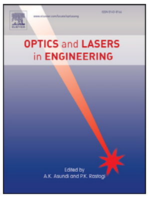
Optics and Lasers in Engineering 110 (2018) 122–131

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng



Virtual field method for identifying elastic-plastic constitutive parameters of aluminum alloy laser welding considering kinematic hardening

Ruixiang Bai[a], Hao Jiang[a], Zhenkun Lei[a,*], Da Liu[a], Yang Chen[a], Cheng Yan[b], Wang Tao[c], Qiaoling Chu[d]

[a] *State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian 116024, China*
[b] *School of Chemistry, Physics and Mechanical Engineering, Queensland University of Technology, Brisbane 4001, Australia*
[c] *State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, China*
[d] *College of Materials Science and Engineering, Xi'an University of Technology, Xi'an 710048, China*

ARTICLE INFO

Keywords:
Elastic-plastic constitutive parameters
Kinematic hardening
Virtual field method
3D-DIC
Laser welding

ABSTRACT

The local high temperature of laser welding affects the mechanical properties of aluminum alloys. In this paper, a three-dimensional digital image correlation system was used to measure the displacement field of the aluminum alloy-laser welding joint under a uniaxial tensile load. By taking into consideration the metal properties of welded joints, an estimation correction scheme for updating stress was designed for anisotropic materials based on the kinematic hardening process, and the proposed method was then applied to the nonlinear virtual field method, the validity of which was verified by a finite element simulation. The elastic-plastic constitutive parameters of various local regions of the welding joint (fusion zone, heat-affected zone, transition base zone, and base zone) were then retrieved from the measured field data, and the stress–strain relationship of each sub-region was established. The results show that the mechanical properties of the laser-welded joint are weakened while the Poisson's ratio decreases with the increase of the weld distance. Furthermore, the elastic modulus of the heat-affected zone is evidently lower than that of the other sub-regions, while it also has the lowest yield strength and the highest plastic strain rate. All these results are consistent with the trend of the hardness measurements.

1. Introduction

Laser welding technology [1], as an important manufacturing process of an integral plate, can greatly reduce the structural weight and production costs, as well as improve welding efficiency, thus leading to the development of integral plate production. An advanced laser welding technology is a good solution to the problem of the excessive-heat-affected area, and it could produce a heat source with a high energy density such that the welding material has a very narrow heat-affected area and thus minimize the deformation and strength loss of the heat-affected zone. However, the laser welding process still has an important effect on the connection quality between the beam and skin, while the thermal effect of the welding degrades the local material properties, resulting in inevitable thermal deformation and residual thermal stress in the welded joint [2–4]. During the welding process, the high-temperature gradient changes the organization of the weld area, which leads to a change in the material properties. At the microscopic level, this change in the properties of the material is caused by the transformation of the microscopic crystal structure of the metal under the action of the laser but the mechanical parameters of the metal from the microscopic crystal structure transform, which is a very difficult and cumbersome process. Therefore, it is necessary to develop an appropriate means of obtaining measurements at the macroscopic level in order to characterize the local mechanical properties of the weld joint. This study aids in finding the fragile areas of the overall panels while providing reliable allowable-load values. Furthermore, it helps to optimize the selection of the welding parameters and manufacturing processes in order to reduce the thermal deformation caused by the welding and provide accurate material parameters for the simulation of the mechanical behavior of the welding parts.

From the microstructure point of view, the welding parts can be divided into three main areas: the fusion zone, heat-affected zone, and parent metal zone. However, the mechanical parameters of the material still have large differences even in the same area. A classic and common method is to use hardness as an indicator for characterizing the degree of weakening of the mechanical properties in various positions of the material. However, this method cannot be used to accurately establish the relationship between the hardness value and Young's modulus or Poisson's ratio [5]. Song et al. [6] used the ultrasonic to estimate the Young's modulus and Poisson's ratio around the welding joint of a titanium-alloy

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[*] Corresponding author.
E-mail address: leizk@dlut.edu.cn (Z. Lei).

https://doi.org/10.1016/j.optlaseng.2018.05.017
Received 20 January 2018; Received in revised form 3 May 2018; Accepted 19 May 2018

test piece and found that as the distance from the fusion line increases, the Young's modulus gradually increases while the Poisson's ratio decreases. Ambriz et al. [7] conducted an indentation experiment at the fusion zone of the aluminum alloy material and found that the Young's modulus in the fusion zone was smaller than that in the basic zone.

In recent years, the methods of obtaining optical measurements, especially the digital image correlation method (DIC), by virtue of its noncontact, low test-environment requirements, strong noise resistance, and other advantages, have become an important means for welding-deformation test measurement. Yoneyama et al. [8] measured the strain field of the tensile aluminum-alloy specimen by using DIC techniques and established stress–strain curves in accordance with the Ramberg–Osgood exponential elasto-plastic constitutive model, and the J-integral of the exponential hardening model was calculated from the displacement field using path integration. Reynolds and Duvall [9] used DIC to obtain the stress–strain curves at various locations of welding parts, and it was found that when the welding nugget undergoes strain hardening, the area away from the welding joint tends to yield slightly while the plastic strain of the base material region remains unchanged. Texier et al. [10] measured the deformation of the welding joint using DIC but did not obtain the constitutive parameters of the weld. In the elastic range, Acar et al. [11] used DIC to study the vertical strain of the welding test piece and found that the larger matching subset of DIC tends to achieve more desirable measurement accuracy for weld-strain measurement. Yan et al. [12] found that the stress at the welding core was higher than that at the base zone. Dong et al. [13] used the integrated DIC method (I-DIC) to determine the thermodynamic properties of the weld. Sutton et al. [14] evaluated the inhomogeneous properties of the welds using the uniform stress method (USM) and the virtual field method (VFM) after obtaining the strain field data of each zone of the weld. Saranath and Ramji [15] used the field data measured using DIC to invert the elasto-plastic mechanics parameters in various zones of the weld and conducted tests using the results of microscopic imaging, followed by the application of the USM to obtain some constitutive parameters and their changing laws in the welding region of a titanium alloy.

The DIC method provides the dense field of displacement and strain data. Owing to the gradient changing material properties of the welds in different regions, this field displacement and strain data are unevenly distributed. Therefore, using this nonuniform field data to accurately mine the mechanical properties of the laser welding zone is a challenging endeavor. Finite element model updating (FEMU) [16,17] involves the establishment of a finite element model with the initial value of the material constitutive parameters in order to calculate the displacement information of each node, then the setting up of an evaluation function of the obtained displacement with the measured field data, and the revision of these constitutive parameters by gradual iteration to minimize the difference. FEMU is widely used and very flexible; however, it has four shortcomings. Firstly, this method relies heavily on the degree of fitness between the numerical model and the actual experiment; however, in the actual experiment, the boundary load distribution is very difficult to determine. Secondly, each iteration of FEMU for updating the model parameters is required to be re-calculated once using the finite element method (FEM), and thus the calculation is very time-consuming. Thirdly, the optimal iteration often cannot converge as it is highly dependent on the initial settings of the deformation parameters. Finally, its data-noise immunity is very poor because of the lack of statistical basis. In recent years, an integrated digital image correlation (I-DIC) has been used to measure coefficient of thermal expansion, multiple thermo-mechanical parameters and residual stress [18,19], and it is an effective inversion method.

Another method based on field data that can be used to solve the mechanical inverse problems is the VFM [20]. Compared with the FEMU, the VFM is usually required to solve a small-scaled linear system without any iterative process. VFM is based on the virtual work equation and the relationship between the material parameters is established by assuming a series of kinematically admissible (KA) virtual displacement fields. Avril et al. [21] proposed a method of setting the KA virtual displacement field such that it is immune to noise effects, while Grédiac summed up the criteria for setting several types of virtual displacement fields [22]. Avril et al. [23] proposed the basic VFM for the inversion of the mechanical parameters of the elasto-plastic materials, and Notta-Cuvier et al. [24] improved his method using coupling identification of the damaged-material parameters. Valeri et al. [25] used the nonlinear VFM to identify the general visco-plastic response of the Johnson-Cook constitutive model. Pierron proposed a VFM scheme for calculating the material parameters of composites [26] and a thick plate [27]. As an interesting application, Cao and Xie [28] determined the principal axis of the fused deposition modeling materials through characterizing an orthotropic constitutive model of behavior by using the elastic VFM. In order to identify the elasto-plastic mechanical parameters of welding materials, Sutton et al. [14] used VFM to obtain the material parameters of the unevenly deformed zone around the weld joint. Louedec et al. [29] studied the elastic-plastic behaviors of friction-stir-welding test pieces at various strain rates. Their results show that the yield stress and hardening modulus of the material at the welding joint are significantly lower than those at the base zone. Saranath and Ramji [30] used the USM and VFM to invert the elasto-plastic constitutive parameters of titanium alloy welds and found that the fusion zone had the highest yield stress and hardening modulus with the lowest Young's modulus of all the zones.

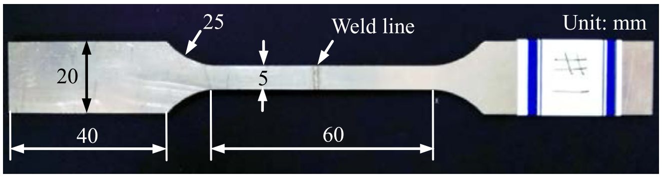

Fig. 1. The tension specimen with a weld in the middle.

This study is divided into three parts. First, uniaxial tensile tests of an aerospace aluminum 6061 standard part and a laser-welded part were conducted to obtain the load–displacement curve. At the same time, the strain field data of the laser-welded specimen was measured using a 3D digital image correlation technique (3D-DIC). Along with the microstructure, the structure around the weld line is partially divided into four sub-zones. Then, based on the kinematic elastic-plastic constitutive model, a nonlinear VFM for the inversion of constitutive parameters is established. The stress-tensor updating estimation correction algorithm based on the constitutive model of kinematic hardening was proposed, which was applied in the nonlinear VFM to identify these elasto-plastic constitutive parameters. After being verified using the FEM, the method proposed in this paper was used to inversely identify the distribution of kinematic elastic-plastic constitutive parameters in each sub-region of the 6061 laser-welded aluminum alloy.

2. Tensile mechanical behavior of laser-welded joints

2.1. Load–displacement curve

Laser-welded samples were fabricated at the State Key Laboratory of Advanced Welding and Joining using an aluminum alloy 6061 plate of a thickness of 2 mm. In the welding process, the welding rate was maintained at 3 m/min with a welding power of 1900 W using ER4047 aluminum wire of a diameter of 1.2 mm as the welding filler. After the welding work was completed, a dog bone tensile test specimen was prepared from the aluminum alloy plate using wire cutting equipment while the residual height was required to be removed. The size of the specimen is shown in Fig. 1.

Before performing the microscopic observation, the cross-section of the specimen was polished, and corrosion was carried out using hy-