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Study on Elastoplastic Crack Propagation Behavior of Laser-welded 6061 Aluminum Alloy Using Digital Image Correlation Method

Y Chen[1], Z K Lei[*1], R X Bai[1], Y P Wei[1] and W Tao[2]

[1] State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian 116024, China
[2] State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, China.

E-mail: leizk@163.com

Abstract. Laser welding is commonly used in the aluminum alloy welding of aerospace field as an efficient and precision welding method. Local high temperature and electrode material change the microstructure of aluminum alloy in the laser welding process. The nonuniform and weakened material properties in the weld zone will result in localized stress concentration, which induced the plastic deformation and the crack initiation of the weld. In this paper, the digital image correlation method was used to study the elastoplastic crack propagation of laser welding 6061 aluminum alloy. According to the method that determines the nominal crack-tip of the weld, we obtained the CTOA and CTOD. The experimental results showed that CTOA, CTOD and J-integral increased nonlinearly with the crack propagation in the heat affected zone.

1. Introduction

Aluminum alloy is widely used in the aerospace field as common component materials. And laser welding is an effective welding method for joining components. The fracture parameters that characterize the crack propagation behavior of crack-tip include crack-tip opening angle (CTOA), crack-tip opening displacement (CTOD), energy release rate and J-integral [1]. CTOA and CTOD can explain the stability of the crack propagation. Laser welding will result in uncoordinated stress, crack tunneling and crack deflection at the crack-tip due to the different strength and strain hardening index between welded metal and base metal [2-3].

Aluminum alloy laser welded joint is nonuniform materials. It is imprecise to analyze the elastoplastic crack propagation behavior by linear elastic damage mechanics and previous measuring method [4-5]. Digital image correlation (DIC) is an optical method for measuring displacement contour, deformation, vibration and strain on the specimen surface. The method can calculate the strain and stress distribution on material surface, observe fluid flow and analyze material’s fracture [6]. Digital image correlation method has the advantages of full-field and non-contact. In this paper, it was applied to measure the elastoplastic deformation of mode-I weld crack in laser welded joint of 6061 aluminum alloy. In the process of crack propagation, we analyzed the strain distribution and plastic zone size of the welded joint, and studied the propagation behavior of the crack in laser seam by changed CTOA, CTOD, J-integral.

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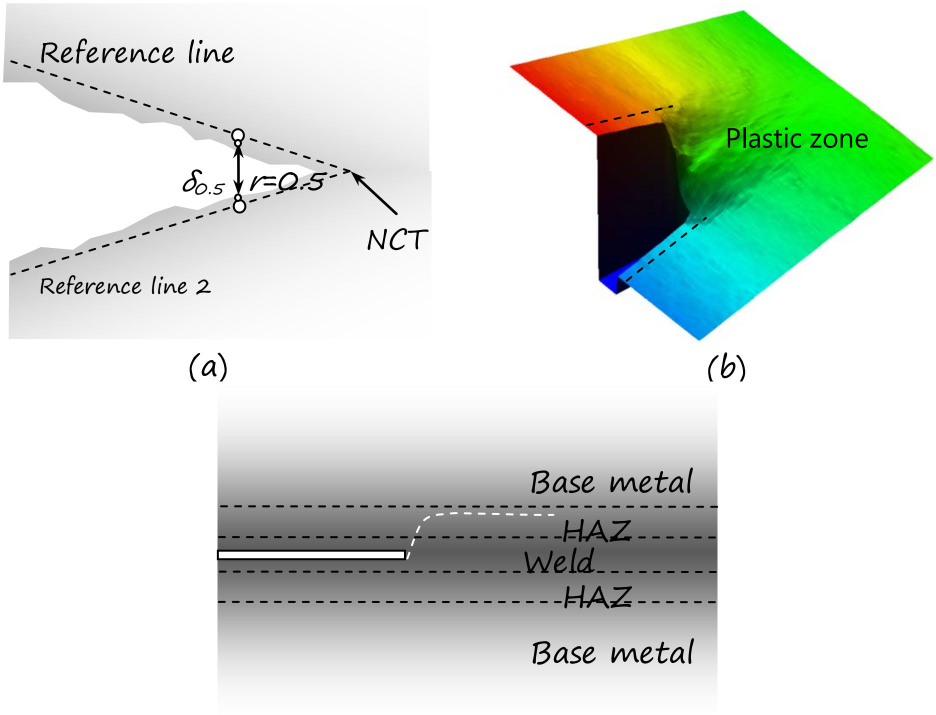
2. Measurement principle of crack parameters

2.1. Elastic crack parameters

For homogeneous brittle materials, the plastic zone at crack-tip can be neglected because of its tiny size, and the mode-I crack normally propagates along the precrack of these materials. A linear fitting method can be used to determine the CTOA at the crack-tip [7]. Two reference lines in elastic zone intersect at a nominal crack-tip (NCT) position and the CTOA is the angle of determined from the angle of the lines, as shown in figure 1(a). The CTOD is the vertical distance at 0.5 mm behind the NCT.



(a) (b)

(c)

Figure 1. (a) NCT determined by the linear fitting method, **(b)** Effect of plastic zone on NCT and **(c)** deflection trajectory of weld crack propagation

2.2. Elastic-plastic crack parameters

For laser welded joint of 6061 aluminum alloy, there is a larger plastic zone near the crack-tip. The linear fitting method can not obtain the fracture parameters for the following reasons.

Firstly, the mode-I crack in laser welded joint was blunted and propagated along the precrack. The nonlinear changed y-displacement in the blunted region is shown in figure 1(b). It is unreasonable to define the NCT by the linear fitting method.

Secondly, the propagation process of mode-I weld crack in 6061 aluminum alloy can be divided into three stages, as shown in figure 1(c). In the first stage, the weld crack was blunted and initially propagated in the fusion zone (FZ) along the precrack. In the second stage, the crack deflected rapidly from the FZ to the heat affected zone (HAZ), as shown in figure 2(a). Finally, the crack propagated along the interface between the HAZ and the base metal (BM) because of the weak material performance in the HAZ. Therefore, a multi-stage linear fitting method is used to determine the NCT by considering the influence of the plastic zone, as shown in figure 2(b).

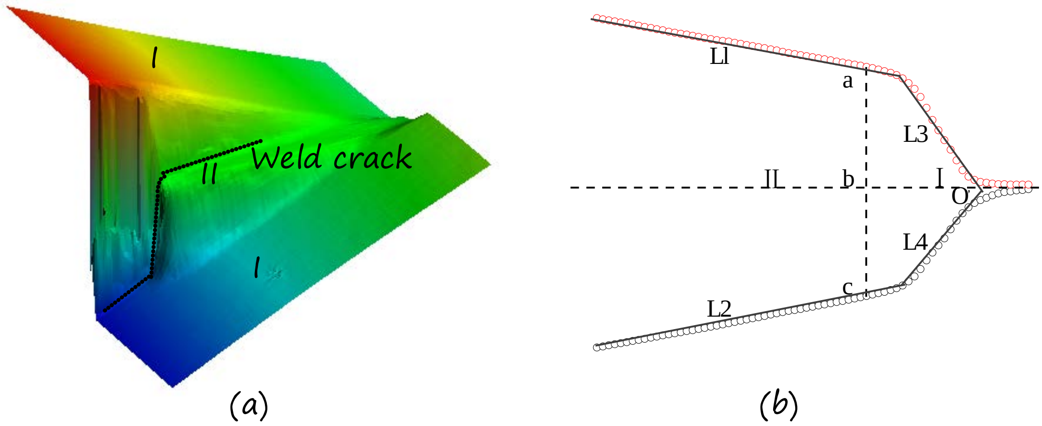


Figure 2. (a) Y-displacement near the weld crack, which deflects to the HAZ and **(b)** a multi-stage linear fitting method

The elastic zone data (I zones in figure 2a) was used to fit the straight line by Lei's method [7]. The CTOA can be obtained from the plastic data of II zone, as shown in figure 2(b). So the area near the crack-tip can be seemed as a combination of elastic zone and plastic zone. L1 and L2 are fitted in the elastic zone. L3 and L4 are fitted in the plastic zone. The NCT is determined by the intersecting fitting lines (L3 and L4). The CTOA is the angle between L3 and L4, as shown in figure 2(b). The CTOD is the vertical distance at 0.5 mm behind the NCT.

2.3. J-integral calculation

J-integral that characterize the fracture properties is expressed by a contour integral,

$$J = \int_{\Gamma} \left(W n_x - T_i \frac{\partial u_i}{\partial x} \right) ds \quad (i = x, y) \tag{1}$$

where Γ is an arbitrary contour around the crack-tip, $T_i=\sigma_{ij}n_j$ is the force acting on the contour unit, σ_{ij} is the stress tensor and n_j is the normal vector of the contour. u_i is the displacement field and $W = \int \sigma_{ij} d\varepsilon_{ij}$ is the strain energy density.

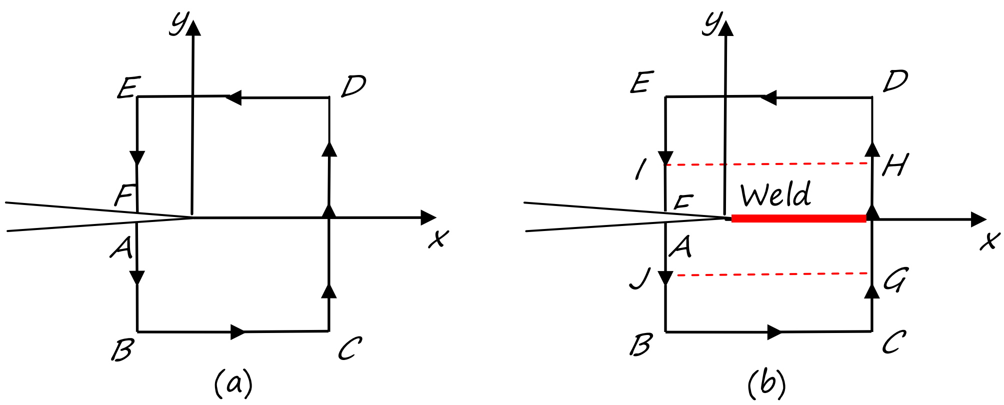


Figure 3. The rectangular integral path of J-Integral

For the mode-I crack in 6061 aluminum alloy, the J-integral can be expressed by a rectangular path (figure 3a) as

$$J = J_{ABCDEF} \tag{2}$$

For the mode-I weld crack in 6061 aluminum alloy, we considered the different properties between weld material and base metal. The J-integral is calculated by three rectangular paths (figure 3b),

$$J = J_{BCGJB} + J_{AJGHIF} + J_{IHDEI} \tag{3}$$

Above J-integral calculations are based on the Ramberg-Osgood constitutive model,

$$\varepsilon = \frac{\sigma}{E} + \frac{\sigma}{E}\alpha\left(\frac{\sigma}{\sigma_0}\right)^{n-1} \tag{4}$$

where σ and ε are the uniaxial stress and strain, respectively. α and n are the hardening coefficient and hardening index, respectively. E and σ_0 are the elastic modulus and yield stress, respectively. The first term of the formula indicates the linear elastic behavior, and the second term indicates the stage of plasticity.

3. Experiments

The experimental material is 2 mm thick 6061 aluminum alloy specimen. ER4047 aluminum wire with 1.2 mm diameter was used as welding filler. The welding system consists of YLS-10000 laser and KR16-2 industrial robots. The welding rate is 3m/min, and the welding power is 1900W. A precrack with 0.17 mm width and 7 mm length was made by wire cutting. The specimen was painted with speckles and fixed in an Instron 3345 tensile tester with a loading rate of 0.5 mm/min. A CCD camera (Guppy F080b) was used to capture the deformed images with a size is 1024×768 pixels, as shown in figure 4. The load increased linearly and then entered the yield stage. The maximum load is 2.0 kN, as shown in figure 5.

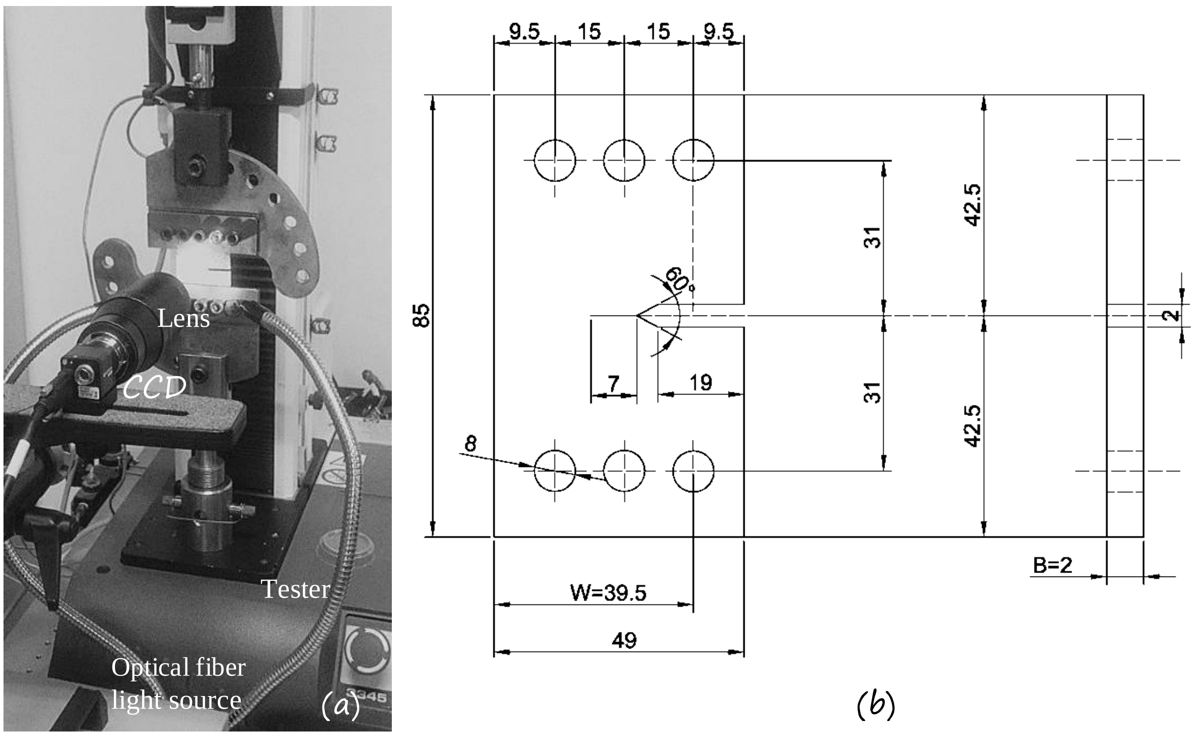
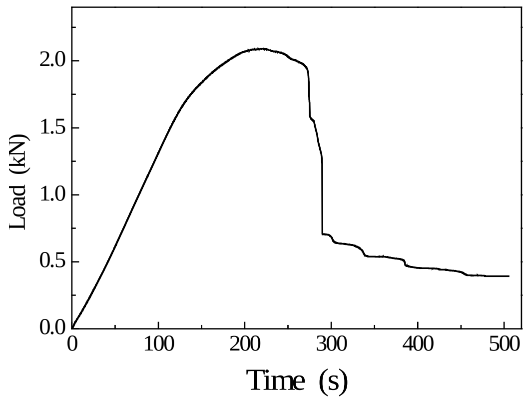


Figure 4. (a) Experimental setup for DIC and (b) specimen with a precrack (in mm)



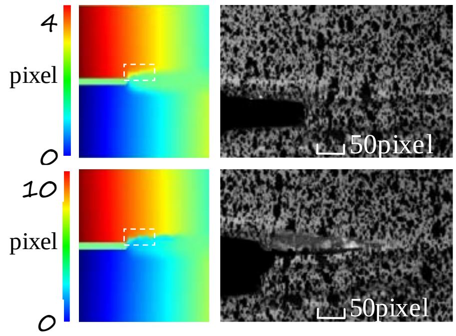


Figure 5. The Loading history **Figure 6.** Y-displacement and crack propagation

4. Results and discussion

4.1. NCT-time curve

The cracked expansion can be seen from the y-displacement obtained by the DIC method. The size of each pixel is 0.0441mm, as shown in figure 6. Four horizontal lines, y coordinates are 86 pixel, 87 pixel, 88 pixel and 89 pixel, were selected near the crack tip. The four y-displacement curves related to four horizontal lines intersect at 104.54 pixel, which is consistent with the NCT determined by the multi-stage linear fitting method, as shown in figure 6(a). Finally, the relationship between NCT position and time was given, as shown in figure 6(b).

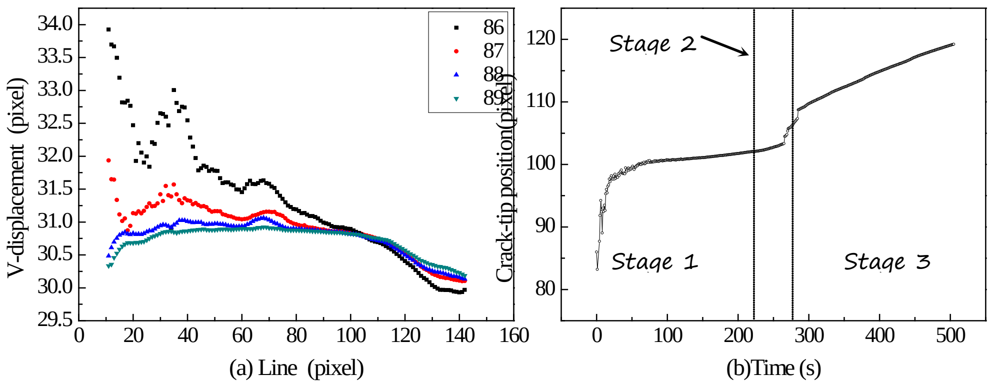


Figure 7. (a) Four y-displacement curves intersected at the crack tip and (b) a NCT-time curve

The NCT position is at 86th pixel before the propagation. The crack propagation process can be divided into three stages, as shown in figure 7(b). In the first stage (<275s), the initial NCT position was in the FZ and fluctuated due to the blunting phenomenon. After the crack trapping initiation, the NCT moved to 102nd pixel. In the second stage (from 275 s to 289 s), the crack expanded from the FZ to the HAZ in a short period. And the crack-tip moved to 106th pixel at the end of this stage. In the third stage, the crack had a stable expansion in the FAZ.

4.2. CTOA and CTOD

The CTOA and CTOD curves can be given by the NCT, as shown in figure 8(a) and figure 8(b). In the first stage, the CTOA had a slow increase, and then grew rapidly to 53.77° at 220 s because of the blunting and trapping effect of crack-tip in the FZ. The second stage, the weld crack propagated from the FZ to the FAZ. The CTOA and CTOD is almost zero. Finally, the crack spreaded at the interface between the HZA and the BM, because the material properties of the HAZ are lower than those of the FZ and BM.

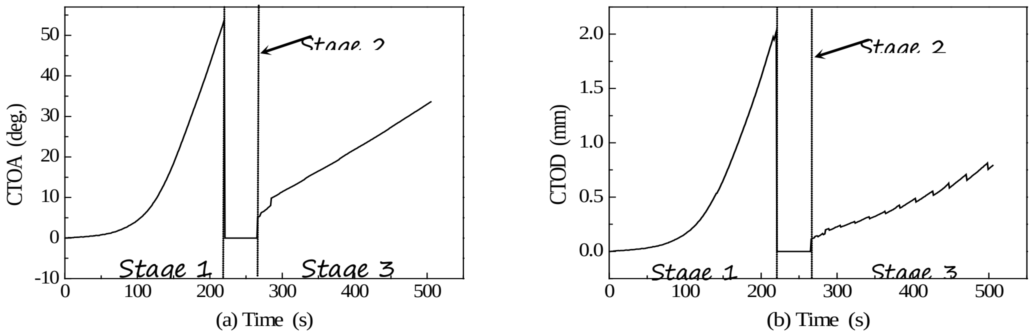


Figure 8. (a) CTOA-time curve and (b) CTOD-time curve

4.3. J-integral and plastic zone

The fracture toughness of weld crack in 6061 aluminum alloy was calculated by equation (3). The constitutive parameters of Ramberg-Osgood model are shown in Table 1.

Table 1. The properties of laser-welded 6061 aluminum alloy

	Elastic Modulus (MPa)	Poisson's ratio	Strain hardening index	Hardening coefficient	Yield stress (MPa)	Scale factor (Pixel/mm)
Base metal	43420	0.33	17.811	0.257	121.5	0.0441
Laser weld	13898	0.38	4.29	4.33	70.80	0.0441

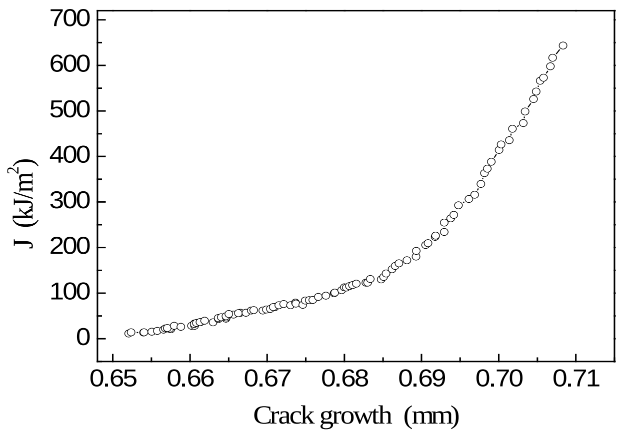


Figure 9. J-integral and time curve in the first stage

In the first stage of weld crack propagation, the J-integral increased slowly, as shown in figure 9. At the crack initiation time, the crack growth determined by the grabbed images is 0.6515mm. The corresponding J-integral value is 7.07 kJ/m^2. It is lower than 23 kJ/m^2, the fracture toughness of 6061 aluminum alloy, due to the lower performance of weld than that of the base material [8].

During the propagation process of weld crack, the strain ε_y distribution is shown in figure 10(a). The high strain shows the lowest performance of the HAZ. So the weld crack propagated to the HAZ. The strain ε_y distribution of 6061 aluminum alloy without laser welding is also given in figure 10(b). The crack propagated in the high strain zone near the crack tip. Comparing the two plastic zone shape shown in figure 10(a) and figure 10(b), we know that the laser weld affected the plastic zone shape.

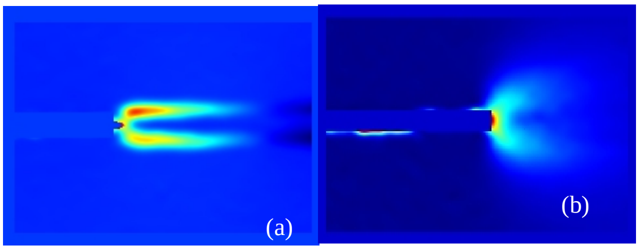


Figure 10. Plastic zone shape of **(a)** weld crack and **(b)** non-weld crack in the aluminum alloy

5. Conclusions

About the full-field displacement measured by the DIC, a new method to determine the NCT and J-integral of the laser weld crack in 6061 aluminum alloy was proposed. And we studied the CTOA, CTOD and J-integral by the method. The experimental results show that the multi-stage linear fitting method is feasible. The crack propagation was divided into three stages: the crack blunting and initiating process, the crack propagation from the HZ to the HAZ and the crack propagation in the HAZ. The conclusions obtained in this study are as follows:

(1) The CTOD and CTOA remained growing during the weld crack blunting and initiating process in the FZ, and then dropped to zero in the stage of the crack propagation from the HZ to the HAZ. Finally, the CTOD and CTOA stably increased in the HAZ.

(2) *The* critical J-integral value is 7.07 kJ/m^2. It is lower than 23 kJ/m^2, the fracture toughness of 6061 aluminum alloy, due to the lower performance of weld than that of the base material.

(3) The weld affected the plastic zone shape near crack tip because of the highest ε_y strain of the HAZ.

Acknowledgments

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