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Effects of keyhole status on melt flow and flow-induced porosity formation during double-sided laser welding of AA6056/AA6156 aluminium alloy T-joint

Zhibin Yang [a,*], Xin Zhao [b], Wang Tao [c], Cheng Jin [a]

[a] School of Materials Science and Engineering, Dalian Jiaotong University, Dalian 116028, China
[b] School of Mechanical Engineering, Dalian Institute of Science and Technology, Dalian 116052, China
[c] State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, China

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ABSTRACT

Effects of the keyhole status on the melt flow during the double-sided laser welding of aluminium alloy T-joint were numerically investigated. And the influencing mechanisms of the flow-induced porosity formation and evolution were also discussed. When the keyhole status changed from complete connection to complete separation, the convection above the keyhole disappeared and vortex flow was formed. Meanwhile, the vortex flow below the keyhole became more complex. As the beam separation distance increased, the vortex flow near the keyhole opening position emerged and became more and more violent, and two vortexes were formed between both sides of the keyhole. The gradually weakened keyhole connectivity and symmetry reduced the pore evolution efficiency dramatically, and subsequently formed porosity defects in the weld seam. The distribution characteristics of the flow-induced porosity defects were found to be in good agreement with the simulation results under the experimental conditions examined.

1. Introduction

In the aircraft manufacturing industry, the riveting is accepted as the dominant technique of joining the fuselage panels. However, riveting increases the fuselage weight and reduces the production efficiency. Therefore, some new trends such as welding including laser beam welding and friction stir welding as well as friction stir spot welding techniques, bonding and extrusion have emerged to replace the use of riveting [1–4]. The current literature indicated that the laser beam welding and friction stir welding offered remarkable advantages over conventional fusion welding process, which had a less detrimental effect on local material properties and a minimum distortion [2]. And, using laser beam welding as a substitute for riveting is also advantageous because of the lower production cost. At present, the double-sided laser welding has recently been identified as a key technique for manufacturing the fuselage panel skin-stringer components and has been first used in series production of the Airbus A318 [5,6].

Porosity formation is a major concern in fusion welding of Al-alloys, particularly in laser beam welding [7–10]. Yu et al. [11] indicated that the unreasonable welding parameters could increase the probability of the large porosity formation because this disturbed the keyhole stability and caused fluctuations in the weld pool. Zhang et al. [12] found that the pool shape characteristics were closely relative to weld porosity, and the porosity could be significantly reduced under optimized welding parameters. Meng et al. [13] described that the shape of the keyhole was changed with the increase of the welding gap, and a large quantity of porosities were formed at the bottom of the keyhole because the bubbles were difficult to escape from there. Lu et al. [14] manifested that the number of pores was mainly determined by the frequency of keyhole collapse, and the number of porosities not only depended on the number of pores, but also relied heavily on the evolution efficiency from pores to porosities. Lin et al. [15] and Panwiswas et al. [16] stated that the violent melt flow around the keyhole was the key cause of flow-induced porosity formation because it resulted in a large fluctuation of keyhole shape and an increasing difficulty of pores escape.

Few studies have been done to investigate the porosity defect in laser welding of aluminium ally T-joint. Ventzke et al. [17] indicated that the incident beam positon and the incident beam angle were the crucial influencing factors of porosity defect formation during one-sided laser welding. And, moderate reduction

* Corresponding author.
E-mail address: yangzhibin@djtu.edu.cn (Z. Yang).

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of the incident beam angle was beneficial to the reduction of the porosity defect due to the opening of the keyhole at the root side of the weld in connection with an equalization of temperature [18]. Compared to one-sided laser welding, Enz et al. [19] and Sun et al. [20] claimed that the double-sided laser welding presented an obvious decrease tendency for porosity defect formation due to a symmetrical temperature distribution and a favourable degassing condition during welding. However, it was impossible to completely eliminate the porosity defect. Dittrich et al. [21] pointed out that the porosity defect in the double-sided laser welded aluminium alloy T-joint had a close relationship with the keyhole characteristics, and the number of porosity defects was the least when the keyholes of the both sides were strictly symmetrical. However, their researches did not explicitly indicate the influence mechanism of the keyhole characteristics on the porosity defects formation. Prisco et al. [22] pointed out that the occurrence of large porosity defects in the weld bead centre due to the keyhole was unstable during the double-sided laser welding. Tao et al. [23,24] found that the melt flow and keyhole stability had a crucial impact on the porosity defect, and stable keyhole behaviour was beneficial to reduce the porosity defect. Meanwhile, they also found that increasing the welding speed was beneficial for pores to escape from molten weld pool and reducing the number of porosity defects due to the variation of fluid flow state. Therefore, summary and review of the above research results show that the keyhole status and its corresponding melt flow have significant influence on the porosity formation. However, there is still lack of the related research works on this topic.

In the present study, we focused on revealing the relationship among the flow-induced porosity defect, the melt flow, and the keyhole status of the double-sided laser welded AA6056-T4/AA6156-T6 aluminium alloy T-joint. Firstly, the different keyhole statuses and their corresponding melt flow were studied by our recently developed 3D mathematical model [25]. Subsequently, the influencing mechanisms on the flow-induced porosity evolution and formation were discussed. Finally, the porosity formation mechanisms were verified by comparing with the corresponding X-ray testing results.

2. Experimental and numerical analyses

2.1. Materials and experimental procedure

The skin-stringer T-joint configuration consists of two dissimilar aluminium alloys, AA6056-T4 and AA6156-T6, both with a thickness of 1.8 mm, used for the stringer and skin components. The Al-Si alloy AA4047 was adopted as filler wire with a diameter of 1.2 mm. The chemical compositions of the aluminium alloys used in this work are given in Table 1. Before welding, the pretreatment of the skin and stringer was conducted by chemical cleaning followed by swashing with fresh running water and finally drying in a drying furnace.

Fig. 1 shows the experimental system for the double-sided laser welding of skin-stringer T-joint. During the double-sided laser welding, the laser beam, filler wire and shielding gas were delivered simultaneously from both sides of the stringer. The welding experiments were carried out by 10 kW fibre laser, 6-axis industrial robot and wire feeder. The fibre lasers with an emission wavelength of 1.06 μm can be delivered in continuous mode. The laser beam passed through a focusing lens with a focal length of 192 mm and was finally focused into a spot with a diameter of 0.26 mm. High-purity argon (99.999%) with a flow rate of 15 L/min was used as shielding gas and was delivered in the trailing direction. The keyhole status was the selection criterion of the welding parameters. The main welding parameters selected in the numerical modelling and experimental verification are shown in Table 2.

The porosity defects in the welded T-joints (100 mm long) were detected using a standard X-ray equipment at an angle of 45° between the X-ray and the skin panel. And then the X-ray films were converted to digital images by photographing. Finally, the porosity defects were extracted by using the MATLAB software.

2.2. Numerical modelling

In this work, our pervious 3D multiphase mathematical model of double-sided laser welding described in [25] was adopted to simulate the keyhole behaviour and melt flow with the selected welding parameters. This model had coupling most of the physical

Table 1
Chemical compositions of the adopted materials in the present work (wt. %).

Materials	Mg	Si	Cu	Mn	Zn	Fe	Al
AA6056-stringer	0.9	1.0	0.8	0.6	0.4	–	Balance
AA6156-skin	0.9	1.0	0.9	0.6	–	–	Balance
AA4047-filler wire	0.01	11.52	<0.01	0.01	0.0001	0.2	Balance

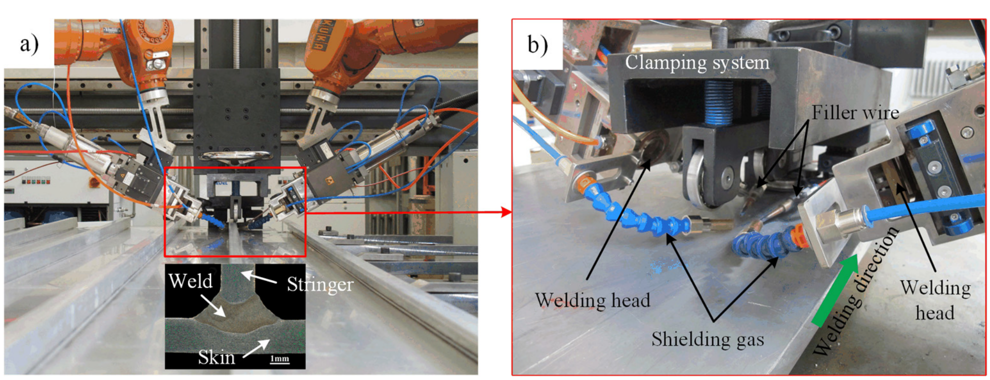

Fig. 1. Experimental system for the double-sided laser welding of skin-stringer T-joint: (a) Experimental equipment, and (b) Partial enlarged detail of (a).