Fatigue Fracture Analysis of Dissimilar Residual Stress in Dissimilar Aluminum Alloy Friction Stir Welded Joints

Xue-feng LI and Guo-qin SUN
School of Mechanical Engineering, Beijing University of Technology, Beijing, China

Keywords: Friction stir welding, Residual stress, Life prediction.

Abstract. 2024 aluminum alloy and 7075 aluminum alloy are often used in daily life with excellent mechanical properties, but they are often welded together to withstand fatigue loads, so it is necessary to stir the friction welded joint of 2024-7075 dissimilar aluminum alloy. A detailed study was conducted at the weak location. In this paper, the weak position of the welded joint is analyzed based on the residual stress, and the relevant theoretical model is established to predict the fatigue life based on the residual stress.

Introduction

With the maturity of friction stir welding technology, this technology is also widely used in aerospace, automotive, marine and other fields, so it is necessary to analyze the fatigue fracture of the friction stir welded joint.

Study on residual stress of friction stir welding. Lin Sen [1] and other researches show that the longitudinal residual stress of 6061 aluminum alloy friction stir welding is numerically significantly larger than the transverse stress, and there is a low stress point in the center of the weld. Guo Zhu [2] and other research on the 7075 aluminum alloy plate found that the residual stress of the joint is mainly longitudinal stress, and has an “M” shape in the vertical welding direction. The forward measurement is higher than the return measurement, and the lateral stress is relatively small. Study on different fatigue life prediction models. Regarding the fatigue life prediction model, the current mainstream in the field of low cycle fatigue life is more commonly calculated using the Morrow modified Manson-Coffin strain life formula. The SWT formula is used in the field of high cycle fatigue life. Wang Wensheng [3] found that the high-cycle fatigue life prediction model established by local stress-strain method based on stress gradient, size, surface processing and other factors to improve strain-life is better in the field of high-cycle fatigue life prediction. Zhang Xinfeng [4] applied a local stress-strain method to consider the microscopic effects of crack formation and the modified Neuber method to establish a relevant fatigue crack life prediction model to predict the fatigue life of the crane. Li Wei [5] and other research found that the fatigue analysis method combined with the main S-N curve method and the LBF method has the advantages of modeling efficiency and calculation accuracy, and can be widely applied to the prediction of fatigue life of spot welding of parts. Guo Qi [6] and others found that both the hot spot stress method and the effective notch stress method can predict the change trend of fatigue life to some extent, and the calculation results are similar.

In this paper, the residual stress distribution of dissimilar aluminum alloy friction stir welding and its influence on the weak position of joints are studied experimentally. At the same time, the fatigue life prediction of joints is carried out by considering the residual stress.

Experiments

DIC Experiment

The experimental materials used herein are a 3 mm thick 7075 aluminum alloy plate and a 3 mm thick 2024 aluminum alloy plate, and the overall size is 300 mm x 150 mm x 3 mm. First, the two plates were welded together on a friction stir welder at a forward speed of 120 mm/min and a rotational speed of 900 rpm. The 2024 side was forwardly tested, and then the standard piece was cut by wire cutting according to the standard tensile test piece. After grinding and polishing, the tensile test was
carried out on the MTS858 fatigue testing machine of the Institute of Mechanical and Electrical Engineering, Beijing University of Technology, and the tensile data was collected in conjunction with the DIC measuring device. The purpose of the experiment was to obtain the elastic modulus of different regions of the joint.

The fatigue testing machine collects the tensile force during the stretching process, and the DIC measuring device collects the real-time strain. The tensile force data is divided by the cross-sectional area of the tensile test piece to obtain the tensile stress, and the elastic modulus of each region is obtained as shown in Table 1.

<table>
<thead>
<tr>
<th>Region</th>
<th>Elastic Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-BM</td>
<td>72</td>
</tr>
<tr>
<td>A-HAZ</td>
<td>71</td>
</tr>
<tr>
<td>A-TMAZ</td>
<td>72</td>
</tr>
<tr>
<td>WNA</td>
<td>75</td>
</tr>
<tr>
<td>R-TMAZ</td>
<td>80</td>
</tr>
<tr>
<td>R-HAZ</td>
<td>70</td>
</tr>
<tr>
<td>R-BM</td>
<td>71</td>
</tr>
</tbody>
</table>

Table 1. Elastic modulus of each region.

Residual Stress Test

The residual stress was tested by X-ray diffraction in order to obtain the residual stress distribution in different areas of the welded joint. The surface detector X-ray diffractometer model used in the test device was D8 DISCOVER With GADDS, which was produced by BRUKER, Germany. The test results are shown in Figure 1.

The residual stress test results show that the longitudinal residual stress of the 2024-7075 dissimilar aluminum alloy friction stir welded joint is greater than the lateral residual stress, and the longitudinal residual stress and the lateral residual stress both exhibit bimodal characteristics, in which the two peaks of longitudinal residual stress appear respectively. The measured and retracted side heat affected zone, in which the maximum longitudinal residual stress of the forward heat affected zone is 86.6 MPa, Xu Guosheng et al [7] found that the weak joint position of the joint is also in the forward heat affected zone. At the same time, the hardness values of the heat affected zone and the heat affected zone on the forward side are all troughs, which is opposite to the residual stress distribution in the heat affected zone and the backward heat affected zone. It is obvious that the distribution of residual stress is closely related to joint hardness and fatigue performance.

Life Prediction

The literature [7] shows that the fatigue crack initiation and small crack stability expansion stages of the 2024 and 7075 aluminum alloy friction stir welded joints account for 55-75% of the total fatigue life, and most of the crack initiation and expansion stages account for 60% of the total life. Therefore, this article is calculated at 60%, namely:

\[ N = 0.6N_f \]  

where

\[ N_f \] — Total fatigue life;  
\[ N \] — Crack initiation life
The key point is to calculate the crack initiation life $N_t$. The most widely used application in the high-cycle fatigue field is the SWT stress-strain life prediction formula considering the influence of average stress on fatigue life [8]. The formula is as follows:

$$\sigma_{n, \text{max}} \varepsilon_1 = \frac{(\sigma_f')^2}{E} (2N)^{2b} + \sigma_f' \varepsilon_f' (2N)^{b+c}$$  \hspace{1cm} (2)

where $\varepsilon_1$—The maximum principal strain amplitude; $\sigma_{n, \text{max}}$—The maximum principal stress on the largest principal strain plane; $\sigma_f'$—Fatigue ductility coefficient; $\varepsilon_f'$—Fatigue strength coefficient; $b$—Fatigue strength coefficient;

The calculation of the relevant material coefficients refers to the general slope method in Zhang Zhen’s [9], and its expression is as follows:

$$\sigma_f' = 1.9018 \sigma_b$$  \hspace{1cm} (3)

$$b = -0.12$$  \hspace{1cm} (4)

$$\varepsilon_f' = 0.7579 \varepsilon_f^{0.6}$$  \hspace{1cm} (5)

$$c = -0.6$$  \hspace{1cm} (6)

where $\sigma_b$—The tensile strength of the material; $\varepsilon_f$—The fracture ductility of the material;

Among them, the tensile strength $\sigma_b$ is indicated in the relevant literature [10] and can be calculated by the following formula:

$$\sigma_b = K \varepsilon^n$$  \hspace{1cm} (7)

where $K$—The material strength coefficient; $n$—The cyclic strain hardening coefficient is $n'$; $\varepsilon$—The true strain at break, taken from the strain data read by the DIC experiment.

The breaking strength is shown in the literature [11] and can be calculated using the following formula:

$$\sigma_f = \sigma_b (1 + \varepsilon_f)$$  \hspace{1cm} (8)

where $\varepsilon_f$—The fracture ductility of the material, that is, the true strain at the time of fracture, where the strain at break is 0.0049;

It is shown in [16] that the cyclic strain hardening coefficient and strength coefficient of a material can be calculated by the following formula:

$$n = \frac{N \sum_{i=1}^{N} x_i y_i - \sum_{i=1}^{N} x_i \sum_{i=1}^{N} y_i}{N \sum_{i=1}^{N} x_i^2 - [\sum_{i=1}^{N} x_i]^2}$$  \hspace{1cm} (9)

$$\ln K = \frac{\sum_{i=1}^{N} y_i - n \sum_{i=1}^{N} x_i}{N}$$  \hspace{1cm} (10)

$$y = \ln \sigma$$  \hspace{1cm} (11)
\[ x = \ln \varepsilon \]  

where

- \( N \) — The number of experimental sampling points;
- \( i \) — The sampling point number;
- \( \sigma \) — Stress;
- \( \varepsilon \) — Strain;

The raw stress data required for the calculation are derived from the tensile test of the laboratory and the strain data of the simultaneous DIC acquisition. The relevant parameters of the materials in each region are calculated by the above calculations as shown in Table 2.

<table>
<thead>
<tr>
<th>Region</th>
<th>n</th>
<th>K</th>
<th>( \varepsilon_f )</th>
<th>( \delta_f )</th>
<th>( \sigma'_f )</th>
<th>( \varepsilon'_f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-BM</td>
<td>0.32</td>
<td>2565</td>
<td>0.0032</td>
<td>408</td>
<td>775</td>
<td>0.024</td>
</tr>
<tr>
<td>A-HAZ</td>
<td>0.37</td>
<td>2705</td>
<td>0.0094</td>
<td>481</td>
<td>915</td>
<td>0.046</td>
</tr>
<tr>
<td>A-TMAZ</td>
<td>0.36</td>
<td>2179</td>
<td>0.0294</td>
<td>615</td>
<td>1205</td>
<td>0.092</td>
</tr>
<tr>
<td>WNZ</td>
<td>0.31</td>
<td>1517</td>
<td>0.0393</td>
<td>556</td>
<td>1056</td>
<td>0.108</td>
</tr>
<tr>
<td>R-TMAZ</td>
<td>0.36</td>
<td>2094</td>
<td>0.0259</td>
<td>561</td>
<td>1093</td>
<td>0.085</td>
</tr>
<tr>
<td>R-HAZ</td>
<td>0.23</td>
<td>1274</td>
<td>0.0049</td>
<td>374</td>
<td>711</td>
<td>0.031</td>
</tr>
<tr>
<td>R-BM</td>
<td>0.31</td>
<td>1495</td>
<td>0.0037</td>
<td>264</td>
<td>504</td>
<td>0.026</td>
</tr>
</tbody>
</table>

The simulation is carried out on the basis of considering the residual stress. The parameters of the simulation are calculated by the above calculation, and the final stress and strain results are substituted into the calculation. Modeling is performed using a two-dimensional variability shell element, the base feature is solid, extrusion is generated, and then the area is selected on the sketch. The elastoplastic properties of the material are imparted, including the elastic modulus, Poisson’s ratio, yield stress and plastic strain of each region. The left end of the test piece is fully constrained, and the residual stress is distributed to the seven partitions in the pre-defined field of the initial step, and then the loading of one cyclic load is completed in the next four steps, namely the average stress, the highest stress, the lowest stress, and the average stress., divide the grid and submit. The stress and strain concentration regions are basically the same under each load stress as shown in Fig. 2.

![Figure 2. Cloud map of strain and stress.](image)

The stress is concentrated in the heat affected zone on the forward side and the heat affected zone on the backward side, but the forward side is more concentrated than the back side, and the strain is concentrated in the heat engine area near the forward side.

Substituting the above calculation results into (1)(2), where the data of the heat affected zone on the forward side is taken into the dichotomy, the calculation results are shown in Figure 3.
Life1—Consider the fatigue life of;
Life2—Failure to consider the fatigue life of

The calculation results show that the life expectancy calculated by considering the residual stress is smaller than the actual life when the stress is 288 MPa. The prediction results under other loading stress amplitudes are larger than the actual life, and the residual stress is not considered. The prediction results are larger, but not much higher under the higher loading stress amplitude, and larger under the low loading stress. In general, the prediction results of the two are similar. Considering the residual stress is relatively more accurate, the residual stress pair can be seen. The weak influence is large and has little effect on fatigue life.

Summary

(1) Residual stress analysis found that the residual stress distribution is closely related to the weak area and hardness of the joint. The maximum longitudinal residual stress is the forward heat affected zone, which is also the weak zone and the smallest hardness value zone.

(2) Using SWT formula to predict the fatigue life prediction results of dissimilar aluminum alloy friction stir welded joints is better, the overall error is within three times, and the prediction of residual stress is relatively more accurate.

References


