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Local zone-wise elastic-plastic constitutive parameters of Laser-welded aluminium alloy 6061 using digital image correlation

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ABSTRACT

The mechanical properties of aluminium alloys can be affected by the local high temperature in laser welding. In this paper, an inversion identification method of local zone-wise elastic-plastic constitutive parameters for laser welding of aluminium alloy 6061 was proposed based on full-field optical measurement data using digital image correlation (DIC). Three regions, i.e., the 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 were obtained using a laser-welded specimen via a uniaxial tensile test. Meanwhile, the local strain data of the laser-welded specimen were obtained by the DIC technique. Thus, the stress–strain relationship for different local regions was established. Finally, the constitutive parameters of the Ramberg–Osgood model were identified by least-square fitting to the experimental stress–strain data. Experimental results revealed that the mechanical properties of the local zones of the welded joints clearly weakened, and these results are consistent with the results of the hardness measurement.

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1. Introduction

Using laser-welding technology for 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. Chen et al. [2] investigated welding cracks in micro laser welded dissimilar metals joints, which caused by a large amount of brittle intermetallic compounds and stress concentration. Ma et al. [3] developed a novel dual beam laser welding with filler wire technique and studied the wire melting and transfer behaviours for the first time. Han et al. [4] developed a new technique of skin embedded wire double-sided laser beam welding to fabricate T-joints of aluminium-lithium alloys for achieving crack-free welds. However, the thermal effect of laser welding degrades the local material properties, resulting in thermal deformation and residual stress in welded joints [5–7].

In general, the finite element method is used to analyse the stress distribution and concentration near the weld [8–10]. Yang et al. [11] developed a three-dimensional model to understand the heat transfer and fluid flow. However, some boundary assumptions are required to simplify the stress conditions on the welding joint to deal with the complex welding situation. Furthermore, some empirical formulas can be used to analyse the mechanical properties of welded joints. However, they can be used only for specific welding processes and materials [12,13]. Hardness can be used as an index to characterise the degree of weakening of the mechanical properties in the weld joint region; however, it cannot accurately establish the elastic-plastic behaviour of the weld zone [14].

The traditional optical technologies for stress or strain measurement also have its own limitations. For example, the photoelastic method is suitable for elastic stress field research. The Moiré method requires the application of two-dimensional gratings on the specimen surface. Holography and speckle pattern interferometry are suitable for studying small deformations. In contrast, the digital image correlation method is suitable for studying large deformations in whole field measurements [15–17].

At present, non-contact optical measurements can be used to obtain the strain distribution of the welding joint area. By using full-field deformation data, it is possible to develop a fine characterization of the local material properties of the welded joint area. There are several kinds of inversion identification methods dependent on experimental data such as dimensional analysis modelling method based on statistical classification of experimental data [18], inverse/genetic method based on nu-

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merical simulation and experiment [19], and parameter fitting method of constitutive models [20]. Kang et al. [19] solved an inverse approximation problem by a combination of finite element method and genetic algorithms for identifying the interfacial parameters. Yoneyama et al. [20] measured the full-field deformation of aluminium alloy tensile specimens by using the DIC technique. The stress–strain curves are in accordance with the Ramberg–Osgood model and the J-integral of the exponentially hardening material was calculated from the displacement field by path integration method. Besides, an integrated digital image correlation (I-DIC) is another effective method for welding materials parameters identification and inversion. Liu et al. used it to measure coefficient of thermal expansion [21], multiple thermo-mechanical parameters and residual stress [22].

Sutton et al. [23] used the uniform stress method (USM) and virtual field method (VFM) to evaluate the inhomogeneous properties of the welded areas obtained from the strain data of each region. Moreover, the uniform stress hypothesis can yield more accurate results. Saranath et al. [24] also used USM and VFM to obtain the titanium alloy constitutive parameters of the weld zone. Viscusi et al. [25] used the DIC technique to study the influence of local welding properties on weld strength. Li et al. [26] used the 3D-DIC technique and inverse modelling method to determine the mechanical properties of the weld joint. A power law material constitutive model is adopted in finite element analysis to simulate the elastic-plastic response of welded structures.

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 simulate the welding mechanical behaviour. In this study, based on metallographic observation and micrometer hardness measurement of a laser-welded joint of aluminium alloy 6061, stress data were obtained by a uniaxial tension experiment and the local strain of a welded joint was measured by the DIC technique. Next, the local stress–strain relation of aluminium alloy laser welding was established. The constitutive parameters corresponding to the Ramberg–Osgood model were identified by a least-square method to summarize the variation in the material parameters in local zones of the welded joint.

2. Parameter identification method

2.1. Elastic-plastic constitutive model

Of all the typical constitutive models of aluminium alloys, the most widely used Ramberg–Osgood model can be expressed as [27]

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

where σ and ε denote the uniaxial stress and uniaxial strain, respectively, and α and n denote the hardening coefficient and hardening index, respectively. E and σ_0 denote the elastic modulus and yield stress, respectively. The first term on the right side of the Ramberg–Osgood model represents a linear elastic behaviour, 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

$$\sigma = F/A_0, \tag{2}$$

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

After entering the plastic stage, the plastic deformation zone in the welded joint undergoes a necking phenomenon and, hence, its 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 ε_i at moment i. This is expressed as [28]

$$A_i = A_0 \exp\left(-\varepsilon_i\right). \tag{3}$$

The real-time stress of local plastic deformation is obtained as

$$\sigma_i = F/A_i \tag{4}$$

In the experiment, the whole-field strain ε_i and time data is obtained by the DIC technique. The load-time data obtained from the testing machine is transformed into real-time stress–time data according to Eqs. (3) and (4). Therefore, the stress–strain curve at any position on the corresponding plastic deformation zone near the local weld can be obtained by the identical time lines in the stress-time curve and the strain-time curve. The Ramberg–Osgood model was further fitted to determine four elastic-plastic parameters: E, α, n, and σ_0.

2.2. Least-square method

The above-mentioned elastic-plastic constitutive model has only four unknowns, which can be solved by at last four linearly independent equations theoretically. However, the experimental process is greatly affected by stochastic factors, resulting in unavoidable measurement errors. Therefore, multiple sets of data are needed to establish the over-determined nonlinear equations. In this study, as the number of equations is much larger than the number of unknowns, the over-determined nonlinear equations are solved in combination with the least-square method and Newton method.

A function g is constructed as

$$g = \left\{\frac{\sigma}{E}\left[1 + \alpha\left(\frac{\sigma}{\sigma_0}\right)^{n-1}\right] - \varepsilon\right\}^2. \tag{5}$$

The above function g is written in the matrix form of Taylor series expansion as

$$(g)_{i+1} = (g)_i + \frac{\partial g}{\partial E}(\Delta E)_i + \frac{\partial g}{\partial \alpha}(\Delta \alpha)_i + \frac{\partial g}{\partial n}(\Delta n)_i + \frac{\partial g}{\partial \sigma_0}(\Delta \sigma_0)_i, \tag{6}$$

where i is the ith iterative step in the Newton iterative method and the incremental terms ΔE, $\Delta\alpha$, Δn, and $\Delta\sigma_0$ denote the corrections to the previous parameters E, α, n, and $\sigma_{0,}$ respectively.

The above formula holds good for 1, 2,…, M (M > 4) data points, and is written in the matrix form as

$$\{g\}_i = -[b]_i\{\Delta\}_i. \tag{7}$$

The corresponding least-square form is

$$\left\{\Delta_i\right\} = -[c]_i^{-1}[b]_i^T\{g\}_i \text{ and } [c]_i = [b]_i^T[b]_i, \tag{8}$$

where

$$[b]_i = \begin{bmatrix} \frac{\partial g_1}{\partial E} & \frac{\partial g_1}{\partial \alpha} & \frac{\partial g_1}{\partial n} & \frac{\partial g_1}{\partial \sigma_0} \\ \frac{\partial g_2}{\partial E} & \frac{\partial g_2}{\partial \alpha} & \frac{\partial g_2}{\partial n} & \frac{\partial g_2}{\partial \sigma_0} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial g_M}{\partial E} & \frac{\partial g_M}{\partial \alpha} & \frac{\partial g_M}{\partial n} & \frac{\partial g_M}{\partial \sigma_0} \end{bmatrix}, \ \{g\}_i = \begin{Bmatrix} g_1 \\ g_2 \\ \vdots \\ g_M \end{Bmatrix}, \text{ and } \{\Delta\}_i = \begin{Bmatrix} \Delta E \\ \Delta\alpha \\ \Delta n \\ \Delta\sigma_0 \end{Bmatrix}.$$

The partial derivatives are written as

$$\begin{cases} \frac{\partial g}{\partial E} = -\frac{2h\sigma}{E^2}\left[1 + \alpha\left(\frac{\sigma}{\sigma_0}\right)^{n-1}\right] \\ \frac{\partial g}{\partial \alpha} = \frac{2h\sigma}{E}\left(\frac{\sigma}{\sigma_0}\right)^{n-1} \end{cases} \text{and} \begin{cases} \frac{\partial g}{\partial n} = \frac{2h\alpha\sigma}{E}\left(\frac{\sigma}{\sigma_0}\right)^{n-1}\ln\frac{\sigma}{\sigma_0} \\ \frac{\partial g}{\partial \sigma_0} = -\frac{2h\alpha(n-1)}{E}\left(\frac{\sigma}{\sigma_0}\right)^{n} \end{cases}, \tag{9}$$

where

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

Using the standard Gaussian elimination method to solve the nonlinear equations, the correction term $\{\Delta\}_i$ for the next Newton iteration

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