Study on Delamination Behavior and Crack Opening Contour of Advanced Hybrid Laminates during Fatigue Crack Propagation Process

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Abstract To study crack opening contour and delamination behavior of one kind of advanced hybrid laminates during fatigue crack propagation process, this research accomplished fatigue crack propagation test under R=0.1 for two kinds of saw-cut length and two kinds of stress level, acquired the basic appearance of crack opening contour and delamination, obtained the effect of saw-cut length and stress level on crack opening contour and delamination size. The results indicate that crack opening contour becomes larger as the stress level or saw-cut length rises. Delamination size increases when the stress level becomes larger. The saw-cut length is almost not able to affect delamination size.

Keywords Fiber metal laminates; Advanced hybrid laminates; Delamination; Fatigue crack propagation; Saw-cut

1. Introduction

Fiber metal laminates (FML) have been developed in recent years[1]. Advanced hybrid laminates (AHL) applied to wing load-carrying structures have been developed from ARALL, GLARE and the concept of Selective Reinforcement[2]. One of the AHL, named CentrAl, developed by GTM-advanced structures and Alcoa Technical Center, will be applied in the wing box structure for airliner and cargo plane[3].

Significant research on fatigue crack propagation behavior has been adequately conducted for ARALL and GLARE. And various prediction models have been developed by researchers[4-15]. As Alderliesten said[13], bridging stress, crack opening contour and delamination shape are in balance. As a result of it, in order to calculate bridging stress and then predict fatigue crack propagation behavior effectively, there is significance for studying crack opening contour and delamination behavior deeply.

Existing a few papers[2, 16] present that it is very different from the fatigue crack propagation behavior of AHL and traditional FML. ARALL and GLARE is thin enough to show a nearly same fatigue crack propagation rate in each aluminum alloy sheet layers and a similar delamination shape and size between each layer. But there is a remarkable difference for crack length and delamination size between each layer because of a thickness effect. As the same time, research on the crack opening contour of AHL has not yet been published.

To understand the fatigue crack propagation behavior of AHL, this research accomplished fatigue crack propagation test under different saw-cut lengths and stress levels, recorded crack opening contour, obtained delamination shape and size by etching, got the initial results from the influence of saw-cut length and stress level on crack opening contour and delamination behavior, laid the foundation of validating theoretical analysis results.

2. Experiment

2.1. Materials and Specimen

The lay-up of AHL in this research is shown in Fig. 1. There is a 3/2 lay-up laminate bonded between two 2mm-thick 2A12-T4 aluminium alloy sheets by adhesive film. Central 3/2 lay-up was laid by three 0.5mm-thick LY12-M aluminium sheets and two prepregs. Prepregs are prepared by

HS2 glass fiber and TDE-85 epoxy resin.

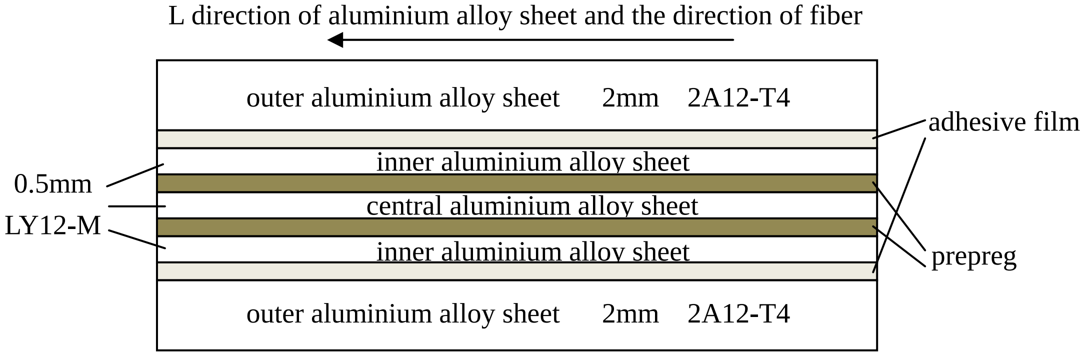


Figure 1. Lay-up of advanced hybrid laminates

Centre crack tension (CCT) specimen was selected for this research, as shown in Fig. 2. Two kinds of saw-cut size, $2a_s$=10mm and 15mm, were processed in order to explore influence of saw-cut length on crack opening contour and delamination behavior.

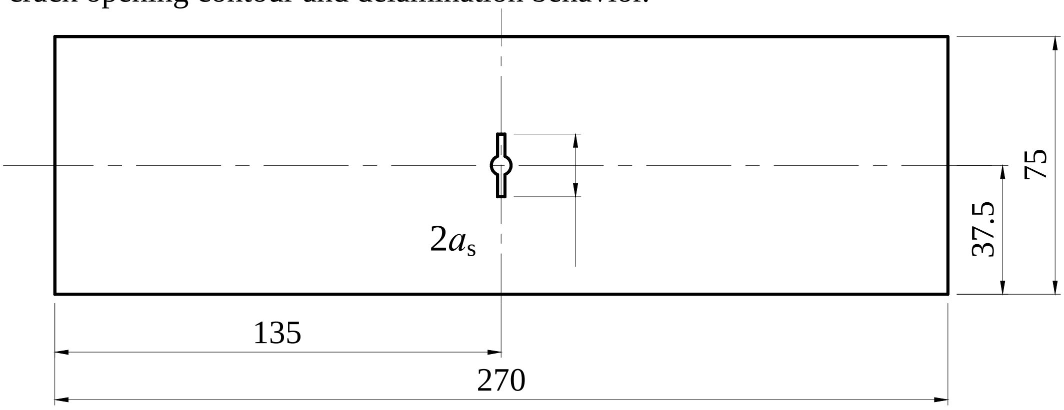


Figure 2. Centre crack tension (CCT) specimen

1.2 Fatigue Crack Propagation Test

Fatigue crack propagation test was finished with constant-amplitude sine wave fatigue loadings, the frequency of 10 Hz and the stress ratio R of 0.1 on 2.5T MTS-858 electohydraulic servocontrolled fatigue testing machine. Crack length was observed by two JDX-B magnification microscopes with scale of 30X. Average crack length a_m is obtained by averaging the front-left side crack length a_1 and back-right side crack length a_2. The matrix of the test is shown in Table 1.

Table 1. Matrix of fatigue crack propagation test

Saw-cut length $2a_s$/mm	Stress level σ_{max}/MPa	Target average crack length a_m/mm
10	60	12，17，22
10	85	12，17，22
15	60	12，17，22

Crack opening contours are captured when a_m reaches nearly 12mm, 17mm and 22mm. Specific measurement method is: take pictures of crack area with a ruler after applying a tension loading which equal to the maximum fatigue loading, then measure the crack opening contour by using image measurement software, and finally obtained the crack opening contour, as shown in Fig. 3.

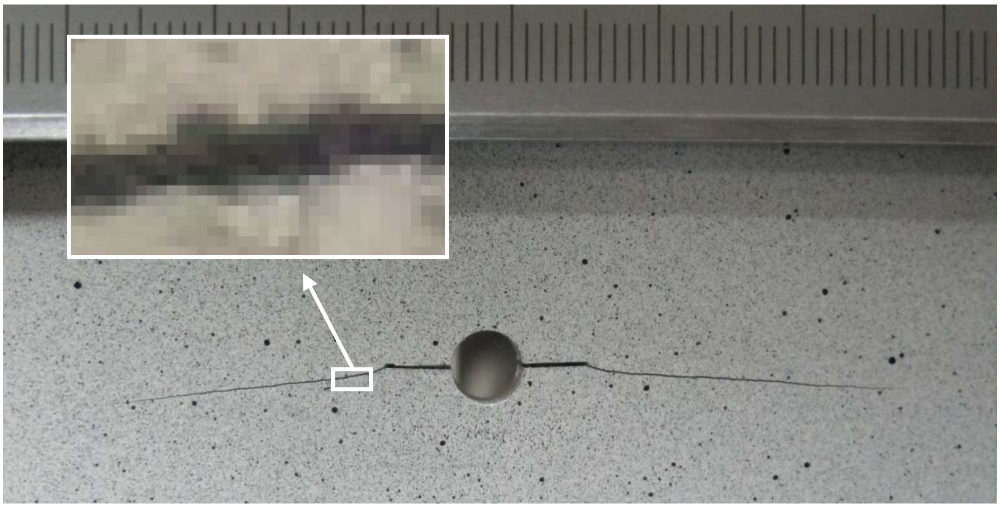


Figure 3. Image analysis measurement method for crack opening contour

To investigate delamination behavior, etch the specimen when a_m reaches nearly 12mm, 17mm and 22mm. Through image analysis measurement method, acquired delamination shape and size finally, as shown in Fig. 4.

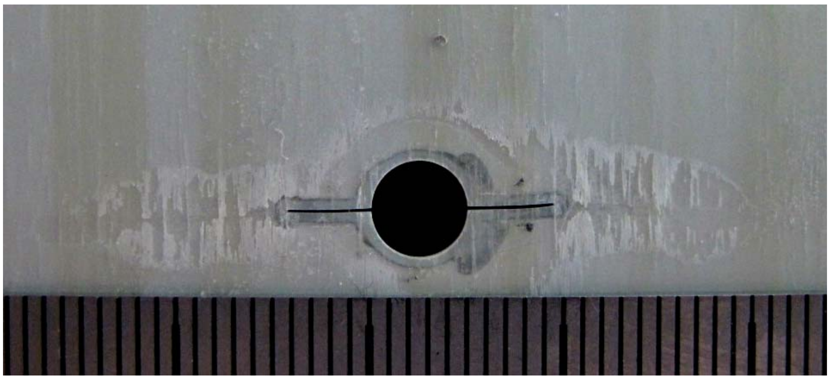
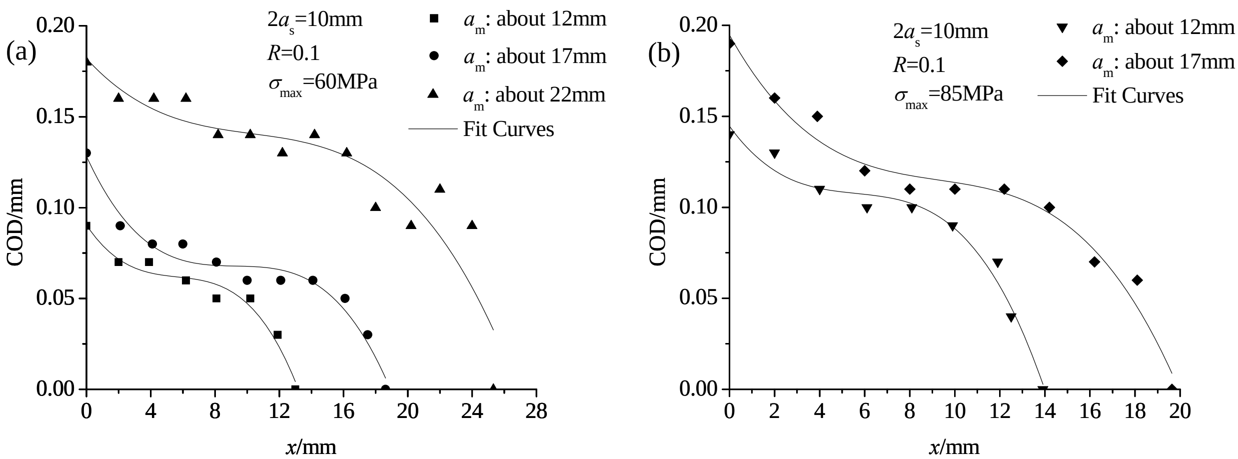


Figure 4. Image analysis measurement method for delamination shape and size after etching

2. Results and Analysis

2.1. Crack opening contour

Experimental data and fit curves are shown in Fig. 5. The direction of axis x represents the direction of crack propagation and the zero point in axis x is the location of the saw-cut tip.



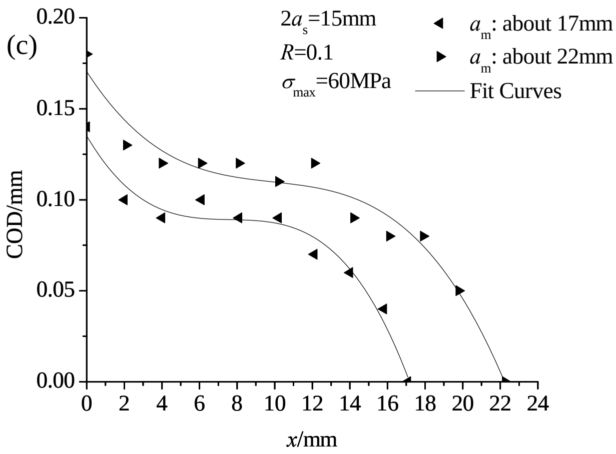


Figure 5. Variation of crack opening contour

As shown in Fig. 5, the crack opening contour can be described as: be maximum value near the tip of saw-cut, decline rapidly along the crack propagation direction, remain almost a constant value in the middle, and decrease to zero at the tip of the crack. Based on the distribution of data, it can be fitted to time by cubic polynomial equation perfectly.

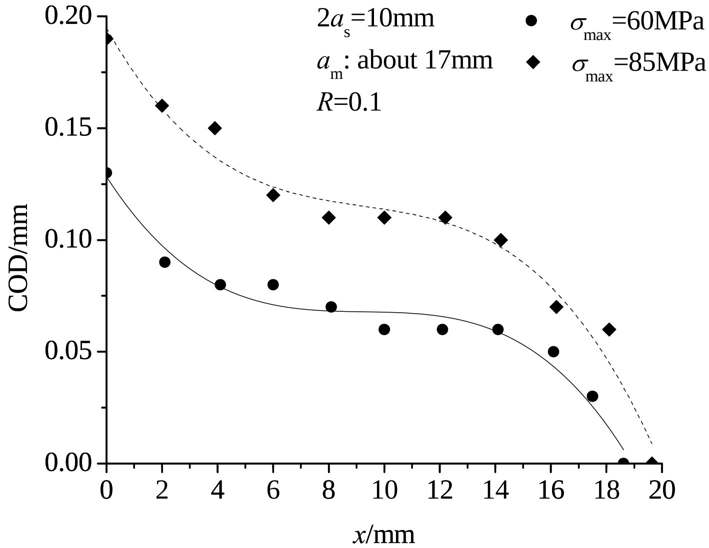


Figure 6. Influence of stress level on crack opening contour

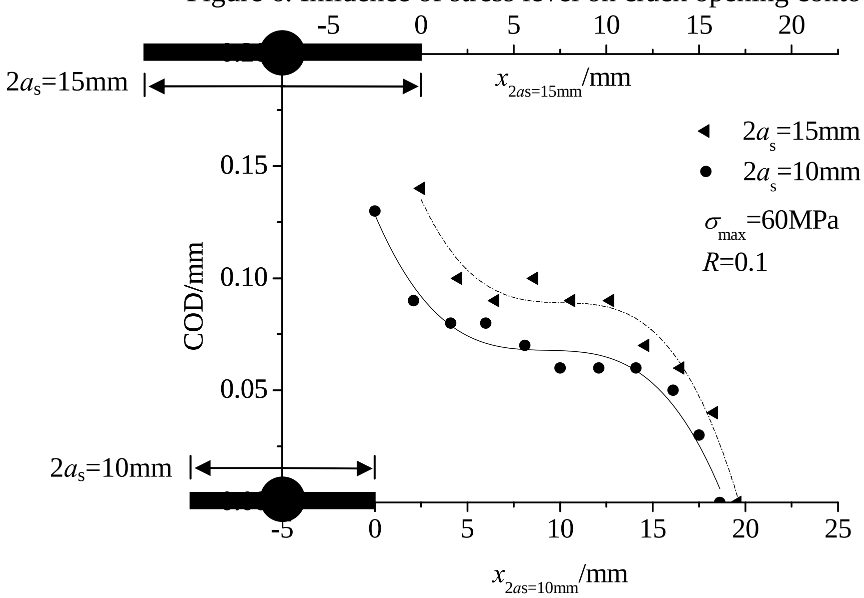


Figure 7. Influence of saw-cut length on crack opening contour

The crack opening contour for a nearly 17mm average crack length under two different stress level is shown in Fig. 6. It can be seen that crack opening contour increase significantly with a higher stress level.

On the other hand, Fig. 7 display the relationship between saw-cut length and crack opening contour. The crack opening contour in a larger 15mm saw-cut length is slightly larger.

2.2. Delamination shape and size

Past studies[2, 16] have described the crack length and delamination in each layer for AHL in detail, as shown in Fig. 8. The outer aluminium alloy sheet, adhesive film and inner aluminium alloy sheet own the same longer length crack without delamination inside. There is a large delamination size between inner aluminium alloy sheet and prepreg, and the sharp point of the delamination locate in the same place with the crack tip of inner aluminium alloy sheet. Crack in central aluminium alloy sheet is obviously shorter than other layers, meanwhile there is a smaller size delamination between prepreg and central aluminium alloy sheet.

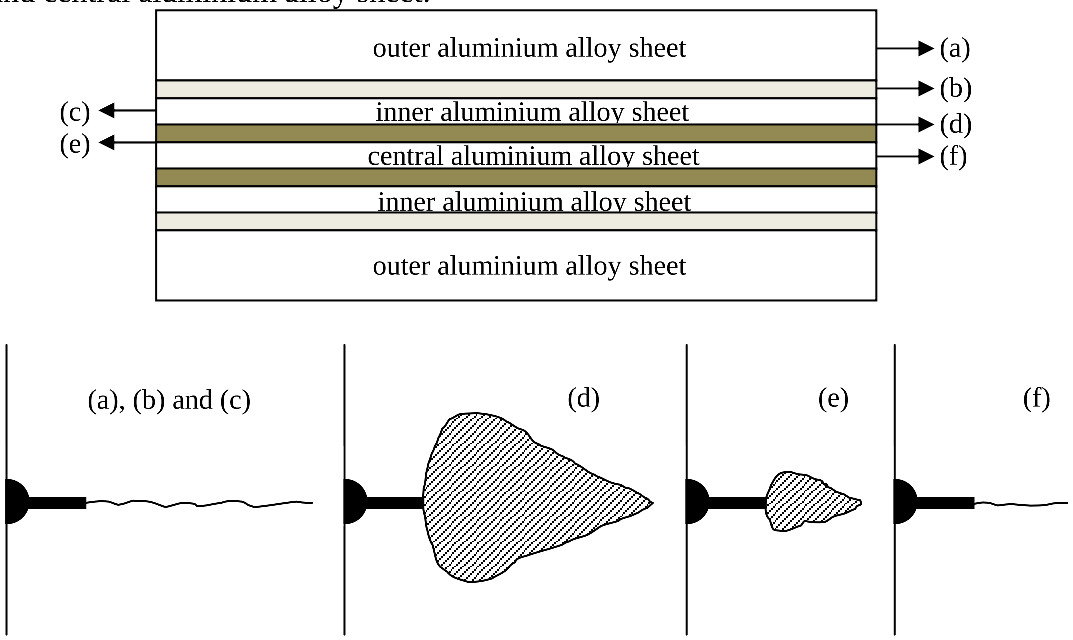


Figure 8. Crack and delamination in each layers

The delamination between inner aluminium alloy sheet and prepreg affect the fiber bridging effect markedly for its large scale, determine the fatigue crack propagation property of AHL, and thus is selected as the study object for delamination behavior.

The results are shown in Fig. 9(a-c). Similar with above, the direction of axis x represents the direction of crack propagation and the point in axis x=0 and axis y=0 is the location of the saw-cut tip.

Fig. 9(a-c) indicates the variation of delamination between inner aluminium alloy sheet and prepreg. With the increase of crack length, delamination grows larger while remaining a similar shape: the size close to zero in the crack tip, increase from crack tip to saw-cut tip, and decrease slightly near the saw-cut tip. Considering the symmetry of the delamination shape, delamination data were grouped and compared after adding together the data from two sides of crack. As shown in Fig. 10, data in axis d represent the width of the delamination shape in Fig. 9, that is $d=|y_1-y_2|$, in which y_1 and y_2 separately indicate the data of upper and lower delamination boundary.

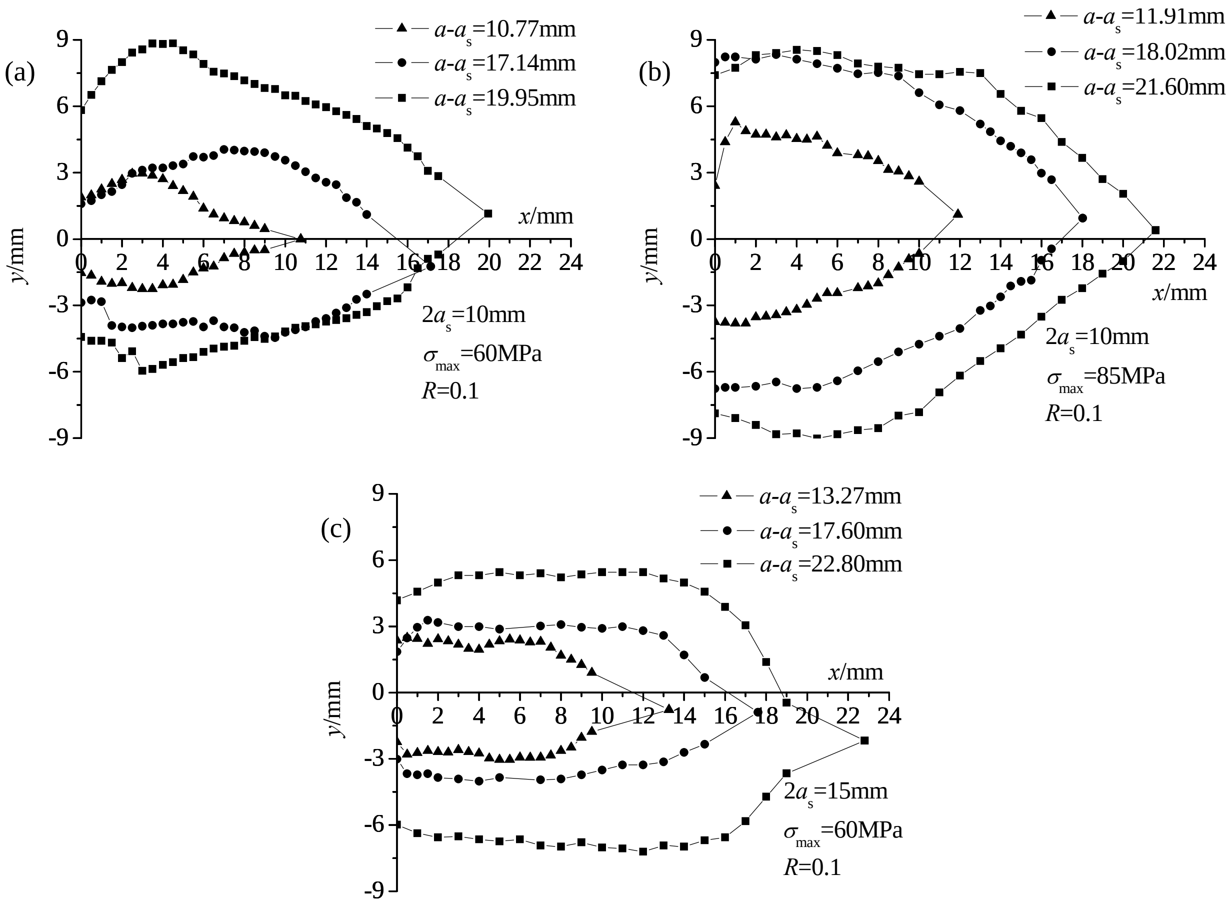


Figure 9. Variation of delamination between inner aluminium alloy sheet and prepreg

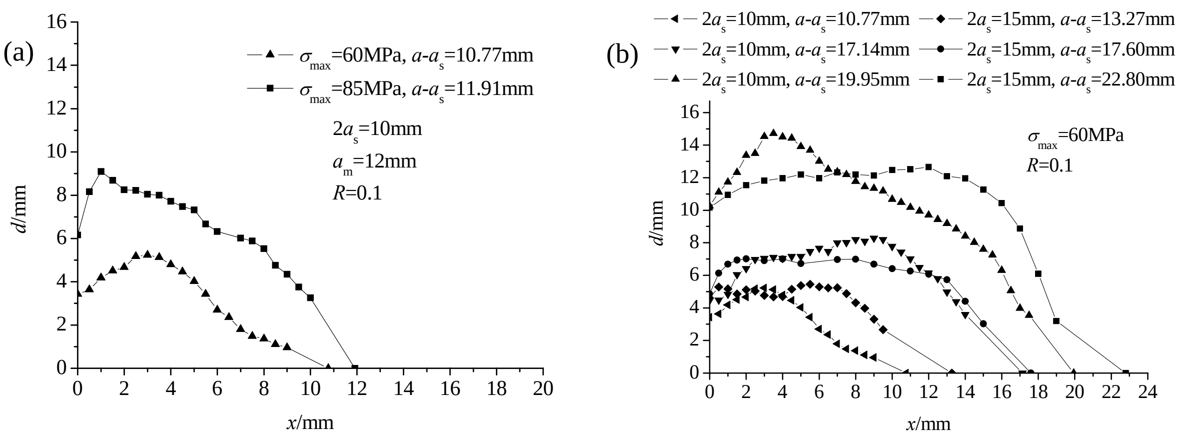


Figure 10. Influence of saw-cut length and stress level on delamination size

Delamination size in the higher stress level is clearly larger than it in lower stress level, as shown in Fig. 10(a). Stress level has a significant impact on delamination behavior. Previous work had shown that the bridging stress becomes too low in case the delamination growth is high, resulting in inefficient fiber bridging[15]. As a result, for AHL, in the condition of high stress level, the bridging effect drops so that the fatigue crack propagation property reduces.

However delamination size seems to be same with different saw-cut length, as shown in Fig. 10(b). Thus it can be seen that the influence of saw-cut length on delamination behavior for AHL is not distinct.

3. Conclusions and prospect

Based on the test data and analysis, it can be concluded as follows:
(1) The crack opening contour of AHL is typically regular, that is be the maximum value at the saw-cut tip, be zero at the crack tip, nearly remaining a constant value in the middle. And the data of crack opening contour is suitable for cubic polynomial fitting.
(2) The crack opening contour becomes larger as the stress level or saw-cut length rises when the other condition is the same.
(3) Delamination shape between inner aluminium alloy sheet and prepreg stays the same basically, that is be nearly zero at the crack tip, increase from crack tip to saw-cut tip, and decrease slightly near the saw-cut tip.
(4) The delamination size increases as the stress level rises when the other condition is the same. The influence of saw-cut length on delamination behavior is not distinct.
Because of the balance of bridging stress, crack opening contour and delamination, there is significance for the data of crack opening contour, delamination shape and size displayed in this research, which can support the creation and verification of fatigue crack propagation predict model for AHL.

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