Crack Propagation and Predication on 2024 Aluminum Alloy under Combination Action of Friction and Fatigue

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Abstract. The crack propagation of 2024 aluminum alloy under the combination action of non-lubricated sliding friction and fatigue was investigated by numerical simulation analysis and experimental methods. The variation regulation of stress intensity factors (SIFs) $K_I$ and $K_{II}$, and the fatigue crack propagation under different initial crack length, tension and contact pressure was obtained. Based on numerical analysis, experiment research and Paris formula, the predication model of fatigue crack propagation rate was established. The results show that the crack is closed owing to friction force when the upper specimen slides toward the crack, while is torn as sliding away. When the upper specimen moves in the near crack zone, there is relative motion between the crack faces caused by contact pressure. The crack appears slip-open effect. In according to numerical analysis and experimental results, the crack propagation is I-II composite crack forms. The comprehensive influence on I-II composite fatigue crack propagation from large to small is tension, contact pressure and initial crack length. The predication model is verified to reasonable and effective by the new test investigation.

1. Introduction

2024 aluminum alloy has been widely used in aviation and aerospace field due to its advantages of high strength, high toughness, low specific gravity and fatigue resistance, and so on [1]. The life prediction and control of aluminum alloy are one of the hot spots in aviation research [2]. Chernyatina et al. [3] studied the mechanical properties and fatigue crack propagation of crack tip of 2024 aluminum alloy, determined the singular term and non-singular term of the crack tip to obtain the crack propagation rate at different conditions. In addition, the crack propagation rate was aggravated by the crack surface oxidation. 2024 aluminum alloy microstructure took place evolution after the aging hardening treatment, in which changed its diffusion direction. So the reasonable control of the aging hardening process can effectively improve the anti-fatigue performance [4]. It is known that the establishment of a reasonable and effective fatigue life prediction model is very important to avoid accidents caused by fatigue. Based on fatigue accumulation and crack propagation process, Shyam et al. [5] established a fatigue crack propagation model, which has a relationship between the number of fatigue striation formation cycles and the number of crack tip opening displacement cycles. At present, the studies are mainly focused on single fatigue failure, the effect of combination action of friction and fatigue on life is rarely reported. However, the study of single fatigue failure is not comprehensive for active systems [6].

In this paper, the fatigue crack propagation of 2024 aluminum alloy with pre-existing crack was carried out by extend the finite element method and experiment method. The model of crack propagation rate was established based on numerical analysis, experimental data, and Paris formula. It provides a foundation for the life predication of 2024 aluminum alloy parts working in active system.
2. Finite Element Analysis

2.1. Analytical Model
To study the propagation of the surface crack under the combination action of sliding friction and fatigue, the finite element model was established in Fig. 1. The sliding block (upper specimen) was established with the size of 12mm×4mm×2mm, and without mass. The cuboid model containing pre-existing surface crack (lower specimen) was established with the size of 40mm×4mm×12mm. The material is 2024 aluminum alloy, assumed to be linear elastic. The Young's modulus is 70GPa, and the Poisson’s ratio is set to 0.33. A end of the lower specimen was subjected to fixed restraint, and the B end was subjected to tensile force. A contact pressure was applied to the top of the upper specimen, which made its bottom surface form a sliding friction pair with the top surface of the lower specimen. The reciprocating motion takes the pre-existing crack as the symmetrical center. The sliding stroke was 20mm, and the sliding speed is 2mm/s. As shown in Fig. 1(b), Hex hexahedral elements of C3D8R element type were selected for structured meshing through ABAQUS. The extended finite element method was used to analyze the effect of different initial crack length, tension and contact pressure on the stress intensity factor (SIF) of the crack tip. The parameters are shown in Table 1.

![Figure 1. Active system and finite element model of the analysis](image)

| Parameters | Value |
|------------|-------|
| Friction coefficient \( f \) | 0.15 |
| Initial crack length \( a_0 \) /mm | 1, 2, 3 |
| Tension \( F \) /kN | 2, 6, 10 |
| Contact pressure \( P \) /N | 100, 150, 200 |

2.2. Results Analysis
Fig. 2 presents the influence of initial crack length on SIFs under the condition of \( F=2 \)kN and \( P=100 \)N. As shown in Fig. 2(a), the \( K_I \) increased with the increase of initial crack length, but the variation of \( K_I \) was basically the same under different initial crack lengths. The value of \( K_I \) for \( a_0=3 \)mm was increased 12% on average than that of \( a_0=1 \)mm. Under the same initial crack length, the variation of \( K_I \) can be divided into three stages as follows: (1) when the sliding block moved to the crack, i.e. in position 1, 2 and 3, the value of \( K_I \) was rapidly increased; (2) the value of \( K_I \) was slowly increased, when the sliding block is in position 4 and 5; (3) the sliding block began to slide away from the crack after passing position 5, the value of \( K_I \) was obviously accelerated. As seen in Fig. 2(b) that the \( K_{II} \) increased with the increase of initial crack length and exhibited a symmetrical distribution peak-valley form. The three curves presented drastic fluctuations in position 4, 5 and 6. The value of \( K_{II} \) for \( a_0=3 \)mm was increased 60% on average than that of \( a_0=1 \)mm, in which indicated an obvious effect of the initial crack length on \( K_{II} \). When the sliding block was far away from the crack, such as positions 1, 2, 3 and 7, 8, 9, the \( K_{II} \) was less affected, showing a slight increase. However, at position 5, the sliding block was directly above the crack, which reduced the relative sliding trend of the crack surface and the \( K_{II} \) reached the minimum. At position 4 and position 6, the edge of the sliding block coincides with the
crack surface in the vertical direction and causing uneven stress on the crack surface, which strengthened the crack sliding effect, so that the $K_{\text{II}}$ reached a maximum.

**Figure 2.** Variation of SIFs with initial crack length ($F=2$ kN, $P=100$ N)

Fig. 3 presents the influence of tension on SIFs under the condition of $a_0=2$ mm and $P=100$ N. As shown in Fig. 3(a), the $K_I$ increased with the increase of tension. The value of $K_I$ for $P=100$ N was increased 25% than that of $F=2$ kN, indicating greater effect of the tension on $K_I$. The $K_I$ increased with the sliding block motion in three stages similar to that in Fig. 2(a), when the tension was small. However, the value of $K_I$ was approximately linear improved with the position of the sliding block for the larger tension. It can be seen from Fig. 3(b) that the increase of tension also leaded to the increase of $K_{\text{II}}$. The value of $K_{\text{II}}$ for $P=100$ N was increased 34% than that of $F=2$ kN.

**Figure 3.** Variation of SIFs with tension ($a_0=2$ mm, $P=100$ N)

Fig. 4 shows the influence of contact pressure on SIFs under the condition of $a_0=2$ mm and $F=2$ kN. As shown in Fig. 4(a), the value of $K_I$ increased with the increase of contact pressure, presenting increasing, basically unchanged to rapidly increasing with the position of sliding block. The value of $K_I$ for $P=200$ N only increased 8% on average than that of $P=100$ N, indicating a less contribution to $K_I$. It can be seen from Fig. 4(b) that the increase of contact pressure would significantly increase the $K_{\text{II}}$. Especially when the sliding block was at positions 4 and 6, the $K_{\text{II}}$ for $P=200$ N was 44% higher than that of $P=100$ N.

**Figure 4.** Variation of SIFs with contact pressure ($a_0=2$ mm, $F=2$ kN)
3. Experimental Studies

3.1. Experimental Design
The experiments were carried out by a HSR-2M reciprocating friction tester at room temperature in a dry sliding. A kind of clamping device is designed, which can control the tension (see Fig. 5). During the experiment, the lower specimen was applied with a predetermined tension through the fixture, and the sliding block reciprocated. The length of the crack at different cycles was observed using the scanning electron microscope (SEM). The experiments were carried out at least three times.

![Figure 5. Experimental apparatus](image)

3.2. Experimental Results and Discussion
Fig. 6 shows the crack propagation curves under different initial crack lengths. When the number of cycles is less than $5 \times 10^5$, the crack growth gradient was small, and then the crack growth gradient became larger. The crack with an initial length of 3mm expands to 4.24mm and the growth rate is 41%. It can be seen that the crack propagation increased with increase the number of cycles (Fig. 7). When the number of cycles is less than $4 \times 10^5$, the tension had little effect on crack propagation. Then, the greater the tension, the faster the crack propagation was. The crack propagation at 10kN tension is 2.6 times that of 2kN, which indicates that tension had significant influence on crack propagation. It can be seen that the crack length increases with the increase of cycle times, and the greater the contact pressure, the faster the crack propagation (Fig. 8). When the number of cycles exceeded $5 \times 10^5$, the crack propagation was approximately linear. The crack length increased by 1.65mm under the contact pressure of $P=200N$, while only increased by 0.78 mm at the contact pressure $P=100N$. The contact pressure has a significant effect on crack propagation.

![Figure 6. $a-N$ curve under different initial crack length](image)
Regardless of the position of the sliding block, the tension always caused the two sides of the crack to deviate from each other, which plays a tearing role on the crack. However, when the sliding block slides towards the crack, the friction force generated by the contact pressure had a closure effect on the crack, and when sliding away from the crack, it had a tear effect on the crack. When the sliding block squeezed the surface crack area, the contact pressure caused relative slippage between the crack surfaces, resulting in the mode II crack propagation. Fig. 9 and Fig. 10 shows the crack morphology observed by SEM. It can be seen that the fatigue crack was deflected, belonging to I-II mixed mode crack, which was consistent with the results of finite element analysis. Under the coupling action of tension, contact pressure and friction force, the crack tip slips and forms a plastic deformation region, which led to the passivation of the crack tip and affected the tearing of the crack. The order of the comprehensive influence on fatigue crack propagation was as follows: tension, contact pressure and initial crack length. So, the effect of sliding friction on crack propagation cannot be ignored.

4. Crack Propagation Rate Model
The power function formula of crack propagation rate proposed by Paris has been widely used in engineering, which is expressed as:

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

Where a is the crack length, N is the number of cycles, da/dN is the crack propagation rate, C and m are the material parameters, ΔK is the amplitude of SIF, whose equivalent form is defined as [7]:

$$\Delta K_{eq} = \left(\Delta K_I^4 + 8 \Delta K_{II}^4\right)^{1/2}$$  \hspace{1cm} (2)

Where $\Delta K_I$ and $\Delta K_{II}$ is the amplitude of SIF $K_I$ and $K_{II}$, respectively.

The crack propagation rate was obtained by the modified secant method based on the experimental data. The crack propagation rate (da/dN)$_i$ at any data point $[a_i, N_i]$ is the average of the slopes of the upper and lower secant lines at that point, and is defined by the following equation[8]:

$$\left(\frac{da}{dN}\right)_i = \frac{1}{2} \left(\frac{a_{i+1} - a_i}{N_{i+1} - N_i} + \frac{a_i - a_{i-1}}{N_i - N_{i-1}}\right)$$  \hspace{1cm} (3)
Where \( a_i \) is the crack length of point \( i \), \( N_i \) is the number of cycles of point \( i \).

With \( \Delta K_I \) and \( \Delta K_{II} \) obtained by extended finite element method, \( \Delta K_{eq} \) can be calculated according to equation (2). Using least square fitting, the relationship curve between crack growth rate and the amplitude of equivalent SIF \( \Delta K_{eq} \) can be obtained, as shown in Fig. 11. It can be seen that the crack propagation rate had a linear relationship with the amplitude of equivalent SIF in logarithmic coordinates, which belongs to the stable fatigue crack propagation area in this study [9]. So, the model of fatigue crack growth rate is expressed as:

\[
\frac{da}{dN} = 2.3057 \times 10^{11} \left( \Delta K_{eq} \right)^{3.058}
\]

(4)

The correlation coefficient \( R \) of the model is calculated to be 0.92172, which shows that the model of crack propagation rate has a good fitting effect. In order to further inspect the validity of the crack propagation rate model, three groups of new experiment data are selected for comparative analysis in Table 2. It can be seen that the relative errors of the three sets of verification experiments are all less than 10\%, indicating that the crack growth rate model has good usability.

**Figure 11. Crack propagation rate vs. equivalent SIF**

| Test point | da/mm | Experimental conditions | Predictive value/×10^-6 | Experimental value/×10^-6 | Relative error/\% |
|------------|-------|-------------------------|-------------------------|---------------------------|-------------------|
|            |       | F/kN | P/N | N/cycs |                     |                   |                  |
| 1          | 1.5   | 2   | 100 | 0.49   | 0.45                 | 8.2               | 0.49             |
| 2          | 2.0   | 7   | 100 | 1.49   | 1.63                 | 9.4               | 1.49             |
| 3          | 2.0   | 2   | 175 | 2.38   | 2.56                 | 7.6               | 2.38             |

5. Conclusions

The following conclusions can be drawn:

1. The effects of initial crack length, tension and contact pressure on the SIFs \( K_I \) and \( K_{II} \) at the crack tip were obtained. The friction force caused a closure effect at sliding block sliding toward the crack. The closer the sliding block is to the crack, the more significant the effect. The contact pressure caused the relative slip between the crack surfaces and the slippage effect occurs.

2. A tension clamp for the specimen is designed. The effects of initial crack length, tension and contact pressure on crack propagation were obtained by experiment. The results shew that the crack propagation is an I-II mixed mode.

3. A crack propagation rate model of 2024 aluminum alloy was established based on the finite element analysis, experimental results and the Paris formula. The validity of the model was verified by the new test points.

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7. References

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