Journal of Materials Science & Technology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Journal of Materials Science & Technology

journal homepage: www.jmst.org

Microstructure and mechanical optimization of probeless friction stir spot welded joint of an Al-Li alloy

Q. Chu[a], W.Y. Li[a,*], X.W. Yang[a], J.J. Shen[b], A. Vairis[a,c], W.Y. Feng[a], W.B. Wang[d]

[a] State Key Laboratory of Solidification Processing, Shaanxi Key Laboratory of Friction Welding Technologies, Northwestern Polytechnical University, Xi'an, 710072, China
[b] Helmholtz-Zentrum Geesthacht, Institute of Materials Research, Materials Mechanics, Geesthacht, 21502, Germany
[c] Mechanical Engineering Department, TEI of Crete, Heraklion, Crete, 71004, Greece
[d] China FSW Center, Beijing, 100024, China

ARTICLE INFO

Article history:
Received 17 July 2017
Received in revised form 12 October 2017
Accepted 18 October 2017
Available online xxx

Keywords:
Probeless friction stir spot welding
Precipitation
Mechanical property
Fracture mechanism

ABSTRACT

In this work, a third generation Al-Li alloy has been successfully spot welded with probeless friction stir spot welding (P-FSSW), which is a variant of conventional friction stir welding. The Box-Behnken experimental design in response surface methodology (RSM) was applied to optimize the P-FSSW parameters to attain maximum tensile/shear strength of the spot joints. Results show that an optimal failure load of 7.83 kN was obtained under a dwell time of 7.2 s, rotation speed of 950 rpm and plunge rate of 30 mm/min. Sufficient dwell time is essential for heat conduction, material flow and expansion of the stir zone to form a sound joint. Two fracture modes were observed, which were significantly affected by hook defect. In addition to mechanical testing, electron backscattering diffraction (EBSD) and differential scanning calorimetry (DSC) were used for microstructure evolution and property analysis. The precipitation of GP zone and Al_3Li as well as the ultrafine grains were responsible for the high microhardness in the stir zone.

1. Introduction

The increasing use of Al-Li alloys offers a potential for substantial weight-saving in structural components to the aerospace industry [1,2]. The new generation Al-Li alloys have outstanding properties compared to conventional Al alloys, such as low density, high specific strength and excellent corrosion resistance [3,4]. Furthermore, Al-Li alloys contain a wide variety of precipitates, depending on the heat treatment conditions selected, which usually include Guinier-Preston (GP) zones, T_1 (Al_2CuLi), θ' (Al_2Cu), β' (Al_3Zr), δ' (Al_3Li), and S' (Al_2CuMg), the reason for excellent mechanical properties [5].

The main problems of traditional fusion welding of Al-Li alloys are porosity, hot cracks and the loss of Li element [6]. Friction stir welding (FSW) is an innovative solid-state joining technology, which is free of defects commonly associated with fusion welding [7]. As a variant of FSW, friction stir spot welding (FSSW) has been applied to the spot joining in light alloys. In order to eliminate the keyhole inherent to FSSWed joints, refill FSSW (RFSSW) and probeless FSSW (P-FSSW) have been proposed. Due to equipment complexity, the application of RFSSW is limited, while P-FSSW is a more simple process, which produces welds of good finish [8].

Although both methods eliminate the keyhole, the hook defect can still be found in the joints, which is formed due to the flow of the heated and softened material [9]. Yin et al. [10] found that the beneficial effect of an increasing bond width on failure load was outweighed by a shape change of the hook defect. Similarly, Rosendo et al. [11] associated hook sharpness with the mode of fracture, which reduced the joint mechanical strength. Cao et al. [12] indicated that the tensile/shear strength decreased monotonically with hook height, which had a positive correlation with welding parameters. Thus, friction stir spot brazing (FSSB) [13] and FSSW-FSW [14] were proposed to eliminate the hook defect. However, the addition of a metal interlayer or modification of the process added to the complexity of the techniques.

This study was aimed to optimize the welding process of P-FSSW and investigate the hook defect. To predict the mechanical strength of the joints, the Box-Behnken mathematical model in response surface methodology (RSM) was used. In addition to mechanical testing, differential scanning calorimetry (DSC) was also used for property and microstructure analysis.

---

* Corresponding author.
E-mail address: liwy@nwpu.edu.cn (W.Y. Li).

https://doi.org/10.1016/j.jmst.2018.03.009

Please cite this article in press as: Q. Chu, et al., J. Mater. Sci. Technol. (2018), https://doi.org/10.1016/j.jmst.2018.03.009

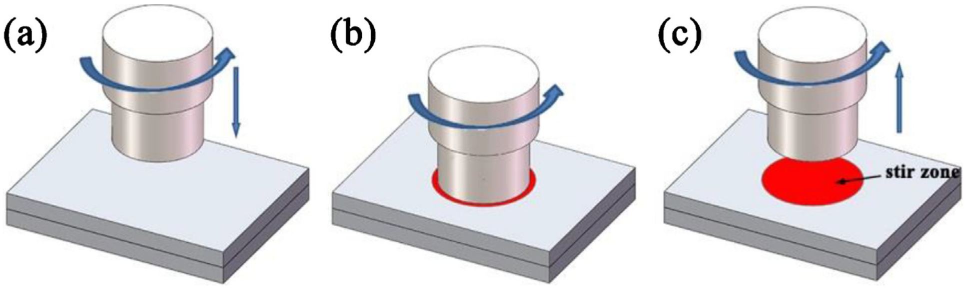

Fig 1. Schematic illustration of the P-FSSW process: (a) plunge stage, (b) dwell stage and (c) retract stage.

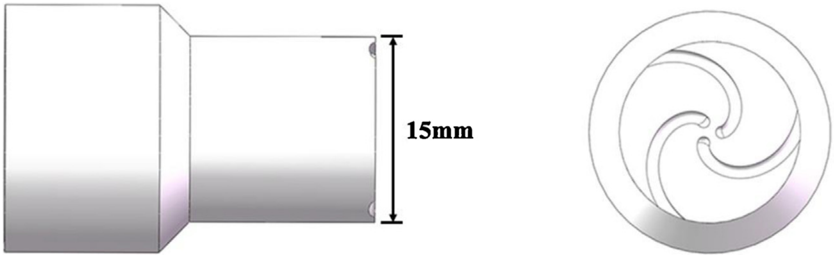

Fig. 2. Schematic illustration of rotation tool.

Table 1
Welding parameters and their levels.

Parameter	Notation	Level		
		Low (−1)	Middle (0)	High (1)
Dwell time (s)	DT	3	6	9
Plunge rate (mm/min)	PR	10	30	50
Rotation speed (rpm)	RS	750	965 (950)	1180

Table 2
Box-Behnken design matrix.

No.	RS (rpm)	DT (s)	PR (mm/min)
1	1180	9	30
2	1180	3	30
3	750	9	30
4	750	3	30
5	1180	6	50
6	1180	6	10
7	750	6	50
8	750	6	10
9	965	9	50
10	965	9	10
11	965	3	50
12	965	3	10
13	965	6	30
14	965	6	30
15	965	6	30
16	965	6	30
17	965	6	30

2. Experimental

The material used in this study was AA 2198-T8 Al-Li alloy with a thickness of 1.8 mm, which was degreased prior to welding. The schematic illustration of P-FSSW is shown in Fig. 1. A probeless cylindrical tool with the shoulder diameter (D) of 15 mm was used which was made of H13, with three involute grooves machined on the shoulder surface, as shown in Fig. 2. The purpose of the grooves feature was to improve the material flow, supported by the Bakavos et a. [15] and Ji et al. [16].

A three-level and three-factorial Box-Behnken experimental design was used to study the dependence of failure load on parameters and optimize the weld process. The selected welding parameters and their levels are shown in Table 1. The P-FSSW experiments were designed according to Table 2. Note that the middle level value of rotation speed was set to 950 rpm instead of 965 rpm due to machine capability.

Samples for morphology analysis were etched using Keller's Reagent (2 ml HF, 3 ml HCl, 5 ml HNO_3, and 190 ml H_2O), and examined by optical microscopy (OM). For the tensile/shear tests, specimens were produced using two 65 mm × 30 mm coupons with an overlap length of 30 mm and the tests were carried out in triplicate for each welding parameter at a head cross speed of 1 mm/min at room temperature. Then the fracture features of the samples were analyzed by a three-dimensional optical microscopy (VHX-5000) and scanning electron microscopy (SEM).

Microhardness was measured across the cross section of the weld zone under a load of 0.2 kg. In addition to mechanical testing, the dissolution and precipitation behaviors of different regions of the weld were investigated with differential scanning calorimetry (DSC). The sample for DSC analyses was 3 mm in diameter with an average weight of 15 mg. The heating rate was 10 K/min and the heating temperature ranged from 293 K to 820 K. Results were corrected for baseline and normalized for the sample weight.

3. Results and discussion

3.1. Microstructure

Fig. 3(a) shows the macrograph of the cross-section of a typical P-FSSWed joint made at the rotation speed of 950 rpm and dwell time of 6 s. The cross-section showed a typical symmetrical 'basin' shape, which was divided into three regions: the stir zone (SZ), the thermo-mechanically affected zone (TMAZ) and the heat affected zone (HAZ) due to the difference in the plastic deformation and temperature during the P-FSSW process. The HAZ showed similar grain morphology to the base material, which appeared to be flattened and elongated due to thermal diffusion during welding process (Fig. 3(b)). During the P-FSSW process, a softened layer was formed in the SZ due to friction heat with the contact and penetration of shoulder. Subsequently, intense deformation and plastic flow occurred in the softened layer, resulting in the break-up of

Please cite this article in press as: Q. Chu, et al., J. Mater. Sci. Technol. (2018), https://doi.org/10.1016/j.jmst.2018.03.009