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# Self-riveting friction stir lap welding of aluminum alloy to steel

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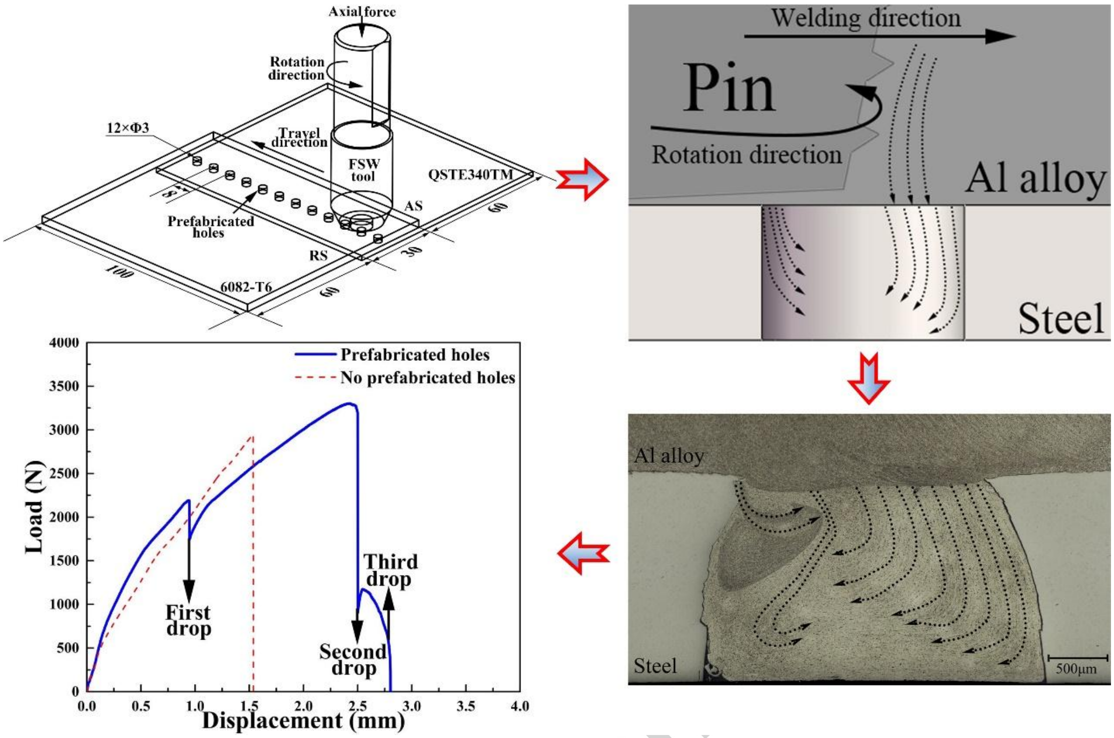
**Abstract**

A novel self-riveting friction stir lap welding technique was developed by the prefabricated holes to realize sound and effective joining of 6082-T6 aluminum alloy to QSTE340TM steel. Partial dynamic recrystallized aluminum flows downwards and fills the prefabricated holes forming self-riveting structure. Metallurgical bonding as diffusion layers formed at the interface of Al/Steel. The joint fracture process contains separation of self-riveting structure and unilateral hole wall, tearing of metallurgical bonding and final failure of self-riveting structure. An average fracture load of 3.21 kN is obtained, which is stronger with high average elongation than that without prefabricated holes. The self-riveting structure is beneficial to prevent total failure of different materials joints with applicative perspectives.

Graphical abstract




**Keywords**: Friction stir lap welding; Metals and alloys; Self-riveting; Diffusion; Mechanical bonding

## 1. Introduction

Energy savings and cost reduction become inevitable issues with the promptly evolution of modern automobile industry, lightweight metals like aluminum alloy have got wider applications in vehicle structure [1,2]. Moreover, steel is still indispensable because of good mechanical properties and low cost. To felicitously combine superiorities of both metals, a proper joining method is essential. As a solid state joining technique [3-7], friction stir welding (FSW) has been widely reported on joining aluminum alloy and steel [8-12]. However, hard and brittle intermetallic compounds is difficult to avoid, which is detrimental to mechanical property. To strengthen Al/steel dissimilar FSW joints, a novel concept with

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assistance of mechanical interlocking via prefabricated geometrical configurations was needed. Evans et al. [13] joined aluminum alloy to steel with prefabricated concave and O-ring dovetail grooves. Plasticized aluminum was extruded into grooves and then mechanical interlocking was created. However, metallurgical bonding was absent, while grooves on steel also weakened the matrix. In this study, a new self-riveting FSLW technique named SRFSLW was developed. The plasticized aluminum was forced into the prefabricated holes, producing self-riveting structure with metallurgical bonding at the interface of Al/Steel. The process provides additional mechanical bonding by self-riveting, while only prefabricated holes are machined on the steel, the matrix is less weakened. The formation of self-riveting structure, interface microstructure and fracture behavior were mainly investigated.

## 2. Experimental procedure

3-mm-thick 6082-T6 aluminum alloy plate and 2-mm-thick QSTE340TM steel plate were used. Fig.1a presents the schematic illustration of experiments. Through-holes (diameter: 3 mm) were drilled on the steel plate with the interval of 8 mm. A backing plate was set under the steel plate to prevent aluminum alloy being extruded through the prefabricated holes. Welding tool consists of concave shoulder with 16 mm diameter and tapered right-threaded pin of 2.8 mm in length, 8 mm in bottom diameter and 5 mm in tip diameter. Lap joining was performed at a rotation speed of 1000 rpm, travel speed of 100 mm/min and tilt angle of 2.5°. Plunge depth of the tool shoulder was 0.1 mm, so the probe tip could nearly contact with steel surface without wear. The weld transverse and longitudinal sections were cut by an electrical discharge machining and prepared by standard

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metallographic procedures. Optical microscopy (OM), scanning electron microscopy (SEM) with energy dispersive spectrometer (EDS) were used. In Fig.1b, three tensile specimens (gauge length 62 mm, width 12 mm, overall length 120 mm) perpendicular to the weld line with two riveting holes each were prepared, performed under a crosshead speed of 0.5 mm/min. The average value was present for discussion.

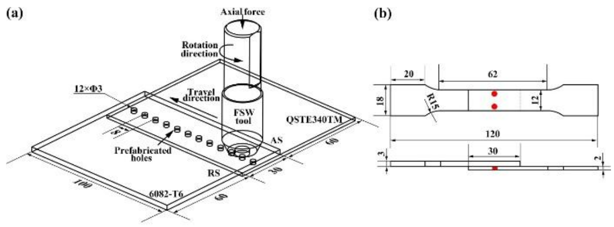


Fig.1. (a) Schematic illustration of FSLW process (Dimensions in mm); (b) Dimensions of the shear tensile specimen

## 3. Results and discussion

### 3.1 Structure of SRFSLW joints

In Fig.2a, the attained weld could be divided into four zones: nugget zone (NZ), thermo-mechanically affected zone (TMAZ), heat affected zone (HAZ) and self-riveting zone (SRZ). Different zones experience varied thermal cycle and plastic deformation, leading to the variations in microstructural features. Prefabricated hole on the steel is fully filled with partial dynamic recrystallized aluminum alloy, as shown by red cycle in Fig.2a, resulting in the formation of mechanical bonding between aluminum alloy and steel. The formation mechanism of self-riveting structure and a flow model are given in Fig.2b and c. Two flow actions occur in opposite directions, illustrating that there are two driving forces prompting the downward flow of plasticized aluminum alloy. With the advancement of welding tool, aluminum alloy ahead of the pin is plasticized, and then thread on the pin

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drives the plasticized metal flow downwards. Normally, material transport is restricted by the lower plate and the material moves upwards, resulting in a flow circulation longitudinally. In this study, plasticized metal flows downwards into the prefabricated holes. Once the pin reaches the hole neck, imposed pressure by the pin bottom can extrude aluminum alloy into the prefabricated hole. Under the combined effects, self-riveting structure finally forms, and mechanical interlocking between aluminum alloy and steel is obtained. Moreover, the longitudinal-section of riveting hole is different from the cross section. This is because that the hole wall of the longitudinal-section specimen (Fig. 2b) appears to be bent due to the extruding motion of the welding tool. The parts where stirring pin firstly contacted the hole and finally left the hole, have no enough support, so imposed force made hole deform.

Apart from mechanical bonding, metallurgical bonding also appears at the joint interface. White squares in Fig.2a present magnified optical images of joint interface within pin affected range on retreating side (RS) and advancing side (AS). These two zones are dominated by frictional heat and direct stirring of the pin. High-rate deformation induces dynamic recrystallization, so the grains are refined and the amount of crystal defects like dislocations increases. Inter-diffusion of Al and Fe is accelerated by increased diffusion channels, shortened diffusion distance and elevated temperature [14], resulting in the formation of diffusion layers. EDS line analysis of local positions marked by white squares in Fig.2a was performed. As shown in Fig.2d and e, a significant amount of inter-diffusion between Al and Fe occurs. Diffusion layer with average thickness of 4.2 μm forms on AS, while 3.5 μm thick diffusion layer appears on RS. The difference in thickness can be attributed to the fact that shear stress on AS is higher than RS, resulting in higher heat input

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on AS [15]. Compared with joints reported in references [13], joint in this study owns metallurgical bonding, which is propitious to the strengthening of joint.

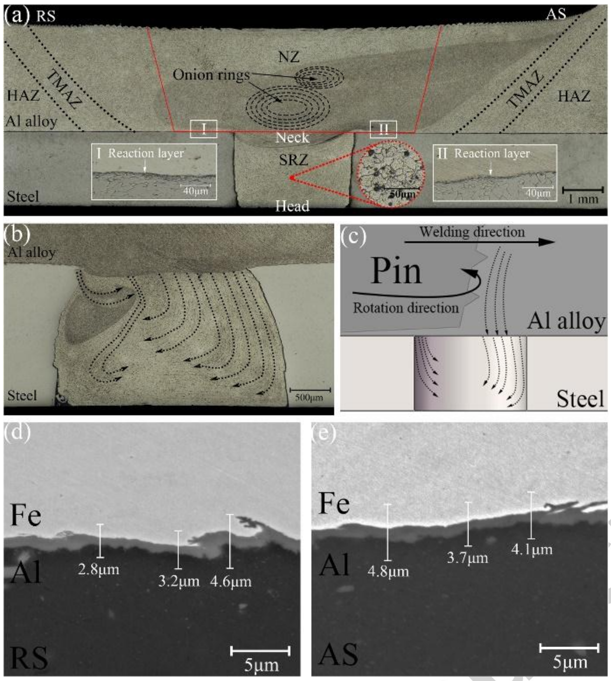


Fig.2. Optical macrograph of (a) joint cross-section and (b) self-riveting structure of longitudinal-section; (c) flow model; Joint interface on (d) RS and (e) AS

### 3.2 Mechanical properties

To reveal the effect of prefabricated holes on mechanical properties, FSLW without prefabricated holes was performed. Fig.3a and b show typical force–displacement curves and mechanical performances of samples with and without prefabricated holes, while fracture surfaces are presented in Fig.3c and d. The sample without prefabricated holes fractures at the interface, and average shear load reaches 2.80 kN. With prefabricated holes, the failure contains combined fractures of the interface and self-riveting structure. The average value of shear load reaches 3.21 kN, which is 14.6% higher than that without prefabricated holes. In Fig.3a, the shear tensile curve of joint with prefabricated holes presents three interesting fluctuations. The first drop is attributed to separation of self-riveting structure and unilateral

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hole wall at 1.0 mm displacement. Self-riveting structure and joint interface bear the load together. With tensile stress increasing, metallurgical bonding at the joint interface fractures, which corresponds to the second plunge. The subsequent small bump at the end is the final failure of self-riveting structure. The self-riveting structure suffers from shear fracture at the neck, as shown in Fig.3c. The prefabricated holes can improve tensile performances of Al/steel dissimilar FSLW joint. It is worth mentioning that average elongation of samples (elongation=total displacement/gauge length) with prefabricated holes is 4.8%, which is almost twice as large as 2.3% of samples without prefabricated holes, indicating that joints with prefabricated holes have the potential to function under fluctuating load. This phenomenon is based on both metallurgical bonding and self-riveting structure. Moreover, since self-riveting structure can bear the load after separation of bonding area at the interface, it helps prevent total failure from the viewpoint of practical application.

The fracture surface at the self-riveting structure neck consists of many dimples, exhibiting ductile fracture (Fig.3e). It is expected that when crack reaches self-riveting structure, its propagation slows down, resulting in a comparatively larger elongation. Fig.3f shows the surface morphology at joint interface on the steel side with flat fracture surface, indicating primarily brittle fracture. Fig.3g presents fracture surface of joint interface on aluminum alloy side. The results of EDS analysis (at.%) performed on each region demonstrate that scattered AlFe might occur at the interface, which is beneficial to the joint ductility, compared to Al-rich intermetallic compounds.

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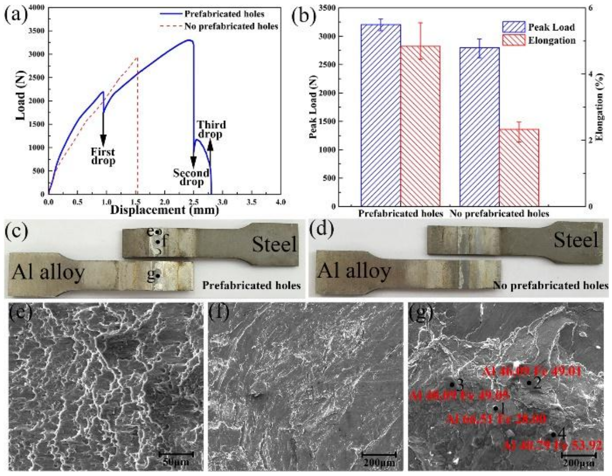


Fig.3. (a) Typical force-displacement curves and (b) mechanical performances of samples with and without prefabricated holes; Fracture appearance of sample (c) with and (d) without prefabricated holes; (e) ductile feature of self-riveting structure and (f) brittle feature on steel side; (g) fracture feature on aluminum alloy side

## 4. Conclusion

In this study, a self-riveting friction stir lap welding method was proposed for strengthening the Al/steel dissimilar joints by prefabricated holes. A self-riveting structure forms in the steel, which is attributed to the flow and filling behavior of severe plastic deformed aluminum alloy with the combined effects of threaded pin and imposed pressure. Metallurgical bonding also exists as diffusion layers with average thickness of 4.2 μm and 3.5 μm on AS and RS, respectively. Fracture of sample with prefabricated holes contains first separation of self-riveting structure and unilateral hole wall, tearing of bonding area at the joint interface and failure of self-riveting structure at the neck. The average maximum fracture load of joint with prefabricated holes is 3.21 kN, which is stronger with high average elongation. Self-riveting structure can prevent total failure of joint for practical application.

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Highlights

- A novel self-riveting friction stir lap welding technique is developed.
- A self-riveting structure forms with plasticized aluminum and imposed pressure.
- The self-riveting structure can bear load even tearing of interfacial bonding.
- The self-riveting structure is beneficial to prevent total failure of joint.
- Enlarged elongation enables joint to function under fluctuating load.

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