Delamination property of 2060 aluminium lithium alloy laminate

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Abstract. Delamination is an significant property of aluminium lithium alloy laminate for damage tolerance design. Double Crack Lap Shear specimens of "2/1" structure are used for testing delamination property. Experiments of 2 stress ratio conditions \( R=0.06, 0.5 \) are conducted, and 5 stress levels for each stress ratio. Delamination growth data \( b-N \) are obtained from 4 crack tips’ locations. The energy release rate, \( G_d \), of the "2/1" structure laminate are calculated. Alderliesten model is used for describing delamination growth \( db/dN \) and energy release rate \( G_d \). Parameters \( C_d \) and \( n_d \) in Alderliesten model are determined for \( R=0.06 \) and \( R=0.5 \) by linear fitting. An analysis is made by comparing the results of different stress ratio conditions.

1. Introduction
Aluminium lithium alloy laminate which is composed of metals and composite is an advanced aerospace material. It's crack growth and fatigue properties are significantly enhanced, and have been applied in aircraft structures [1]. Both metal layer and metal/fiber interface are observed crack growth or delamination growth after the metal crack for laminate\[2,3\]. Bridging effect of fibers is the main reason for crack growth delamination growth. Crack tip opening will be restrained by fibers which do not fracture while metal layer's crack grows. Part of loads in crack region of metal layers are sustained by fiber layer, which are called bridging stress. These bridging stress make crack growth rate reduce significantly. Shear deformation which is between metal layer and fiber layer leads to delamination by bridging stress. Delamination may cause a serious failure for laminate, so the behavior of delamination is important for damage tolerance design of aircraft.

Fatigue performances are studies by many scholars. Huang [4] investigates behaviors of crack growth and delamination when laminate bearing single overloads. Martin Kadlec [5] measures the crack growth rate of a composite made of carbon fibre fabric reinforced multifunctional epoxy using double cantilever beam specimens. Huang [6] studies Al–Li alloy and glass fibre laminate's delamination shape, crack growth rate under constant amplitude cyclic loading. Alberto Diaz [7] uses a plates model without singular stresses to analyses laminate delamination's strain energy release rates. However, previous studies are more focus on load effect on crack growth. Delamination growth behaviors with different stress ration for design are uncommon.

In this paper, "2/1" structure Double Crack Lap Shear specimens are used for testing delamination property. Experiments of 2 stress ratio conditions \( R=0.06, 0.5 \) are conducted, and 5 stress levels for
each stress ratio. Delamination growth data $b\cdot N$ are obtained from 4 crack tips' locations. "2/1" structure laminate’s energy release rate $G_d$ are calculated. Alderliesten model are used for describing delamination growth $db/dN$ and energy release rate $G_d$. Parameters $C_d$ and $n_d$ in Alderliesten model are determined for $R=0.06$ and $R=0.5$ by linear fitting. An analysis is made by comparing different stress ratio conditions' results.

2. Material and specimen

Base metal 2060 aluminium lithium alloy with a thickness of 2mm is used for specimen preparation. The material’s chemical components are shown in Table 1. High strength glass fibre is used for the laminate.

| Element | Si  | Fe   | Cu  | Mn  | Mg  | Ag  | Zn  | Zr  | Li  | Ni  | Al   |
|---------|-----|------|-----|-----|-----|-----|-----|-----|-----|-----|------|
| Content(%) | <0.05 | <0.07 | 3.74 | 0.28 | 0.79 | 0.33 | 0.37 | 0.12 | 0.68 | <0.05 | surplus |

DCLS specimens of "2/1" structure are used for testing delamination property. Figure 1 shows the sketch of laminate specimen.

![Fig.1. The sketch of laminate specimen](image)

3. Experiments

Experiments are conducted on an electro-hydraulic fatigue testing machine. The testing machine and the force measurement are verified statically in accordance with ASTM E4 "Practices for Force Verification of Testing Machines".

The tests are all conducted in lab air. The load shape is sine wave. The frequency is 10 Hz. 2 stress ratio conditions, $R=0.06$, 0.5, are conducted, and 5 stress levels for each stress ratio. Fatigue load is applied for cracking the prefab notch. Visual inspection is adopt for measuring the crack length.

Figure 2 shows the principle of measuring the delamination size. Distances between 4 tips and the base line are recorded, and the mean value of the delamination size $b$ is obtained.

![Fig.2. Principle of delamination size measure by visual inspection](image)
4. Results and Discussion

An example of $b$-$N$ data and fitting line are shown in Figure 3. For each stress level, a $b$-$N$ data is fitting to calculate $\frac{db}{dN}$.

\begin{align*}
R &= 0.06 \\
S_{\text{max}} &= 50 \text{ MPa} \\
b &= 0.000109N + 4.548
\end{align*}

Fig.3. An example of delamination growth rate $\frac{db}{dN}$ and fitting line

According to the Alderliesten model, the relationship between $\frac{db}{dN}$ and $G_d$ can be expressed as the Paris equation as follows:

$$
\frac{db}{dN} = C_d \left( \Delta \sqrt{G_d} \right)^n_d
$$

where $C_d$ and $n_d$ are constants of delamination growth.

For "2/1" structure, energy release rate $G_d$ can export:

$$
G_d = \frac{t_{fm} F_{Al}}{2 j E_{fm} F_{Al} + F_{fm} F_{Al}} \left[ \sigma_{fa} - (1 + \frac{F_{fm}}{F_{Al}}) \sigma_{r, fm} \right]^2
$$

where $j$ is the number of interbeds, $\sigma_{fa}$ is stress of delamination zone in fibre.

$F_{fm}, F_{Al}$ are stiffness of the fibre material and the metal:

$$
F_{fm} = E_{fm} t_{fm}
$$

$$
F_{Al} = E_{Al} t_{Al}
$$

where $t_{fm}, t_{Al}$ are the thickness of the fibre material and the metal, respectively. $E_{fm}, E_{Al}$ are elasticity modulus of the fibre material and the metal, respectively.

Energy release rate $G_d$ is obtained by Equation (2).

Equation (1) is used for fitting $\frac{db}{dN}$-$G_d$ data, and Table 2 shows the $\frac{db}{dN}$ and $G_d$ data used for fitting. The $\frac{db}{dN}$-$G_d$ data and fitting lines are shown in Figure 4 and Figure 5. Table 3 shows the result of the constants of delamination growth.
Tab. 2. Results of fitting $\frac{db}{dN}$ and $\Delta \sqrt{G_d}$

| $S_{\text{max}}$ / MPa | $R$ | $\frac{db}{dN}$ / mm/cycle | $\Delta \sqrt{G_d} / (N/\text{mm})^{\frac{1}{2}}$ |
|------------------------|-----|-----------------------------|---------------------------------|
| 70                     |     | $6.78 \times 10^{-5}$       | 0.2639                          |
| 75                     |     | $1.74 \times 10^{-4}$       | 0.2827                          |
| 80                     | 0.5 | $2.84 \times 10^{-4}$       | 0.3016                          |
| 85                     |     | $2.29 \times 10^{-4}$       | 0.3204                          |
| 90                     |     | $1.12 \times 10^{-3}$       | 0.3393                          |
| 50                     |     | $1.09 \times 10^{-4}$       | 0.3544                          |
| 60                     | 0.06| $2.23 \times 10^{-4}$       | 0.4252                          |
| 70                     |     | $6.21 \times 10^{-4}$       | 0.4961                          |
| 80                     |     | $4.58 \times 10^{-3}$       | 0.5670                          |
| 90                     |     | $9.63 \times 10^{-3}$       | 0.6379                          |

Fig. 4. $\frac{db}{dN}$- $G_d$ data and fitting line ($R=0.06$)

Fig. 5. $\frac{db}{dN}$- $G_d$ data and fitting line ($R=0.5$)
Tab.3. Constants of delamination growth base on Paris equation

| $R$   | $C_d$  | $n_d$ |
|-------|--------|-------|
| 0.06  | 0.32   | 7.75  |
| 0.5   | 78.95  | 10.46 |

From Table 3, parameters $C_d$ and $n_d$ of 2060 laminate aluminium lithium alloy are obtained for aircraft design. A comparison of $db/dN- G_d$ fitting line between $R=0.5$ and $R=0.06$ are given in Figure 6. It can be found that $R=0.06$ has more energy release than $R=0.5$ with the same delamination growth rate. This is mainly because $R=0.5$ condition needs huger stress to delaminate, and in that case fibres suffer more stress, so the delamination energy release is relative weaker.

![Fig.6. Comparison of $db/dN- G_d$ fitting line between $R=0.5$ and $R=0.06$](image)

5. Conclusion

Experiments on 2060 aluminium lithium alloy laminate's delamination are conducted. The energy release rate, $G_d$, of the "2/1" structure laminate are calculated. Alderliesten model are used for describing delamination growth $db/dN$ and energy release rate $G_d$. Parameters $C_d$ and $n_d$ in Alderliesten model are determined for $R=0.06$ and $R=0.5$ by linear fitting for aircraft design's reference. An analysis is made by comparing different stress ratio conditons' results, and it's shows that delamination in $R=0.06$ has more energy release with the same delamination growth rate.

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