Fatigue Crack Growth Rate of an Al-Cu-Mg Alloy

Jun He¹, Yilun Liu¹, Chi Liu¹,⁎, Qing Wang¹, Liyong MA²

¹College of Mechanical and Electrical Engineering, Central South University, Changsha, Hunan, 410083, P. R. China
²School of Mechanical Engineering, Hebei University of Architecture, Zhangjiakou, Hebei, 075051, P. R. China

⁎Corresponding author's e-mail: liuchi001@csu.edu.cn

Abstract. In this study, fatigue crack growth rates of industrial 2524-T3 aluminium alloy plates under various stress ratios $R$ ($R=0.1$, 0.2, 0.3, and 0.5) were examined. The microstructure was observed by using a scanning electron microscope (SEM). The results showed that, for a given stress intensity factor range $\Delta K$, the increase in stress ratio led to an increase in fatigue crack growth rate. Besides, the SEM images showed that the fatigue striations were predominant in the fracture, and the spacing of the fatigue striations also drastically increased as the stress ratio increased in different samples. This phenomenon can be explained well by crack closure effects.

1. Introduction

The Al–Cu–Mg based 2000 series aluminium alloys are widely used for constitutive parts, such as fuselage and skin materials, because of their high strength and low density [1]. The 2524-T3 alloy which has been used in Boeing 777 aircraft is an excellent example [2]. 2524-T3 alloy exhibits higher fracture toughness and better fatigue damage performance when compared to former 2024-T3 alloy [3]. Fatigue crack growth is the most important issue in the life prediction of aircraft structures [4]. The study of the fatigue crack growth rate of materials under constant, variable and random loads is of practical significance for many aerospace applications. Usually, fatigue crack growth ratio is described by crack growth rate $da/dN$ and the stress intensity factor range $\Delta K$, while effects associated with stress ratio $R$ on crack growth behaviour are of prime concern [5]. Studies have shown that in the same type of fatigue crack growth test for the same material, different stress ratios $R$ can significantly affect the crack growth rate, and different materials have different sensitivity to stress ratio $R$.

Many experimental and theoretical studies about the fatigue properties of 2524 alloy have been reported. Z.Q. Zheng et al [6]. studied crack initiation and micro-crack propagation characteristics. It was found that cracks were initiated at second particles and defects. L.P. Maduro et al. [2] had reported that TL cracks propagate faster than LT cracks in 2524-T3 aluminium alloy sheet, and T.S Srivatsan. [7] investigated the influence of test temperature on high-cycle fatigue properties and an increase in test temperature was found to have a detrimental influence on cyclic fatigue life. However, studies of the fatigue properties under different stress ratios of the 2524 alloy are limited. In this work, samples of four different stress ratios were used to obtain fatigue data and a life prediction model was used to explain the effect of stress ratios.

2. Materials and experimental details

The 2524-T3 alloy used for this work was provided by China Southwest Aluminium Group with the chemical composition shown in table 1. The material was received as plates with 5.00 mm in thickness.
and solution heat treated, stretched, and naturally aged (T3). Compact tension specimens for the tests were cut in the LT orientation from 2524-T3 sheet.

Table 1. Chemical compositions of alloy 2524-T3 (wt. %).

|    | Cu  | Mg  | Mn  | Fe  | Zn  | Si  | Ti  | Cr  | Al  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|    | 4.26| 1.36| 0.57| 0.03| 0.024| 0.089 | 0.01 | 0.002| Balance |

All fatigue crack growth tests were performed on a MTS-810 fatigue tester with different stress ratios ($R=0.1$, 0.2, 0.3, and 0.5). The tests were conducted at room temperature in laboratory air and the frequency of sinusoidal waveform load was kept constant at 10 Hz. During the tests, the crack opening displacement (COD) method was used to calculate the crack length and the fatigue crack growth rate. The microstructures of samples after fatigue crack growth tests were observed by a scanning electron microscope (TESCAN MIRA3, Czech Republic) with an accelerating voltage of 20 kV.

3. Results

3.1. Fatigue crack growth rates

In figure 1, the measured fatigue crack growth rates $da/dN$ which was obtained by the five point incremental polynomial technique, are plotted against the stress intensity factor range $\Delta K$ values in log–log scale. The $da/dN$ versus $\Delta K$ curves in figure 1 can be divided into three regions: the near-threshold region I, the stable crack growth region II, and the rapid crack growth region III. As expected, the samples clearly revealed the effect of crack growth rate of 2524-T3 aluminium alloy by various stress ratios. For a given $\Delta K$, $R=0.1$ exhibited the lowest fatigue growth rates, while fatigue growth rates of $R=0.5$ were much higher. With increase in stress ratio from $R=0.1$ to $R=0.5$, the $\Delta K$ value where the curves deflect from region I to region II decreases from 9 MPa$\cdot$m$^{1/2}$ to 7 MPa$\cdot$m$^{1/2}$, and the $\Delta K$ value where the curves deflect from region II to region III decreases dramatically from 26 MPa$\cdot$m$^{1/2}$ to 20 MPa$\cdot$m$^{1/2}$, suggesting that under the same $\Delta K$, increasing $R$ has a tendency to increase the fatigue crack growth rates, which means that samples have shorter fatigue life.

3.2. Fatigue fracture surface

Examination of the fatigue fracture surfaces of 2524-T3 alloy in stable crack growth region with different stress ratios was performed. Figure 2 is the low magnification fracture surfaces, and figure 3 is the magnified images. Both figure 2 and figure 3 confirmed that the fatigue crack growth occurred by a transgranular mechanism in all samples. In the fracture diagram of $R=0.1$, many fatigue facets containing fatigue ridges can be observed, which are connected to each other by tearing ridges (arrowed),
and in the fracture diagram of $R = 0.5$, the fatigue plateaus are larger and the tearing ridges are longer. At the edge of the fatigue plateaus, micro-void formation around coarse second-phase particles due to the localized micro-plastic deformation can be observed. Comparing the fracture structure along the direction of fatigue crack propagation, the microscopic deformation of the fracture decreases as the stress ratio increases.

The region of stable crack growth revealed uniformly spaced fatigue striations for all different stress ratios, as shown in figure 3. The direction of the fatigue striations is roughly orthogonal to the direction of crack propagation and the direction of cyclic stress, while the width is different. In figure 3 (a), (b), (c) and (d), the lengths of five adjacent fatigue striations were measured, which were distributed between 1.3 and 2.2 μm. It is apparent that the space between fatigue striations increases as the stress ratio increases under the same stress intensity factor range, which is consistent with the experimental data. On the fatigue striations of the sample of $R=0.1$, the traces of the coarse second phase particles naturally peeling off during the expansion process can be seen. It can be explained that the dislocations and the entanglement caused the deformation to exceed the combination of the particles and the matrix. As the stress ratio increases, the stress concentration is smaller, and in the sample with $R = 0.5$, more particles are attached to the matrix (figure 3 (d)).

(a) $R=0.1$  (b) $R=0.2$  (c) $R=0.3$  (d) $R=0.5$

Figure 2. SEM images of stable crack growth region.
4. Discuss

Among the many fatigue crack growth life prediction models relating the fatigue crack growth rate \( \frac{da}{dN} \) with the stress intensity range \( (\Delta K) \) in stable crack growth region (region II), the Paris potential equation is the most widely used in engineering [8]. The Paris potential equation states that the stress intensity factor range \( \Delta K \) is the main driving force for the rate of crack growth:

\[
\frac{da}{dN} = C (\Delta K)^n
\]  

(1)

Where \( C \) and \( n \) are material-related parameters.

This model does not consider the effects of the stress ratio \( (R) \) on the crack propagation. In order to explain the \( R \) effects, Elber introduced the concept of crack closure and the effective stress intensity factor range \( \Delta K_{\text{eff}} \) [9]. Elber’s model indicates that the crack front will remain in contact during a portion of each loading cycle, while \( \Delta K_{\text{eff}} \) corresponds to the stress intensity factor that crack front keeps open, so \( \Delta K_{\text{eff}} \) is affected by \( R \), and the results of the constants \( C \) and \( n \) independent of the stress ratio can be obtained. The modified formula is:

\[
\frac{da}{dN} = C (\Delta K_{\text{eff}})^n, \quad \Delta K_{\text{eff}} = K_{\text{max}} - K_{\text{cl}}
\]  

(2)

Where \( K_{\text{max}} \) is the maximum stress intensity factor and \( K_{\text{cl}} \) is crack closure stress intensity factor.

This model has been widely accepted that the crack closure effect explains the effect of stress ratio \( R \) on crack growth. Evaluate the effective stress intensity factor range using the empirical formula under the Elber’s model:

\[
\Delta K_{\text{eff}} = U \times \Delta K, \quad U = 0.5 + 0.4R
\]  

(3)

Combining Equations (2) - (3) the fatigue crack growth rate can be expressed as follows:

\[
\frac{da}{dN} = C \left( (0.5 + 0.4R) \Delta K \right)^n
\]  

(4)
As can be seen in figure 4, the results of fatigue crack growth rates versus $\Delta K_{\text{eff}}$ are plotted, where $C=1.847 \times 10^{-6}$, $n=2.485$. In the interval of $\Delta K_{\text{eff}}$ from 5.2 MPa-$\sqrt{m}$ to 11.2 MPa-$\sqrt{m}$, the three curves with $R$ of 0.1, 0.2 and 0.3 almost coincide, while the stress ratio is 0.5, it deviates from the first 3 curves. This indicates that the Elber’s model can fit well when the stress ratio is relatively small (0.1~0.3), and when the stress ratio reaches 0.5, the crack closure effect is no longer obvious, resulting in the crack growth rate being lower than the ideal model under the same effective stress intensity factor range.

![Figure 4. Elber’s model fitting results of crack growth rates under different stress ratios.](image)

5. Conclusion

The stress ratio $R$ has a significant effect on the fatigue crack growth rate of the 2524-T3 aluminium alloy. High stress ratio leads to an increase in the fatigue crack growth rate and the $\Delta K$ value of the fatigue crack propagation into stable crack growth region and rapid crack growth region decreases. Space between fatigue striations increases as the stress ratio increases at the same stress intensity factor range. When $R=0.1\sim0.3$, the Elber’s model, which can explain the influence of $R$, fits 2524-T3 alloy well, and there is a certain deviation in the fitting result when $R=0.5$.

Acknowledgments

This work was supported by the Fundamental Research Funds for the Central Universities of Central South University (2018zzts472), 2018 Zhangjiakou City Science and Technology Plan Financial Support Project (1811009B-12), 2018 Zhangjiakou City Science and Technology Plan Financial Support Project (1811009B-10).

References

[1] Yin, D, Liu, H., Chen, Y., Yi, D., Wang, B., & Wang, B., et al. (2016). Effect of grain size on fatigue-crack growth in 2524 aluminium alloy. International Journal of Fatigue, 84, 9-16.
[2] Maduro, L. P., Baptista, C. A. R. P., Torres, M. A. S., & Souza, R. C. . (2011). Modelling the growth of lt and tl-oriented fatigue cracks in longitudinally and transversely pre-strained al 2524-t3 alloy. Procedia Engineering, 10(10), 1214-1219.
[3] Lumley, R. N., Polmear, I. J., Morton, A. J., Buha, J., Lumley, R. N., & Crosky, A. G., et al. (2014). Recent developments in advanced aircraft aluminium alloys. Materials & Design, 56(4), 862-871.
[4] Molent, L., & Barter, S. A. . (2007). A comparison of crack growth behaviour in several full-scale airframe fatigue tests. International Journal of Fatigue, 29(6), 1090-1099.
[5] Baptista, C. A. R. P., Adib, A. M. L., Torres, M. A. S., & Pastoukhov, V. A.. (2012). Describing fatigue crack growth and load ratio effects in al 2524 t3 alloy with an enhanced exponential model. Mechanics of Materials, 51(none), 66-73.
[6] Zheng, Z. Q., Cai, B., Zhai, T., & Li, S. C. (2011). The behavior of fatigue crack initiation and propagation in aa2524-t34 alloy. Materials Science & Engineering A, 528(4), 2017-2022.

[7] Srivatsan, T. S., Kolar, D., & Magnusen, P. (2001). Influence of temperature on cyclic stress response, strain resistance, and fracture behavior of aluminum alloy 2524. Materials Science & Engineering A (Structural Materials: Properties, Microstructure and Processing), 314(1-2), 118-130.

[8] Paris, P., Erdogan, F., (1963). A critical analysis of crack propagation laws. J.Basic Eng. Trans., ASME, 85(4):528–534.

[9] Elber, W., (1971). The significance of fatigue crack closure. Damage Tolerance in Aircraft Structure. ASTM STP 486:230–247.