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Application of a novel friction stir spot welding process on dissimilar aluminum joints

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ABSTRACT

Intermediate layer friction stir spot welding (IL-FSSW) is introduced in this study as a novel spot welding technique to eliminate the keyhole associated with the conventional friction stir spot welding (FSSW). This process is utilized for fabricating a joint of 6061-T6 and 2024-T3 aluminum alloys. The welding process is based on preventing the keyhole occurrence owing to the addition of an intermediate layer (IL), rendering additional post-treatments unnecessary. Results indicated a decent joint appearance without a keyhole along with improved mechanical performance yielding a lap shear force over 4.5 kN. The microstructure of the weld cross-section indicated that the IL contributed to the nugget zone and revealed its influence on the formation of a hooked structure. The fracture surface showed ductile features within the IL boundary, whereas mixed failure was prevalent outside it.

1. Introduction

The advent of 6XXX and 2XXX series aluminum alloys coincides with the need for fabricating lightweight structures requiring high strength-to-weight ratio and decent corrosion resistance. Moreover, aluminum alloys are environmentally friendly used for easy recycling, and concomitantly attract interest in the development of welding technology that can fabricate joints with satisfactory mechanical properties. A typical drawback for fusion welding of aluminum joints is the formation of brittle intermetallic compounds that lead to severe cracking [1]. Therefore, manufacturing of sound aluminum joints remains as a challenge.

Friction stir spot welding (FSSW) is a modification of the friction stir welding (FSW) process that can effectively replace the resistance spot welding (RSW) technique abundant in the automotive industry. FSSW exhibits several advantages in welding dissimilar materials [2]. Mazda Motor Company, for example, used the FSSW technique for the production of some components [3]. However, the keyhole, which inevitably remains at the center of the weld after retraction of the FSSW tool, is considered as a critical issue that causes stress concentration and a decrease in the active welding area of the spot weld. Furthermore, keyhole areas are difficult to reach during body painting, so corrosion is expected to occur at these locations. Thus, numerous publications have proposed refilling strategies or approaches on removing the keyhole defect [4–10].

A new friction stir spot welding called refill FSSW (RFSSW) technology was developed to fill the keyhole [11,12]. In this process, a sleeve-pin pair is responsible for pushing the accumulated material to completely refill the keyhole during the retraction stage thereby leaving a flat surface. Zhao et al. [13] welded a 1.9 mm thick 7075 aluminum alloy sheet by applying a similar refilling technique with a movable tool assembly. This process yielded a joint failure load of 12 kN at a plunge depth of 3 mm. However, a welding post-treatment was required to eliminate the formation of groove defects. Reimann et al. [14] used friction stir plug welding process named as FSpW to weld 4.8 mm thick 6061-T6 aluminum alloy. A cylindrical plug of the same workpiece material is inserted into the keyhole as an additional part followed by RFSSW to join the plug and adjacent materials. The influence of the plug and heat treatments on the joint strength is investigated. Accordingly, it was asserted that the high strength spot welds have been achieved without any defect. Joining of 6061-T6 aluminum alloy to 780 TRIP steel was performed with a two-step RFSSW approach. Traditional FSSW is performed in the first step. After the second step, a new but smaller keyhole as compared with the original one is created [15].

Several other refill methods have been developed to prevent the keyhole defect. Uematsu et al. applied a keyhole-refill process utilizing a double-acting welding tool with a shoulder and a retractable pin. This refilling process shows 30% improvement in the joint strength of 2 mm

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thick Al-Mg-Si aluminum alloy sheets [16]. Sajed recently welded similar sheets of 2 mm thick 1100 aluminum alloy by a two-stage welding process [17]. This process requires two independent tools, namely, a traditional FSSW tool and a pinless refilling tool. The analysis of welding parameters indicated that the welding rotational speed has a major effect on the weld joint strength reaching a maximum of 6.96 kN.

The common aspect of all these mentioned attempts is that the keyhole creation is followed by a variety of refilling strategies for removal. Regardless of the benefits, certain limitations exist. Most of these processes require special welding tools and/or equipment increasing the complexity, cost, and duration of the process [17,18]. The present work aims to eliminate the keyhole problem and thus enhance the joint appearance by developing an FSSW process employing an intermediate layer (IL). Intermediate layer FSSW (IL-FSSW), is a one-step and cost-effective process that can be implemented on any milling machine. The mechanical properties and microstructural evolutions of the joints are evaluated and failure mechanisms are discussed based on fracture surface observations.

2. Experimental methods

Conventional FSSW is modified by placing an intermediate material layer at the center between the sheets to be joined. With the virtue of this layer, the upper sheet is elevated. The shoulder presses the upper sheet to affix it with the IL and the lower sheet, leading to a convex protrusion enclosing the intermediate material. This protrusion creates contact at the interface between itself and the welding tool at a level higher than the upper sheet. The stationary shoulder also prevents the sheets from moving during the process.

When the welding tool begins to rotate and descends simultaneously, frictional heating occurs at the top of the protrusion. Temperature increases as the tool moves downwards, resulting in stirring and plastic deformation of the upper and lower sheets with the IL. A flat welding spot is created after the welding tool reaches the base of the protrusion at the original surface level of the upper sheet. The absence of a keyhole expels the necessity for any post-weld processing. The principle of operation is further explained in Fig. 1.

1 mm thick sheets of aluminum alloys of 6061-T6 and 2024-T3 are joined utilizing a 1 mm thick and 6 mm diameter intermediate layer of 6061-T6 alloy. A pinless welding tool fabricated from tool steel with 10 mm diameter is used. Using a tool rotational speed of 1500 rpm and a plunging rate of 25 mm/min, overlap spot joints are prepared according to the American Welding Society (AWS) standard as shown in Fig. 2 [19]. With the same process parameters, conventional FSSW samples are prepared to better indicate the mechanical performance of the introduced technique.

For the evaluation of the joint strength, mechanical test samples are prepared and tested under a tensile load at a displacement rate of 0.025 mm/s utilizing an Instron mechanical test frame where force and displacement values were captured. Base material strength levels were also determined. Experiments were repeated on 3 samples for each condition. Standard metallographic sample preparation techniques including grinding, polishing and etching were utilized. Samples were etched with Keller's reagent (190 ml H_2O, 5 ml HNO_3, 3 ml HCl and 2 ml HF). Optical microscopy and scanning electron microscopy (SEM) were used for characterizing the weld zones. SEM observations were performed inside a JEOL microscope operating at an accelerating voltage of 20 kV.

3. Results and discussion

3.1. Weld geometry and microstructural analysis

Fig. 3 displays the appearance of spot weld joints using both the conventional FSSW, and the technique presented herein. Accordingly, the absence of a keyhole is clear in the latter joint surface. Macroscopic views of the samples showed that sound joints can be fabricated as shown in Fig. 4. Both top and cross-sectional views of the joint demonstrate that the welding spot is flat with no keyhole or any type of defect.

In addition, material flow during welding can be traced by examining Fig. 4b. As the tool plunges down, compression forces and frictional heating transform the circular IL into a hooked structure. The hooks spread inside the upper sheet and overlap an enclosed portion of the latter. Few defects were also noticed outside of the bonding region.

Improved bonding can be explained from two perspectives. First,

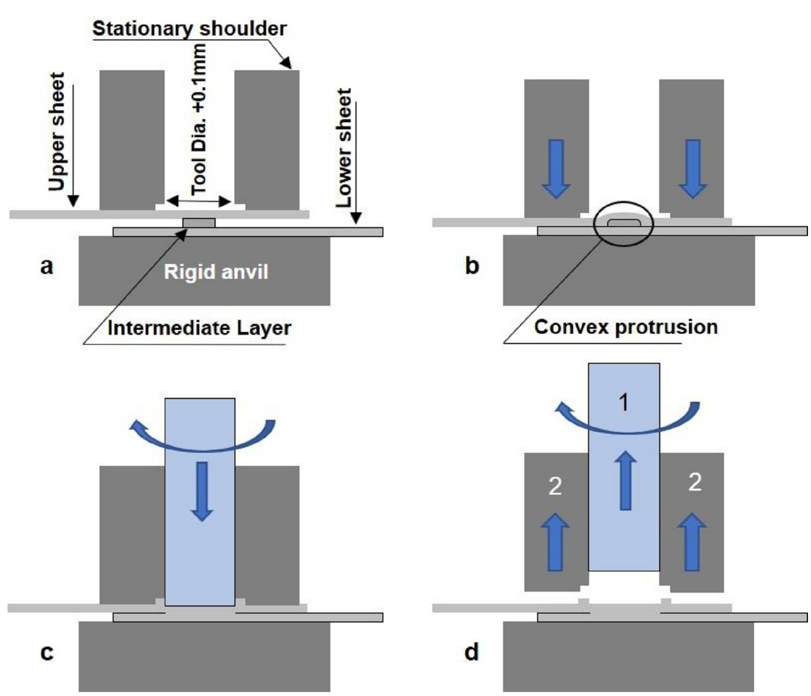

Fig. 1. Schematic of the IL-FSSW process: a) welding fixture; b) part clamping; c) tool plunge; d) tool retraction.