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Fatigue crack propagation of new aluminum lithium alloy bonded with titanium alloy strap

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Abstract A new type of aluminum lithium alloy (Al–Li alloy) Al–Li–S–4 was investigated by test in this paper. Alloy plate of 400 mm × 140 mm × 6 mm with single edge notch was made into samples bonded with Ti–6Al–4V alloy (Ti alloy) strap by FM 94 film adhesive after the surface was treated. Fatigue crack growth of samples was investigated under cyclic loading with stress ratio (R) of 0.1 and load amplitude constant. The results show that Al–Li alloy plate bonded with Ti alloy strap could retard fatigue crack propagation. Retardation effect is related with width and thickness of strap. Flaws have an observable effect on crack propagation direction.

1. Introduction

Large commercial aircraft is being manufactured in China. Plane design is a cross-disciplinary technology which focuses on aviation safety and reliability, besides flight dynamics, feasible propulsion systems, reduced fuel consumption, noise reduction and others.

Researches show that consumption of fuel will reduce 2900 kg/year if the weight of aircraft structure is lightened by 1 kg. It has been reported that the latest Boeing 787 with less weight can increase fuel efficiency by 20%.[1] With the development of welding technology, integral structures can bring the benefits of reducing parts quantities, saving weight and simplifying inspection. However, integral structures do not contain special parts which could retard crack growth, so extra components should be added in some dangerous positions where crack might initiate at manufacture stage.

The need for higher safety promotes design philosophy of airplane structure shafting from safe-life or fail-safe to damage tolerance safety. One of the promising solutions is to use selective reinforcement or bonded straps in airplane structure,[2–6] which is a novel method based on durability design. This has not being widely used in the aircraft design in China before. Liu[7] studied the effectiveness of composites on preventing fatigue crack propagation and extending fatigue life of steel plates; his results showed that double-sided repairing scheme increased fatigue life by 2.2–2.7 times over un-patched steel plates when normal modulus carbon fiber reinforced polymer/plastic (CFRP) sheets were used, and by 4.7–7.9 times when high modulus CFRP sheets were used. Brighenti[8] optimized the shape of a patch repairing for a cracked plate by genetic algorithm method. His research results illustrated that

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stress-intensity factor can be reduced to about 40%–60% by optimizing patch shape. Zhang and Boscolo[2] studied aluminum alloy panels bonded with three kinds of different straps by numerical modeling and experimental tests. The results indicated that fatigue life can be significantly improved by bonding discrete straps to an integral structure.

All these work and data are available to Chinese plane design. There are many design parameters, such as materials, dimension and condition, that influence the fatigue crack growth rate. At the same time, many experiments are needed before new materials and novel design methods are used on plane.

This paper focuses on fatigue crack propagation of new type Al–Li alloy and the effectiveness of crack growth retardation by Ti alloy straps bonding on the Al–Li plates. We wonder whether this special structure made of Al–Li alloy and reinforced by Ti alloy straps could retard crack growth effectively.

2. Specimens and experiments

2.1. Materials

Al–Li–S–4 is a new type of Al–Li alloy, which is specially used for Chinese commercial aircraft design and made by Aluminum Company of American. Compared with similar aluminum alloys, the alloy has better properties, such as, strength, fracture toughness and elongation. Material composition and properties are given in Tables 1 and 2.

FM 94 film adhesive in this study was imported from Cytec Company of the United States, and mechanical properties of adhesive and Ti alloy strap described are given in Table 3.[2,9]

Table 1 Composition of Al–Li–S–4 (mass fraction, %).

Si	Fe	Cu	Mn	Mg	Zn	Ag	Li	Zr	Ti	Al
0.014	0.028	3.64	0.29	0.71	0.36	0.32	0.68	0.12	0.026	Bal.

Table 2 Properties of Al–Li–S–4 at ambient temperature.

Property	Al–Li–S–4	
Elastic modulus E (GPa)	75.9	—
Poisson's ratio v	0.33	0.33
σ_b (L) (MPa)	532	547
σ_b (L–T) (MPa)	533	541
σ_y (L) (MPa)	475	504
σ_y (L–T) (MPa)	464	485
Elongation (L) (%)	12.5	10.7
Elongation (L–T) (%)	12.7	10.9

Table 3 Properties of adhesive and Ti alloy.

Property	Adhesive	Ti–6Al–4V
Elastic modulus (GPa)	1.9	113.8
Poisson's ratio	0.52	0.342
σ_b (MPa)	43.7	900
Elongation (%)	—	5

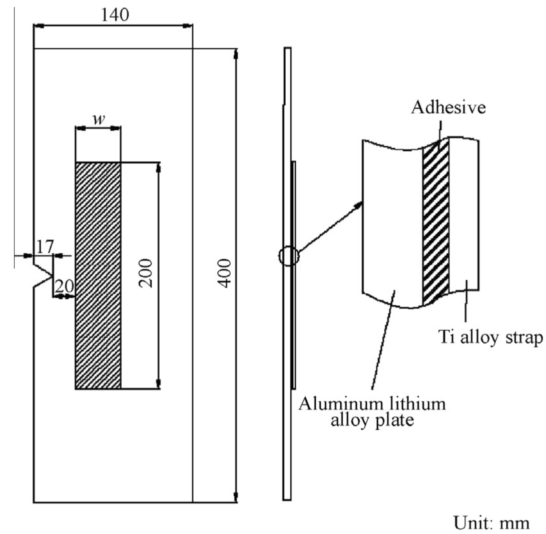

Fig. 1 Sketch of Al–Li plate bonded with strap.

Fig. 2 MTS810 test system.

2.2. Specimens and test equipment

Experimental Al–Li alloy plate bonded with strap is shown in Fig. 1. The thicknesses of Al–Li alloy, adhesive and Ti alloy strap are 6, 0.2, and 2 mm separately.

The single edge notch tension plate of Al–Li–S–4, 6 mm thick, was subject to fatigue loading. The cracked plates were prepared according to the ASTM E-647 specifications. Initial notch of 17 mm length was cut using wire-cut technique. Straps were made of Ti alloy, which shows high specific strength and toughness (shown in Table 3) combined with light weight and excellent corrosion resistance,[10] bonded to Al–Li alloy plate using FM 94 adhesive cured at 121 °C.

Fatigue crack growth tests were carried out on experimental system MTS810, as shown in Fig. 2. The experimental system is mainly used for the testing of static and dynamic mechanical properties of materials at different temperatures ranging from −200 to 1200 °C, including tensile, fatigue (high and low-cycle fatigue), fracture toughness tests and so on.

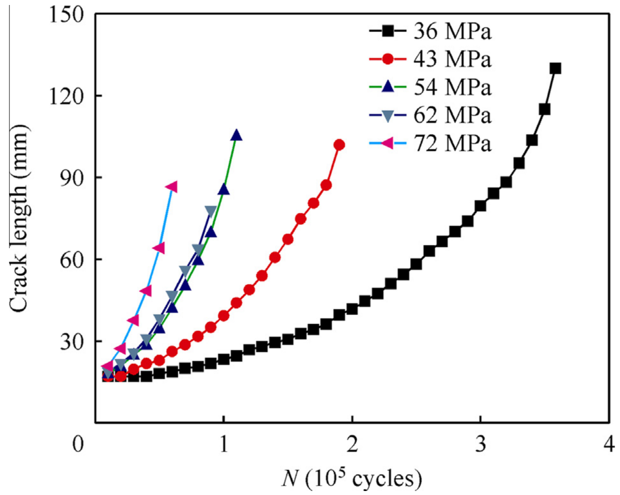

Fig. 3 Number of cycles vs. crack length under different loading.

2.3. Sample preparation

Surface treatment process of aluminum alloy refers to ASTM D 3933.[11] Ti alloy strap surface treatment method was prepared according to ASTM D 2651.[12] Assembling details of sample are described in Ref. [13].

3. Results and analysis

3.1. Results of crack propagation

3.1.1. Effect of stress on sample crack propagation

Fig. 3 show the crack length (the length from fringe of Al–Li plate) data versus the number of cycles from tests for Al–Li alloy plate bonded with straps. Results show that crack propagation rate speeded up when cyclic stress amplitude gradually became higher. Under 72 MPa cyclic loading, cycles of sample was 57400 as it broke down, while it was 358000 under 36 MPa load. The crack length became larger when tests were finished. At the same time, crack growth rate slowed down. Cycle life

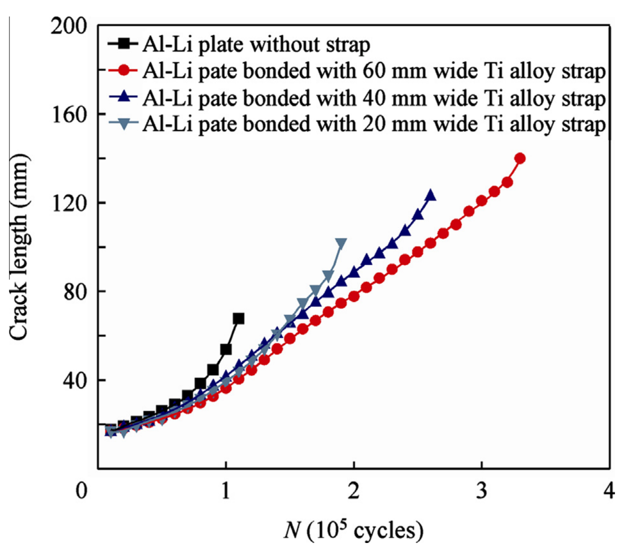

Fig. 4 Number of cycles vs. crack length under 43 MPa.

were about 200000 under 43 MPa loading, while crack length was about 40 mm after 230000 cycles under 36 MPa cyclic load, far from the cycle life of component. Bonded strap retarded the crack propagation by exerting a bridging force on the crack surfaces. This is called bridging effect.[2,14]

3.1.2. Effect of strap width on crack propagation

Fig. 4 depicts a set of test data of crack length versus the number of cycles for Al–Li alloy plate without or with different width straps bonded. The fatigue life of samples varied significantly. The life of the sample without strap was only 110109 cycles before collapsing under normal cyclic loading of 43 MPa, while the plate bonded with 60 mm wide strap underwent 328971 cycles. This comparison clearly showed that Al–Li alloy plate bonded with straps performed much better than that without strap. Retardation of fatigue crack growth rate was obvious. Further, it shows that the width of straps had an effect on the fatigue life. The plate bonded with 20 mm wide strap increased the fatigue life by more than 1.75 times contrasting to Al–Li alloy plate without strap, while fatigue life of Al–Li alloy plate bonded with 60 mm wide strap increased by more than four times relative to that of plate without strap. This improvement in fatigue life performance was due to the increasing areas which retarded crack propagation and lowered stress intensity factor at the crack tip in the presence of strap. During experimental process, an interesting case was observed that plate bonded with 60 mm wide strap sustained crack propagation until the Al–Li alloy plate broke and only then the strap disjointed from plate. Also lower K (stress intensity factors) results in longer broken crack.[6]

3.1.3. Effect of strap stiffness on crack propagation

Schijve[6] and Bagnoli et al.[15] hold that crack retardation effect of strap bonded to aluminum plate is related to the global stiffness ratio, defined as

$$\mu = \frac{\sum \left(E_{\text{strap}} A_{\text{strap}}\right)}{E_{\text{Al}} A_{\text{Al}} + \sum \left(E_{\text{strap}} A_{\text{strap}}\right)} \tag{1}$$

where μ is global stiffness ratio; E_{strap} elastic modulus of repair strap, GPa; A_{strap} section areas of strap, mm^2; E_{Al} elastic modulus of aluminum alloy, GPa; A_{Al} section areas of aluminum lithium alloy, mm.[2]

Jiang et al.[16] uses numerical method to study the relationship between stress intensity factor and non-dimensional parameter β, her results show that the stress intensity factor is reduced significantly for bigger β values, and

$$\beta = \frac{E_{\text{strap}} B_{\text{strap}} t_{\text{strap}}}{E_{\text{Al}} t_{\text{Al}} L_{\text{Al}}} \tag{2}$$

where β is non-dimensional parameter; B_{strap} width of strap, mm; t_{strap} thickness of strap, mm; t_{Al} thickness of aluminum alloy, mm; L_{Al} length of aluminum alloy, mm.

Schubbe[17] defines a stiffness ratio S to treat a strap as a repair patch:

$$\beta = \frac{E_{\text{strap}} t_{\text{strap}}}{E_{\text{Al}} t_{\text{Al}}} \tag{3}$$

His research also shows that the increase in the stiffness ratio improved the fatigue life of the repaired panels.

In order to evaluate the effect of stiffness ratio on fatigue life, the straps were selected of 2 mm and 4 mm thickness,

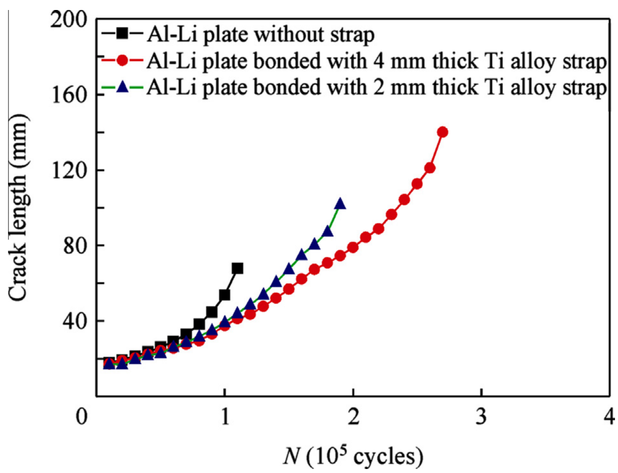

Fig. 5 Number of cycles vs. crack length under 43 MPa cyclic loading.

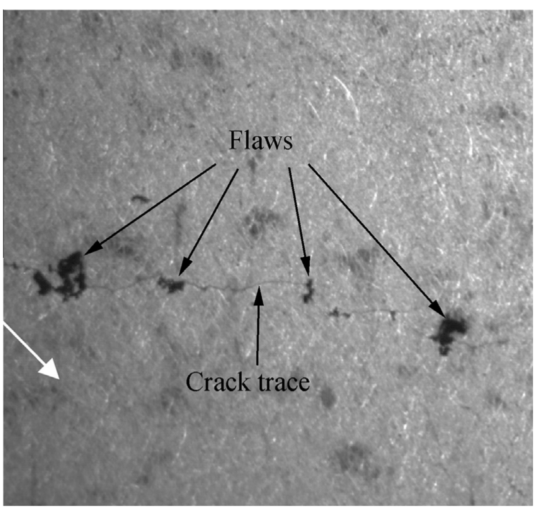

Fig. 6 Trace of crack growth.

respectively, while the length and width of strap kept constant as 200 mm and 20 mm. Fig. 5 shows the measured crack lengths versus number of cycles for plates bonded with different thickness straps, as well as crack growth curve for the Al–Li–S–4 alloy without a strap. It can be seen that the thickness of the straps has an effect on fatigue life of Al–Li alloy plate. The fatigue life of plate bonded with 4 mm thick strap is much longer than that of plate bonded with 2 mm thick strap.

It was observed that as the crack tip progressed through the strap, the rate of the crack propagation slowed down. This is because of the strap undertaking a part of cyclic loading of Al–Li plate, reducing the stress intensity factors. Zhang and Boscolo[2] think that adhesive disbanding induces separating strap from the substrate at post cyclic stage, leading to invalidation of retardation.

3.2. Trace of fatigue crack growth

Flaws in alloy substrate affect the direction of crack propagation. For some reason, there are always flaws existing in materials, for examples, mircrocrack, cavity, slight microcutting and so on. These flaws were perhaps created in the process of plate production, transport or surface treatment before bonding. All these flaws around crack influenced propagation direction of crack. One of the crack traces in this investigation is shown in Fig. 6.

It can be seen that crack propagation trace went through flaws. Stress concentration was created at these pits under cyclic loading, crack originated at these pits firstly, then grew and joined together so as to form a twisted trace. Flaw was one of the reasons why crack trace curved.

4. Conclusions

1. The crack propagation rate becomes faster as cyclic loading becomes larger. Bridging effect shows obvious under 36 MPa load.
2. Different wide straps have various effects on the retarding crack propagation. Generally speaking, the wider strap is, the longer fatigue life has. At the same time wider strap leads to heavier structure weight. The retardation effect presents from the beginning stage of crack, and crack of Al–Li plate bonded with Ti alloy strap propagates slower than that without strap. This effect becomes more significant when strap is behind advancing crack tip and strap undertakes a part of cyclic loading of Al–Li plate, reducing the stress intensity factors.
3. Thickness of the straps has an effect on the fatigue life of Al–Li alloy plate. Fatigue life of Al–Li alloy plate bonded with 4 mm strap rises about 170% than Al–Li alloy without strap.
4. Flaws in alloy substrate near crack tip affect direction of crack propagation. Crack passes through these flaws and curves.

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