Identification of Constitutive Parameters of Laser Welded Aluminum Alloy Using Digital Image Correlation

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Abstract. An inversion identification method of local wise elastic-plastic constitutive parameters for laser welding of aluminum alloys 6061 was proposed based on full-field optical measurement data using digital image correlation (DIC). Three regions, fusion zone, heat affected zone and base zone of the laser welded joint were distinguished by means of microstructure optical observation and micrometer hardness measurement. The stress data was obtained by the laser welded specimen under uniaxial tensile test, meanwhile, the local strain data of the laser welded specimen was measured by the DIC technique, so the stress-strain relationship for different local regions was established. At last, the constitutive parameters of Ramberg-Osgood model were identified by least-square fitting to the experimental stress-strain data. Experimental results reveal that the mechanical properties for the local zones of welded joint are obviously weakened, which are consistent with the hardness measurement.

Introduction

The laser welding technology for the integral panel manufacturing can greatly improve the production efficiency and reduce the component weight [1]. The laser welding process has an important effect on the connection quality of beam and skin. The thermal effect of laser welding degrades the local material properties, resulting in the existence of thermal deformation and thermal residual stress of welded joints [2].

In general, the finite element method is used to analyze the stress distribution and the stress concentration near the weld [3-4], but some boundary assumptions are needed to simplify stress conditions on the welding joint in order to deal with the complex welding situation. In addition, some empirical formulas can be used to analyze the mechanical properties of welded joints, but only for specific welding processes and specific materials [5]. Hardness can be used as an index to characterize the degree of weakening of the mechanical properties in the weld joint region, but it can not accurately establish the elastic-plastic behavior of the weld zone [6].

Therefore, it is necessary to develop appropriate measurement methods to characterize the local mechanical properties of weld joints, which can help optimize the selection of welding parameters and manufacturing processes to reduce the thermal deformation of welding and provide reliable data to simulation of welding mechanical behavior. In this paper, based on metallographic observation and micrometer hardness measurement of laser welded joint of aluminum alloy 6061, the stress data were obtained by uniaxial tension experiment and the local strain of welded joint was measured by the DIC technique. Then the local stress-strain relation of aluminum alloy laser welding was established. The constitutive parameters corresponding Ramberg-Osgood model are identified by a least-square method to summarize the variation of the material parameters in local zones of the welded joint.
Parameter Identification Method

For the typical constitutive models of aluminum alloy, the most widely used Ramberg-Osgood model can be expressed as [7]

\[ \varepsilon = \frac{\sigma}{E} + \frac{\sigma}{E} \alpha \left( \frac{\sigma}{\sigma_0} \right)^{n-1} \]  

where \( \sigma \) and \( \varepsilon \) denote the uniaxial stress and the uniaxial strain respectively, \( \alpha \) and \( n \) denote the hardening coefficient and the hardening index respectively. \( E \) and \( \sigma_0 \) denote the elastic modulus and the yield stress respectively. The first term on the right side of the Ramberg-Osgood model represents a linear elastic behavior, and the second term represents a plastic phase.

In the linear elastic phase of the constitutive model, the stress of the uniaxial tensile specimen is assumed as

\[ \sigma = \frac{F}{A_0} \]  

where \( A_0 \) is the initial cross-sectional area of the specimen, and it can be obtained directly on the original tensile specimen. \( F \) is the real-time load.

After entering the plastic stage, the plastic deformation zone in the welded joint occurs a necking phenomenon and the cross-sectional area changes significantly. It is assumed that the local cross-sectional area \( A_i \) in the necking zone is related to the real-time plastic strain \( \varepsilon_i \) at the moment \( i \), namely [8]

\[ A_i = A_0 \exp(-\varepsilon_i) \]  

And the real-time stress of local plastic deformation is obtained as

\[ \sigma_i = \frac{F}{A_i} \]  

In the experiment, the whole-field strain \( \varepsilon_i \) and time data is obtained by the DIC technique. The load-time data obtained from the testing machine are transformed into real-time stress-time data according to Eqs. (3) and (4). Therefore, the stress-strain curve at any position of the corresponding plastic deformation zone near the local weld can be obtained. The Ramberg-Osgood model was further fitted to determine four elastic-plastic parameters: \( E, \alpha, n \) and \( \sigma_0 \).

Experimental Procedure

Welding Sample Preparation

The experimental material is aluminum alloy 6061 with a thickness of 2 mm. Laser welding work was completed in the State Key Laboratory of Advanced Welding and Joining. The welding parameters were used as the welding speed of 3 m/min and welding power of 1900 W. In the laser welding process, using ER4047 aluminum welding wire as a filler, the aluminum wire has a diameter of 1.2 mm. Fig. 1(a) shows a photo for the butt welding of the aluminum alloy plates.
After the laser welding of the aluminum alloy plate, the dog-bone specimens were prepared by wire-cutting machine, and the welding surplus height needs to be cut off, as shown in Fig. 1 (b). As a comparison, the standard dog-bone specimens of aluminum alloy without the laser weld were prepared by the same wire-cutting. The geometrical dimensions of the specimen are 180 mm (effective length) × 8 mm (width) × 2 mm (thickness). Meanwhile, the small samples with weld were prepared with a size of 20 mm (length) × 10 mm (width) × 2 mm (thickness) for microscopic observation, as shown in Fig. 1 (c).

**Microscopic Observation**

Prior to the microscopic examination, the small samples were processed by cross-section grinding and polishing treatment, the use of hydrofluoric acid for corrosion. The etched samples were observed under a metallographic microscope (Leica, MEF4A), as shown in Fig. 2.

![Figure 2. Microstructure of weld fusion line by metallographic microscope (200×).](image)

It can be seen from the microstructure photo that the welding zone is divided into three regions: Fusion Zone (FZ), Heat Affected Zone (HAZ) and Base Zone (BZ). There are majority of cast structure in the fusion zone.

**Hardness Measurement**

A cross-section hardness measurement was performed on the micro-observed samples using a Vickers micro-hardness meter (MVC-1000B). As shown in Fig. 4, the hardness measurement takes the weld as the center, and starts from the position A to the position B cross three regions. The total length of AB is about 3.5 mm with an interval of 0.1 mm. The indenter force is 0.98 N and the duration time is 15 s.
The hardness measurement results, as shown in Fig. 4, reveal that there is a w-shaped distribution across the welding line. The hardness in the BZ is the largest, and decreased in the HAZ and FZ. The hardness in the HAZ is the lowest. From the three obvious differences in the hardness distribution, the FZ length is about 1.0 mm, and the HAZ range is about 0.75 mm.

**Tensile Testing**

Before the tension experiment, the aluminum alloy specimens were alternately sprayed with white paint and black paint. The size of produced speckle particles is about 5-8 pixels. Then the specimen was mounted on a testing machine (Instron 3345) and illuminated with a cold light source, as shown in Fig. 5(a). A tensile speed of 1 mm/min was performed. Fig. 5 (b) shows the uniaxial tensile load and displacement curves of the aluminum alloy specimens with and without the laser welding, all of which show an obvious elastic-plastic behavior.

During the uniaxial tension experiment, the surface speckle image of the specimen was collected with a camera. The image frame rate was 1 fps and the image size was 1024 × 768 pixels.
Results and Discussion

The speckle image of the aluminum alloy welded specimen in the ROI, as shown in Fig. 6(a), was also analyzed using the DIC method. The full-field strain distributions at different moments are obtained, as shown in Fig. 6(b). It can be seen that the longitudinal strain of welded specimen is not uniform and the strain value of the weld zone is higher than the base metal, indicating that the laser welding will affect the local mechanical properties of aluminum alloy.

The data on the vertical weld line (dotted line in Fig. 6b) is extracted from the longitudinal strain at yield moment, as shown in Fig. 6(c). The HAZ at the interface between the weld and the base metal has the greatest strain, which means that the HAZ firstly reached the yield stage, followed by the FZ.

Total 12 points from P1 to P12 are selected at equal intervals of 0.2 mm in the HAZ of the weld shown in Fig. 6(c). The strain-time curve corresponding to each point can be obtained from the longitudinal strain field at different times. For example, Fig. 7(a) shows the strain-time curve of the P3 and performs a Savitzky-Golay smoothing. The other points are smoothed in the same way.

Similarly, the real-time stress values of the elastic and plastic stages are obtained according to the Eqs. (2) and (4) respectively. The stress-strain curves of these 12 points across the weld line were obtained. Fig. 7(b) is the stress-strain curve of the P3 on the weld, which shows a typical elastic-plastic behavior. Moreover, the Ramberg-Osgood model parameters from the stress-strain
curve of the P3 are also fitted by the least-square method and quasi-Newton method. The other points are fitted in the same way.

Figure 8. Variation of constitutive parameters at different positions from the weld center, (a) elastic modulus and (b) yield stress.

It can be seen from Fig. 8(a) that the elastic modulus of the laser welded specimen has a w-shape distribution, which gradually decreases with the distance to the weld center. The elastic modulus of the FZ and HAZ is obviously lower than that of the BZ, which is 8.32 GPa in the HAZ and much smaller than that of the BZ of 43.42 GPa. Then, the elastic modulus of the FZ is gradually increased to the maximum value of 16.56 GPa at the center of the weld. However, the elastic modulus of the weld center is much smaller than that of the base metal.

It can be seen from Fig. 8(b) that the variation trend of the yield stress in the weld zone is basically the same as that of the elastic modulus. The yield stress also reaches the minimum value of 52.68 MPa in the HAZ, which is less than that of the BZ of 121.52 MPa, and the yield stress of the weld center reaches 82.56 MPa. The variation trend of elastic modulus and yield stress are all similar to that of hardness (Fig. 4), which reflects the rationality of fitted parameters.

Summary
In this paper, the microscopic observation and hardness measurement experiments of the laser welded of aluminum alloy 6061 were used to identify the various zones of welded joint. The uniaxial tensile test of standard specimen and laser welded specimen were carried out and the corresponding stress-strain relations of the specimens were established by the DIC method. The constitutive parameters of the Ramberg-Osgood model were obtained by the least-square method. It was found that there is the casting microstructure in the FZ of the laser welded joint, which is different from the BZ. The hardness in the welded joint has a w-shape distribution, which is the largest in the BZ, followed by the FZ, and the smallest is in the HAZ. Correspondingly, the elastic modulus and the yield stress of the welded joint have a similar w-shape distribution.

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