Journal of Materials Processing Tech. 263 (2019) 129–137

Contents lists available at ScienceDirect

Journal of Materials Processing Tech.

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

Material flow and mechanical properties of aluminum-to-steel self-riveting friction stir lap joints

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ARTICLE INFO

Keywords:
Self-riveting friction stir lap welding
Aluminum/steel
Material flow
Microstructure
Mechanical bonding
Metallurgical bonding

ABSTRACT

High-quality aluminum /steel joint was achieved via self-riveting friction stir lap welding (SRFSLW) characterized by the prefabricated holes in steel sheet. According to the origination of filling materials, the prefabricated holes were filled with the plasticized aluminum materials in this order: the deformed aluminum ahead of a pin firstly, the stirred aluminum by the pin body secondly and the driven aluminum by the pin tip finally. The strength of the SRFSLW joint reached maximum value of 317 N/mm at the hole diameter of 3 mm, which was 23% higher than that by conventional friction stir welding (FSW). The optimized joints failed at both the aluminum/steel interface and the formed aluminum rivets. The synergistic effect of mechanical bonding induced by the riveting and metallurgical bonding induced by the Al/Fe IMC layer contributed to high strength of the SRFSLW joint.

1. Introduction

Joining mechanisms in aluminum/steel friction stir welded joint consist of two major behaviors: metallurgical bonding and mechanical bonding (Movahedi et al., 2011). Intermetallic compounds (IMCs) play a significant role on metallurgical bonding. Many researchers investigated the influences of welding parameters such as rotational speed (Derazkola et al., 2015), welding speed (Ramachandran et al., 2015a, 2015b), tool axis offset (Ramachandran et al., 2015a, 2015b) and plunge depth (Shen et al., 2015) on joint strength, and attempted to strengthen metallurgical bonding by adjusting the thickness or type of the IMCs. Kimapong and Watanabe (2005) stated that the increase in rotational speed and the decrease in welding speed resulted in a thick $FeAl_3$ layer, deteriorating the joint quality. The prolongation of the dwell time could also lead to high thickness of the IMC layer (Hsieh et al., 2017). Fereiduni et al. (2015) found that the IMCs layer with a thickness of 2.3 μm was the critical value for friction stir spot welded 5083 aluminum alloy/St-12 steel. Tanaka et al. (2015) obtained high-quality aluminum/steel butt joints with the IMCs layer thinner than 300 nm. Previous studies showed that the formation of the Al-rich IMCs like Fe_2Al_5 and $FeAl_3$ at the interface had more negative effects on the joint strength compared to the Fe-rich IMCs like FeAl and Fe_3Al (Haghshenas et al., 2014). Adding element Zn into the joint by using Zn filler metal (Zheng et al., 2016) or Zn-coated steel (Suhuddin et al., 2017) could promote the formation of Al-Zn eutectic structure rather than Al/Fe IMCs and thus enhance joint strength (Chen et al., 2008). Enlarging the metallurgical bonding area in aluminum/steel joint is another effective approach to increasing the load-bearing capacity of the joint. Abrasion circle friction stir spot welding method (Chen et al., 2012) and keyhole refilled friction stir spot welding (Chen et al., 2016) were developed to increase the bonding area of aluminum/steel spot-welded joints and were both proven to be effective to enhance the joint strength. Leitao et al. (2016) adopted multipass friction stir welding (FSW) to maximize the bonding area and obtained high-quality aluminum/steel lap joints successfully.

Mechanical bonding is another joining mechanism in aluminum/steel joint besides metallurgical bonding (Silva et al., 2010). The mechanical bonding features, including hook (Liu et al., 2015), saw tooth interface (Mahto et al., 2016) and swirl-layered structure (Fereiduni et al., 2016), were beneficial to improve the joint strength. Pourali et al. (2017) pointed out that mechanical mixing was the dominant factor to shear tensile strength of the aluminum/steel friction stir lap welded joint at a low welding speed. Novel mechanical bonding assisted FSW methods were developed to expand mechanical bonding and improve the joint strength. Thomas et al. (2006) employed stir-lock technique, whereby a rivet head was formed into a countersunk hole, to realize the mechanical interlock between aluminum alloy and steel sheets during FSW. Lazarevic et al. (2013) adopted friction stir forming (FSF), a modification of friction stir spot welding, to join aluminum alloy and steel by forming mechanical interlocking features in the steel sheet.

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https://doi.org/10.1016/j.jmatprotec.2018.08.011
Received 23 October 2017; Received in revised form 7 August 2018; Accepted 9 August 2018

Table 1
Chemical compositions of the two base materials (wt.%).

Material	Fe	Al	Si	Mg	C	Mn	Cu	Cr	Ti	P	S
6082-T6	0.5	Bal.	1.0	0.8	–	0.6	0.1	0.25	0.1	–	–
QSTE340TM	Bal.	–	0.35	–	0.12	1.3	–	–	–	0.03	0.025

Evans et al. (2015) developed friction stir extrusion to fabricate aluminum/steel joints. Aluminum alloy was extruded into a pre-fabricated concave groove in the steel sheet and only mechanical bonding existed due to the non-penetrating of the pin into the steel sheet. Huang et al. (2016) proposed self-riveting friction stir lap welding (SRFSLW) and obtained good aluminum/steel joints with metallurgical bonding and mechanical bonding. However, material flow behavior during SRFSLW and the effect of geometric size of the prefabricated holes on the joint strength have not been reported.

In the present study, dissimilar lap joints between 6082-T6 aluminum alloy and QSTE340TM steel were fabricated by SRFSLW at different diameters of the prefabricated holes. Material flow, microstructural features and the effect of geometric size of the prefabricated holes on mechanical properties of the SRFSLW joints were investigated in detail.

2. Experimental procedure

The base materials were 6082-T6 aluminum alloy sheets with dimensions of 3 mm × 330 mm × 90 mm and QSTE340TM steel sheet with dimensions of 2 mm × 330 mm × 90 mm. Chemical compositions of 6082-T6 aluminum alloy and QSTE340TM steel are listed in Table 1. Schematics of the SRFSLW process and the adopted welding tool are shown in Fig. 1a. The welding tool was made of H13 tool steel. The geometry was a concave shoulder with a diameter of 16 mm and a right-threaded conical pin with a length of 3.0 mm. The concave shape of the shoulder with the angle of 10° was employed to prevent the softened aluminum alloys flowing outwards during welding process. The right-threaded feature and the conical shape of the pin are both designed to enhance the downward flow of aluminum alloys into the prefabricated holes. The top and bottom diameters of the pin were 5 mm and 7 mm, respectively. Three kinds of straight-through holes with diameters of 2 mm, 2.5 mm and 3 mm and two kinds of countersunk holes were produced in steel sheets. The lower diameters of the two kinds of countersunk holes were both 3 mm, while the upper diameters were respectively 4 mm and 5 mm. The upper diameters of the holes were all designed to be not more than the top diameter of the pin, for guaranteeing that the thermal-mechanical effect of the pin on the aluminum alloys was enough to squeeze sufficient materials into the prefabricated holes. The interval between adjacent holes were fixed at 8 mm. The welding tool travelled across the holes and the aluminum alloy was squeezed into the holes, forming aluminum rivets under the high temperature and severe plastic deformation during the welding process. Joints were produced perpendicular to the rolling direction with the aluminum alloy sheet at the upper side and the steel sheet at the lower side. Rotational speed, welding speed, tilt angle and shoulder plunge depth were fixed at 1000 rpm, 100 mm/min, 2.5° and 0.1 mm, respectively.

To clarify the filling process of plasticized aluminum alloy into the prefabricated holes, the investigation of material flow was conducted. When the leading edge of the pin tip reached pre-set positions, the tool was lifted up without dwelling time and the longitudinal sections of the joints were investigated. The position was recorded as positive value when the leading edge of the pin tip exceeded the trailing edge of the hole, otherwise as negative value. The pre-set positions of the pin tip were −2 mm, −1 mm, 0 mm, 1 mm, 2 mm, 4 mm, 6 mm and 8 mm distances away from the trailing edge of the holes along the welding direction. Schematic of the pre-set positions is shown in Fig. 1b.

The microstructural specimen was cut along and perpendicular to the welding line by electrical discharge machining process. The steel side was etched by a solution (2.5 ml HNO_3 and 97.5 ml ethanol), while the aluminum side was etched by Keller's reagent (1.0 ml HF, 1.5 ml HCl, 2.5 ml HNO_3 and 95 ml H_2O). The microstructure was observed by an optical microscopy (OM), a scanning electron microscopy (SEM) and a transmission electron microscopy (TEM). Grain size was measured and calculated by the general intercept procedures method according to the standard of ASTM E112-13 (ASTM E112-13, 2013). Microscopically determined grain size number G was calculated by the formula as follows.

$$G = -3.2877 - 6.6439\log_{10}\bar{\ell} \tag{1}$$

Where, $\bar{\ell}$ presents the mean intercept measured in two-dimensional grain sections and the value is in millimeters at 1X magnification. SEM with energy dispersive spectroscopy (EDS) was conducted in a FEI Quanta 200 FEG at 30 kV acceleration voltage and a working distance of 10 mm. TEM experiment was performed on a JEM 2100 operated at 200 kV. The TEM specimen of the cross-section of the joints was prepared by Ar^+ ion milling technique in a GATAN 695 at the acceleration voltage of 6 kV and the etching angle of 8°. Three shear tensile specimens perpendicular to the welding line with two riveting holes were prepared (Fig. 1c). Shear tensile strength was evaluated by *F*/*w* ratio, in which *F* presented the ultimate shear tensile load and *w* indicated the width of the shear tensile specimens. Shear tensile tests were performed at ambient temperature under a crosshead speed of 0.5 mm/min. The fracture surface of the shear tensile specimens were characterized by the SEM with EDS (FEI Quanta 200 FEG). Vickers microhardness profiles of the produced aluminum rivet in the prefabricated hole were measured using an indentation load of 200 g for a dwell time of 10 s. The interval between the adjacent indentations was 0.5 mm in the

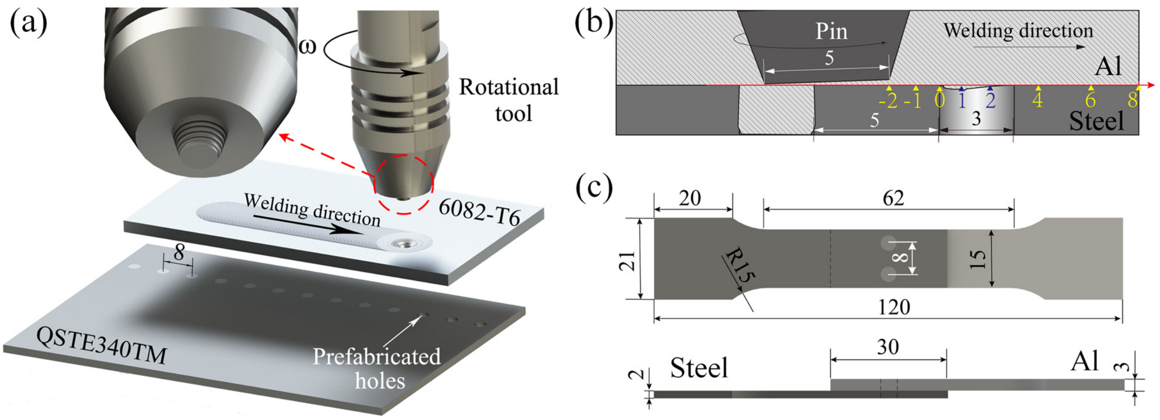

Fig. 1. Schematics: (a) SRFSLW of aluminum/steel, (b) pre-set positions in material flow investigation and (c) dimension of shear tensile specimen (unit: mm).