Fatigue Behavior of Friction Stir Welded Lap Joints for Dissimilar AA7150-AA2524 Aluminum Alloy

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Abstract. The detail fatigue rating (DFR) value of friction stir welded (FSW) lap joints for dissimilar AA7150-AA2524 aluminum alloy was experimentally investigated. The metallographic analysis was carried out on by optical microscope (OM). Fatigue fractography was observed under scanning electron microscope (SEM). The results indicate that DFR value of AA7150-AA2524 FSW lap joints is 191.54MPa. There is no distinct different boundary between HAZ and BM of the upper AA7150 sheet. The grains in the upper NZ of AA7150 are coarser than those in the bottom NZ of AA2524. Fracture morphologies shows that lots of hook defects in the FSW lap joint. Fractography indicates that fatigue crack is initiated from the AA2524 bottom surface around the weld center, where weak-bonding defects can be seen. The hook defects and weak-bonding defects have obvious influence on the fatigue property of friction stir welding lap joints, which seriously reduce the fatigue strength.

1. Introduction

As a typical solid-state joining technology, friction stir welding (FSW) is very suitable for joining aluminum alloys. FSW allows the materials to be welded well below the melting temperature of the materials. Many metallurgical reactions between the dissimilar materials at the elevated temperature can be avoided. Thus FSW is a prospective welding process which can also join the dissimilar materials having incompatibilities [1]. Lots of investigations have been studied the defects, microstructure, lap shear failure loads and fracture modes of the FSW for dissimilar materials joints [2,3].

In aerospace industry, 2xxx and 7xxx series aluminum alloys are two outstanding high-strength aluminum alloys which are usually used to fabricate structural components. For instance, AA2524 is used to skins of aircraft fuselage panels and airplane wings, and AA7150 is used extensively to stingers of civil airplane fuselage panels. In this case, dissimilar AA2524 and AA7150 lap joints are inevitably involved. Chen studied the fatigue performance of FSW butt joints for 2524-T3 aluminum alloys based on detail fatigue rating (DFR) [4]. Dubourg carried out process optimization and mechanical tests of friction stir lap welded of AA7075-T6 stringers on AA2024-T3 skin [5]. However, only a few researches for friction stir lap welded dissimilar joints of AA2524 and AA7150 aluminum alloys can be found.

In this present study, the fatigue property of FSW lap joints for dissimilar AA7150-AA2524 aluminum alloy was investigated. The DFR value of FSW lap joints was calculated based on the fatigue test results. The macro and microstructures of weld structure were examined by optical microscope.
2. Experiment

AA2524-T3 and AA7150-T77511 aluminum alloy were used to perform FSW experiments. The nominal chemical compositions of both alloys are listed in Table 1. Dimension of the AA2524-T3 sheet was 400 mm × 320 mm × 1.8 mm, which was cleaned with emery paper to wipe off the oxidation layer prior to welding. Dimension of the AA7150-T77511 stringer formed into Z-section pultruded geometry was 28 mm × 2 mm × 400 mm. All welds were made in the lap joint configuration with AA7150-T77511 on top and AA2524-T3 on the bottom as shown in Figure 1. The flange and web of stringer were cut in order to convenience of fatigue test. The measured process parameters were a rotational speed of 800 rpm and a travel speed of 200 mm/min. The lap joints were welded by China Friction Stir Welding Center.

| Table 1. Chemical compositions of AA2524 and AA7150 (mass fraction, %). |
|---------------------------------------------------------------|
| Materials | Fe  | Cu  | Mn  | Mg  | Zn  | Si  | Al  |
|------------|-----|-----|-----|-----|-----|-----|-----|
| AA2524     | 0.08| 4.8 | 1.3 | 1.9 | /   | 0.06| other|
| AA7150     | 0.08| 2.11| /   | 2.33| 6.42| 0.05| other|

The cross-section surface of the weld was polished and etched with the Keller etchant (3mL HNO₃, 6mLHCL, 6mLF H, 150mL H₂O). The metallographic analysis was carried out on an optical microscope (OLYMPUS-GX51).

Fatigue tests (Figure 2) were conducted under INSTRON-8801 servo-hydraulic material testing machine with a load cell of 100 kN. The specimens were loaded in uniaxial tension with an R ratio of 0.06. All tests were performed in load control mode at a frequency of 20 Hz. In all performed tests, only the number of cycles until failure is recorded. After the fatigue test, the fracture features of the FSW lap joint specimens were analyzed.
3. Results and Analysis

3.1. Fatigue behavior

The detail fatigue rating (DFR) means the maximum nominal of $10^5$ cycles under constant amplitude loading with stress ratio 0.06, 95% confidence level and 95% confidence. Nowadays, this method is widely used for fatigue life analyses of aircraft structures because of its advantages of simplicity and convenience. The relationship between the DFR and other fatigue parameters is shown as follows [6].

\[
DFR = \frac{(1-R)\sigma_{m0}}{0.94\sigma_{m0}/\sigma_{\text{max}}S^{(5-\lg N)}} - (0.47S^{(5-\lg N)} - 0.53) - R(0.47S^{(5-\lg N)} + 0.53)
\]

(1)

\[
N_{95/95} = \frac{\hat{\beta}}{S_C \cdot S_R \cdot S_T}
\]

(2)

\[
\hat{\beta} = \left(\frac{1}{n} \sum_{i=1}^{n} N_i^\alpha\right)^{\frac{1}{\alpha}}
\]

(3)

Where $\sigma_{m0}$ is material life curve and the $\sigma_m$ axis intersection value, $S$ is a constant $S$-N of the slope of the curve parameter, $\hat{\beta}$ is the point estimation of characteristic fatigue life, $S_C$ is the confidence level factor, $S_R$ is the reliability level factor, $S_T$ is the specimen factor, $n$ is number of valid data, $N_i$ is experiment life, $\alpha$ is the scale parameter, which determines the shape of the distribution density curve of Weibull distribution.

$S_C$ with a 95% confidence level for $n=6$ is 1.15. $S_C$ with a 95% confidence level is calculated as $S_C=2.1$. Specimen factor $S_T$ is determined as 1.3.

For aluminum alloy: $\sigma_{m0}=310$MPa, $S=2$ and $\alpha=4$.

The results of fatigue reliability assessment of AA7150-AA2524 FSW lap joint are shown in table 2. The DFR value of AA7150-AA2524 aluminum alloy with FSW lap joint is 191.54MPa.

| $\sigma_{\text{max}}$(MPa) | Fatigue life (cycle) | $\hat{\beta}$ | $N_{95/95}$ | DFR(MPa) |
|-----------------------------|----------------------|---------------|-------------|----------|
| 192                         | 367113 / 218166 / 368258 / 221223 / 267024 / 310275 | 310218 | 98811 | 191.54 |
3.2. Metallographic analysis

The cross-sections and microstructure of AA2524 and AA7150 aluminum alloy lap joint are shown in figure 3. Three typical regions can be distinguished on the cross-sections, corresponding to the nugget zone (NZ), the thermo-mechanical affected zone (TMAZ), the heat affected zone (HAZ) and base material (BM). There is no distinct different boundary between HAZ and BM of the upper AA7150 sheet. Material in the TMAZ undergoes both the thermal cycle and the mechanical stirring during the welding process. Therefore, the grains in TMAZ of AA7150 are strongly distorted. Microstructure in NZ is characterized by fine and equiaxed grains because of undergone complete dynamic recrystallization. The grains in the upper NZ of AA7150 are coarser than those in the bottom NZ of AA2524. The heat in FSW process mainly originates from the shoulder's friction with the surface of the top sheet. The BM adjacent to this HAZ of the bottom AA2524 sheet mainly consists of grains elongated along the rolling direction.

![Figure 3. Macro and microstructures of AA7150-AA2524 lap joint.](image)

3.3. Fracture morphologies

Figure 4 illustrates the fracture position of the AA7150-AA2524 FSW lap joint after fatigue test. Fatigue fracture morphologies represent that the crack initiates from the tip of the hook defect on advancing side (AS), propagates upwards along the NZ/TMAZ interface and finally fractures in the NZ. As shown in figure 4, a lot of hook defect presented in the FSW lap joint, which seriously reduced the joint properties of fatigue strength. The reason is that the hook defect provides a favorable orientation for crack propagation and causes stress concentration.
3.4. Fatigue fractography

The fatigue morphologies of AA7150-AA2524 FSW lap joint specimens were analyzed by using SEM (Model: Quanta600). The following micromorphologies characteristic were observed on the fatigue fracture surface as shown in figure 5.

As seen in figure 5a, the SEM fractography consist of three parts: fatigue crack initiation area, fatigue crack propagation area and final fracture area. Figure 5a shows that the critical fatigue crack was initiated from the AA2524 surface. The detailed view of the crack initiation site is shown in figure 5b, where weak-bonding defects can be seen at the AA2524 bottom surface around the weld center. It also can be seen some inclusions inside the crack initiation area of specimens. The weak-bonding defects and inclusions have obvious influence on the fatigue property of friction stir welding lap joints, which shorten the fatigue lives. Fatigue striations (figure 5c) can be observed in the crack propagation area, associated with some secondary cracks at an intermediate stage of propagation extensively existed. Final fracture area (figure 5d) presents a ductile dimpled characteristic. There are many dimples and microscopic voids with different size in this area. A large number of primary voids are seen due to the broken constituent particles during FSW.
4. Conclusions
The DFR value of FSW lap joints for dissimilar AA7150-AA2524 aluminum alloy is 191.54MPa. There is no distinct different boundary between HAZ and BM of the upper AA7150 sheet. Material in the TMAZ undergoes both the thermal cycle and the mechanical stirring during the welding process. The grains in the upper NZ of AA7150 are coarser than those in the bottom NZ of AA2524. The BM adjacent to this HAZ of the bottom AA2524 sheet mainly consists of grains elongated along the rolling direction. Fatigue fracture morphologies shows that the crack initiates from the tip of the hook defect on AS, propagates upwards along the NZ / TMAZ interface and finally fractures in the NZ. The hook defect provides a favorable orientation for crack propagation and causes stress concentration, which is the main reason for the FSW lap joints fracture. The critical fatigue crack was initiated from the AA2524 bottom surface around the weld center, where weak-bonding defects and inclusions can be seen. The hook defects and weak-bonding defects have obvious influence on the fatigue property of friction stir welding lap joints, which shorten the fatigue lives.

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