading portion below the crack opening load contributed to the fatigue crack growth. It was thus suggested that the conventional definition of ΔK_{eff} should be modified to take the contribution into account.This certainly results in a larger effective crack driving force compared with the conventional crack closure evaluation. Paris et al[6] have proposed a partial crack closure model which can be described as follows

$$\Delta K_{eff,p}=K_{max}-\frac{2}{\pi}K_{op} \tag{8}$$

Eq.(8) indicates that the effect of crack closure has been lessened by introducing a coefficient of $\frac{2}{\pi}$.

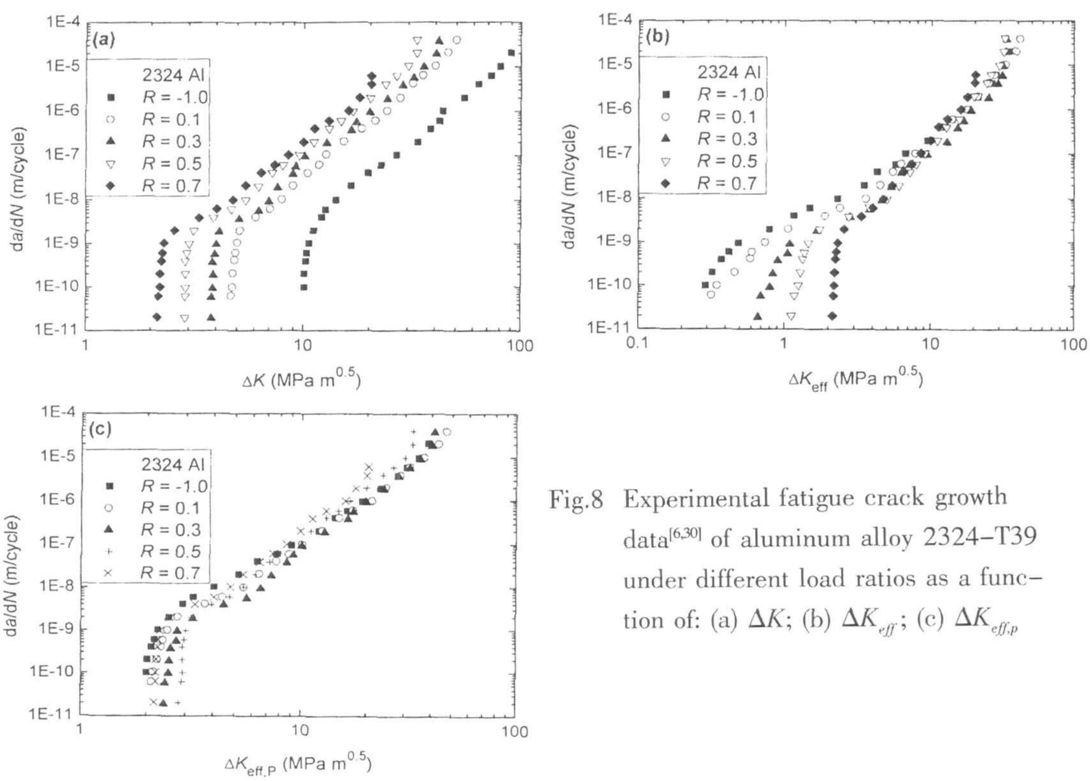

Fig.8 Experimental fatigue crack growth data[6,30] of aluminum alloy 2324-T39 under different load ratios as a function of: (a) ΔK; (b) ΔK_{eff}; (c) $\Delta K_{eff,p}$

Fig.8 gives the experimental fatigue crack growth data[6,30] of aluminum alloy 2324-T39 with five load ratios ranging from -1 to 0.7 as a function of ΔK, ΔK_{eff} and $\Delta K_{eff,p}$ respectively. ΔK_{eff} and $\Delta K_{eff,p}$ represent the effective stress intensity factor range separately defined by Eq.(1) and Eq.(8). Fig.9 is derived from Fig.8 and shows the experimental data of ΔK_{th} and $\Delta K_{eff,th}$ under different load ratios at fatigue crack growth rate, da/dN=1.0E-10 m/cycle. $\Delta K_{eff,th}$ and $\Delta K_{eff,th,p}$ correspond to threshold effective stress intensity factor range with the full and partial crack closure concept respectively.

In Fig.8(a) and Fig.9 it is apparent that ΔK_{th} continues to decrease with increasing load ratio R. In Fig.8(b) it should be noted that for different load ratios significant scatter exists near the threshold region though the effective stress intensity factor range given by Eq.(1) is adopted. This effect is minimized at higher crack growth rates where crack closure loads are much lower relative to the maximum applied loads[6].It was reported[6,30] that significant crack closure was observed in terms of compliance measurements for the tests with load ratios from -1 to 0.5 and at load ratio R=0.7 no crack closure occurred.So in Fig.9 it is clear that $\Delta K_{eff,th}$ is equal to ΔK_{th} at load ratio R=0.7 and is still lower than ΔK_{th} at R=0.5.Then the critical load ratio, R_c should be between 0.5 and 0.7.It is evident that $\Delta K_{eff,th}$ exhibits obvious increase below R_c and decrease above R_c . Fig.8(c) shows the experimental results with the effective stress intensity factor range given by Eq.(8) describing the fatigue crack growth. It can be seen that compared with Fig.8(b) $\Delta K_{eff,th,p}$ for load ratios with crack closure certainly becomes larger as also shown in Fig.9 and the experimental data accordingly collapse into a relatively narrow band.Furthermore, It is still distinct that $\Delta K_{eff,th,p}$ tends to increase below the critical load ratio,R_c which is between 0.3 and 0.5 and decrease above R_c. It should be mentioned that $\Delta K_{eff,th,p}$ is much larger than $\Delta K_{eff,th}$ and nearly equal to ΔK_{th} at R=0.5 and then the critical load ratio, R_c will accordingly become lower.

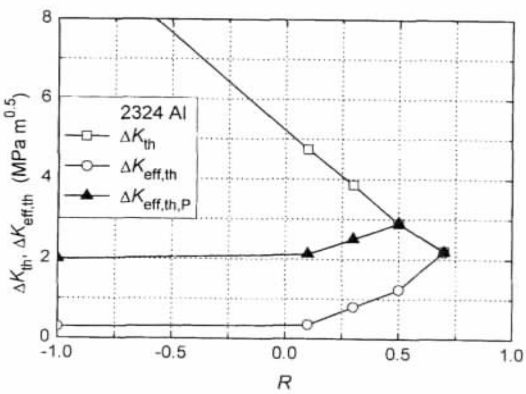

Fig.9 Experimental data of ΔK_{th} and $\Delta K_{eff,th}$ of aluminum alloy 2324-T39 with five load ratios ranging from -1 to 0.7 at fatigue crack growth rate, da/dN=1.0E-10 m/cycle

Based on the above discussion,it can be concluded that the variation range of $\Delta K_{eff,th}$ becomes smaller after employing the partial crack closure concept and the trend of $\Delta K_{eff,th,p}$ with increasing load ratio R is still quite similar to that of $\Delta K_{eff,th}$.

6 Function of $\Delta K_{eff,th,p}$ against load ratio, R

The experimental data[6,30] of modified $\Delta K_{eff,th}$ with the partial crack closure model of aluminum alloy 2324-T39 with five load ratios ranging from -1 to 0.7 at crack growth rate 1.0E-10 m/cycle are employed to perform the curve fitting. The function of $\Delta K_{eff,th,p}$ against load ratio, R, is proposed based on the Lorentz distribution as follows:

$$\Delta K_{eff,th,p}=1.986\,3+\frac{0.069\,59}{4(R-0.435\,42)^2+0.059\,32} \tag{9}$$

The experimental data and the corresponding fitting results are illustrated in Fig.10. Error analysis for $\Delta K_{eff,th,p}$ between the experimental data and the fitting results is listed in Tab.2. It is shown that the fitting results agree well with the corresponding experimental data. The critical load ratio, R_c, according to the fitting results is about 0.44 which is between 0.3 and 0.5 as mentioned above. Furthermore, the fitting results of $\Delta K_{eff,th,p}$ exhibit increase with increasing load ratio below R_c and decrease above R_c. Therefore, Lorentz distribution is in reasonably good agreement with the presented experimental data under different load ratios. However, the experimental data are very limited and the function of $\Delta K_{eff,th,p}$ versus load ratio, R should be further studied based on more experimental data.

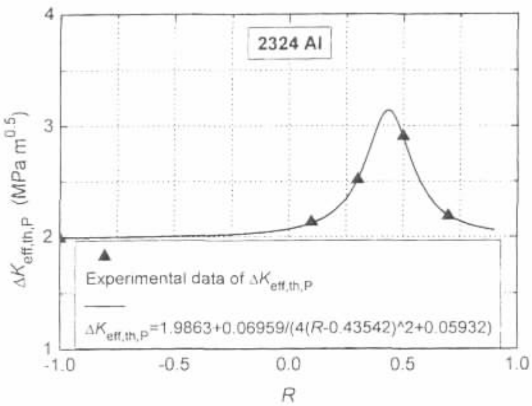

Fig.10 Experimental data of modified $\Delta K_{eff,th}$ with the partial crack closure model under different load ratios and the corresponding fitting curve

Tab.2 Error analysis for $\Delta K_{eff,th}$ of aluminum alloy 2324-T39 between experimental data and fitting results under different load ratios

R	$\Delta K_{eff,th}$ (MPa$\sqrt{m}$)		
	Experimental data	Fitting results	Error (%)
-1	1.991	1.995	0.200
0.1	2.132	2.123	-0.426
0.3	2.509	2.511	0.072
0.5	2.903	2.902	-0.020
0.7	2.188	2.191	0.177

7 Summary and conclusions

The threshold effective stress intensity factor range, $\Delta K_{eff,th}$, is normally viewed as a constant under different load ratios. Plenty of efforts have been devoted to develop the models to attempt to condense fatigue crack growth data under different load ratios to a single curve. However, in fact, the predicted results always collapse into a relatively narrow band. On the other hand, sensitivity analyses for $\Delta K_{eff,th}$ based on the extended McEvily model show that $\Delta K_{eff,th}$ has significant effect on the fatigue crack growth rate especially near the threshold region where most of the fatigue life is consumed. Then $\Delta K_{eff,th}$ is regarded as a variable for different load ratios in this paper.

Based on the simple model of $\Delta K_{eff,th}$ proposed by Schmidt and Paris[12],$K_{max,th}$ is independent of load ratio below the critical load ratio, R_c and ΔK_{th} keeps constant above R_c. However,experimental results reveal that $K_{max,th}$ tends to increase as load ratio increases.Furthermore, ΔK_{th} continues to decrease above R_c which has been vastly verified by the experimental data. So, combined the simple model with the collected experimental data,it is apparent that $\Delta K_{eff,th}$ tends to increase below R_c and continues to decrease above R_c.

The direct experimental data of $\Delta K_{eff,th}$ with the traditional full crack closure concept also show that $\Delta K_{eff,th}$ will firstly increase with increasing load ratio below R_c and then decrease above R_c. $\Delta K_{eff,th}$ is commonly underestimated by using the full crack closure concept. Then the partial crack closure model is suggested to lessen the crack closure effect. However, the trend of $\Delta K_{eff,th,p}$ with increasing load ratio is still similar to that of $\Delta K_{eff,th}$ with the full crack closure concept though the variation range of $\Delta K_{eff,th,p}$ becomes smaller after adopting the partial crack closure concept.

Therefore, the above discussions sufficiently indicate that $\Delta K_{eff,th}$ should be taken as a variable for different load ratios and $\Delta K_{eff,th}$ exhibits consistent increase below the critical load ratio R_c and reversed decrease above R_c. Furthermore, the function of $\Delta K_{eff,th,p}$ against load ratio R can be obtained through the curve fitting method according to the experimental data. Results show that Lorentz distribution is in reasonably good agreement with the presented experimental data.However, the experimental data are very limited and the problem should be further studied based on more experimental results.

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有效应力强度因子范围门槛值与载荷比关系的研究

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摘要：不同载荷比下的有效应力强度因子范围门槛值 $\Delta K_{eff,th}$ 往往被看作一个常数，然而疲劳实验数据结果通常散落在一个较窄的带宽范围内，而不是所期望的一条曲线。另外，基于改进的 McEvily 模型对 $\Delta K_{eff,th}$ 进行的灵敏度分析表明 $\Delta K_{eff,th}$ 对疲劳裂纹扩展率具有重要的影响，尤其是在占有大部分疲劳裂纹扩展寿命的近门槛值区域。因此，文章认为不同应力比下的 $\Delta K_{eff,th}$ 为变量，并且通过三个方面对 $\Delta K_{eff,th}$ 与应力比 R 的关系进行了深入的研究：(a) Schmidt 和 Paris 提出的一个关于 $\Delta K_{eff,th}$ 的简化模型和相应的试验数据；(b) 基于传统的裂纹完全闭合概念的 $\Delta K_{eff,th}$ 试验数据；(c) 基于裂纹局部闭合模型的 $\Delta K_{eff,th,p}$ 试验数据。分析结果表明，在应力比低于临界应力比时，随着应力比的增加，有效应力强度因子范围门槛值也相应增加；而应力比高于临界应力比时，有效应力强度因子范围门槛值随应力比的增加而减小。另外，通过对试验数据的曲线拟合分析表明，Lorentz 分布能很好地描述相应的试验数据。

关键词：疲劳裂纹扩展；灵敏度分析；裂纹闭合；有效应力强度因子范围门槛值；载荷比

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