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On visualizing material flow and precipitate evolution during probeless friction stir spot welding of an Al-Li alloy

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ABSTRACT

The precipitate evolution and material flow visualization during probeless friction stir spot welding (P-FSSW) of an Al-Li alloy has been investigated experimentally and numerically in this work. Due to severe heat input during welding, the main strengthening phases of T_1 fully dissolved in the stir zone followed by the re-precipitation of GP zone and δ′ phases, assisted with the refinement of the intermetallic particles and grains. The history of material flow was three-dimensionally visualized with a tracer, studied with X-ray tomography. The experiments and the simulation results provided a consistent interpretation of a circumferential material flow which moved inwards radially near the top surface. Upward flow in the bottom sheet improved with dwell time, causing the interface to bend. Local abrasion between the two sheets due to flow difference led to the disruption of oxide layer, and formed a connection at the interface.

1. Introduction

With the rapid development of the aerospace industry, the use of Al-Li alloys offers a potential for substantial weight-saving in structural components [1]. These alloys have attractive properties, such as low density and high specific strength, due to the complex precipitate components [2,3]. However, it is hard to be fusion welded due to the defects of porosity and hot cracks following welding [4].

Friction stir welding (FSW), as a solid state joining method, produces joints with sound microstructure and properties, which are free of defects commonly associated with fusion welding [5–9]. Friction stir spot welding (FSSW) is derived from FSW, which shows potential to replace traditional single-point joining processes [10]. Tozaki et al. [11] found that the tensile/shear strength of FSSWed joint increased with probe length, but left a keyhole defect. In order to eliminate the keyhole defect, probeless friction stir spot welding (P-FSSW) was proposed.

More recently, the microstructure evolution of Al-Li alloys during friction stir welding has been studied [12–15]. Tao et al. [14] found that a large number of fine δ′ (Al_3Li) phases and a high density of dislocations were fairly homogeneously distributed in the stir zone. Sidhar et al. [15] indicated that the homogenization of δ′ (Al_3Li) precipitation was responsible for the high strength of FSWed joints. As mentioned in the relevant Refs above, a wide variety of precipitates are present in Al-Li alloys, and they play a remarkable role in impacting mechanical properties of the joint. However, limited research has been performed so far related to the precipitates evolution of Al-Li alloys during P-FSSW, which is severely affected by the thermal cycle.

In addition, the hook defect, as a significant feature in FSSWed joints, is considered to be detrimental to joint performance [16–20]. Many researchers identified that the formation of hook defect was due to material flow, which was mainly investigated by welding dissimilar materials [21], or a tracer [22,23]. Leon et al. [22] clarified the material flow by observing the Ag distribution on the cross-section of FSSWed joint, which was originally applied in the lap-weld interface. Similarly, Sarkar et al. [23] filled the holes with steel wires in different positions in the stir zone to explain the complex material flow along the thickness direction. In addition, numerical simulation was also used to reveal the material flow during FSSW [24]. However, most of these methods cannot visually identify the tridimensional flow behavior.

In this work, an Al-Li alloy has been P-FSSWed with optimized welding parameters. Precipitates evolution assisted with thermal cycle during the P-FSSW was investigated in detail. The material flow was three-dimensionally visualized using a tracer with X-ray tomography.

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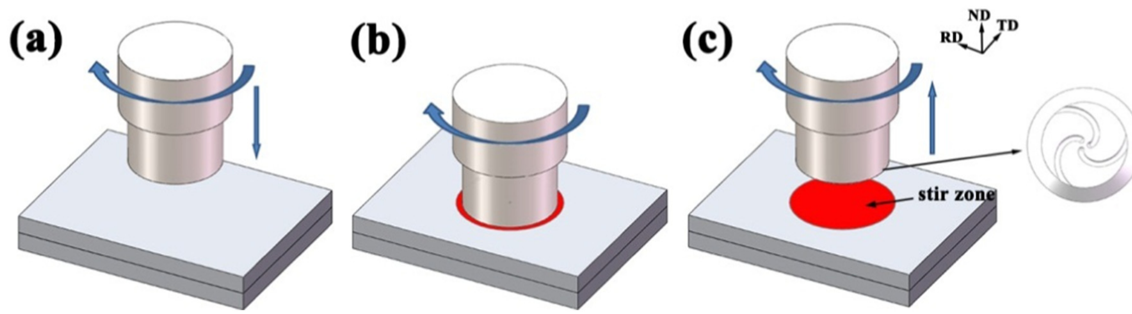

Fig. 1. The welding process of P-FSSW: (a) plunge, (b) dwell and (c) retract.

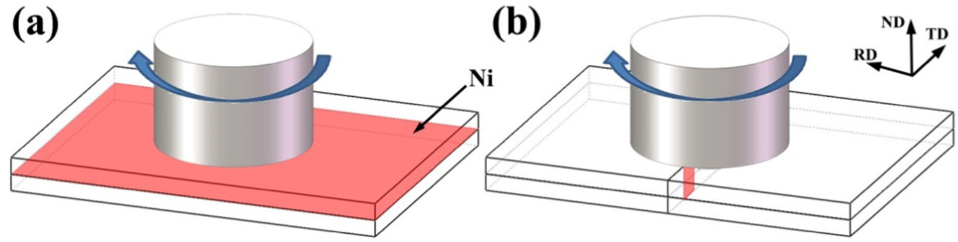

Fig. 2. The positioning of the nickel foils: (a) horizontal section and (b) cross section.

Table 1
Constants for Johnson-Cook material model.

Material	A	B	C	m	n
2198	510	200	0.02	1.61	0.45

2. Experimental Procedure and Numerical Modeling

2.1. Experimental Procedure

1.8 mm thick sheets of AA2198-T8 Al-Li alloy were lap-welded with probeless friction stir spot welding. The tool used in this work had a shoulder diameter of 15 mm with three involute grooves machined on the shoulder surface. Fig. 1 shows the welding process.

The macrostructure was examined using optical microscopy (OM) on the cross section perpendicular to the rolling direction (RD). Electron backscattering diffraction (EBSD) was used to examine microstructure in the stir zone (SZ). Specimens for EBSD were electrolytically etched with a reagent consisting of 5 ml $HClO_4$ and 95 ml C_2H_5OH. A lower limit boundary misorientation of 2° was used to eliminate spurious boundaries caused by orientation noise. The precipitate behavior was investigated with transmission electron microscopy (TEM) and differential scanning calorimetry (DSC). TEM samples were prepared by grinding followed by twin-jet electropolishing in a nitric acid-methanol solution. The sample for DSC analysis was 3 mm in diameter with weight of 15 mg each. The heating rate was set to 10 K/min with the heating temperature ranging from 20 °C to 550 °C. Results were corrected for baseline and normalized for sample weight.

The material flow during welding was studied with X-ray tomography. In order to map the material flow, 0.02 mm thick nickel foils were placed in positions shown in Fig. 2. In Fig. 2b, the nickel was placed exactly at the inside edge of the shoulder. It was possible to identify the position of the nickel tracer as the whole volume of the welding area was scanned in one run along the normal direction (ND). And electron microprobe analysis (EMPA) was used to confirm these results on the cross section.

2.2. Numerical Modeling

A three-dimensional (3D) thermodynamic coupled model was developed with the finite element analysis (FEA) software ABAQUS to estimate the temperature and material flow in the P-FSSW.

The elastic-plastic Johnson-Cook equation was used as the material model in the simulations.

$$\sigma = (A + B\varepsilon^n)[1 + C\ln(\dot{\varepsilon}/\dot{\varepsilon}_0)]\{1 - [(T - T_r)/(T_m - T_r)]^m\}$$

where σ is the yield stress, ε is the plastic strain, $\dot{\varepsilon}$ is the plastic strain rate, the transition plastic strain rate is 0.01 s^{-1}. The room temperature is 25 °C, and the solidus temperature for AA2198 is 502 °C. A, B, C, m and n are constants for describing the material plastic behavior, presented in Table 1.

During P-FSSW, the heat convection coefficient was assumed to be 30 W/m^2 °C for the natural convection heat transfer between aluminum

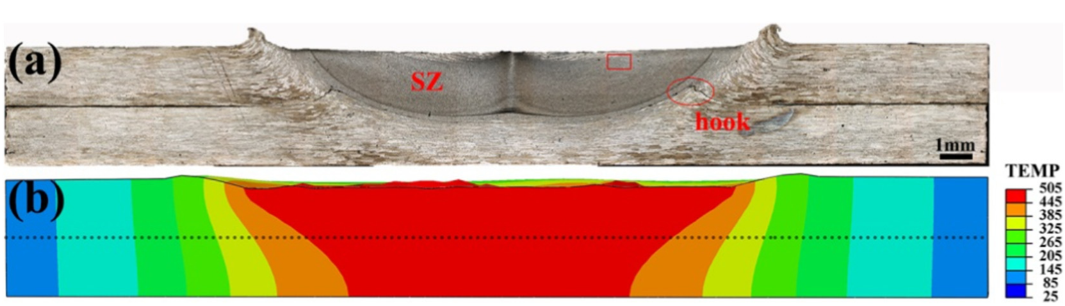

Fig. 3. (a) Macrostructure of a typical P-FSSWed joint under the rotation speed of 950 rpm and dwell time of 6 s, and (b) temperature distribution (TEMP) at one reference moment.