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Improving mechanical properties of pinless friction stir spot welded joints by eliminating hook defect

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ABSTRACT

Hook defect (HD) seriously decreases the mechanical properties of friction stir spot welded (FSSW) joints. In this study, two methods were therefore used to eliminate the HD in pinless FSSW joints. The one is changing welding parameters such as rotating speed and dwell time. The other one is FSSW plus subsequent friction stir welding (FSSW-FSW), which is an innovative method proposed in this study. Experimental results showed that the HD in pinless FSSWed AA2024 joints was successfully eliminated by using FSSW-FSW, not by changing process parameters. The joints without HD exhibited a tensile–shear load of as much as 12 kN, which was higher than that of 6.9 kN in the joints with HD. Furthermore, it was proved that the tensile–shear load is not greatly improved only by increasing the nugget zone when HD still existed in the FSSW joints. In addition, the fracture morphology analysis demonstrated that the shear fracture of the FSSW-FSW joints took place along the boundary between the upper and lower sheets through the weld nugget, and the faying surface between the two sheets was completely sheared off.

1. Introduction

Friction stir spot welding (FSSW) is a new variant of friction stir welding (FSW) where the rotating tool is plunged into two overlapping sheets at a specified position and gets out after a dwell time. A stir zone is created during welding, but leaving a keyhole in stir zone due to the pulling out of rotating tool. The FSSW process has shown a great potential in substituting the conventional resistance spot welding (RSW) and riveting in joining lightweight structural metals, such as aluminum and magnesium alloys, in the automotive and aerospace industries [1–7]. However lots of attempts have proved that the keyhole [8] and the hook defect (HD) [9,10] presented in the FSSW joints, as shown in Fig. 1(a) [11,12], seriously reduced the joint properties such as tensile–shear strength and fatigue strength. In order to eliminate the keyhole and HD, plenty of work has been done.

Among them, the re-filling FSSW process has been developed to eliminate the keyhole [13]. Uematsu et al. [14] proved that the tensile strength of the FSSW joints was enhanced by re-filling the keyhole, but the fatigue strength of these joints was slightly decreased. Furthermore, the equipment for the re-filling FSSW process is extremely complex and the HD still remains as shown in Fig. 1(b). As a consequence of these, the re-filling FSSW process has still not been used in industry. The pinless FSSW process was proposed in 2009 and has received increasing attention in the recent years. Bakavos and Prangnell [15] proved that the pinless FSSW process could completely avoids the keyhole because the welding tool has no pin. Moreover, Tozaki et al. [10] found that the tensile–shear strength of the pinless FSSW joints was slightly higher than that of the pin FSSW joints. Although some efforts on the pinless FSSW process have been done, the joint properties cannot be greatly improved because the HD remains in joint as shown in Fig. 1(c).

According to the open literature, the HD is a partially metallurgical bond region or an unbonded region inside of the FSSWed joints [9,10,12,16–18]. Yin et al. [9,17] investigated the HD formation in the FSSWed AZ31 welds and found that the HD was formed during the plunging stage. Importantly, they proved that the failure strength of the FSSWed joint was significantly affected by the dimension of the HD. In addition, Badarinarayan et al. [12,16] declared that the hook shape was determined by the tool geometry and finally affecting the tensile–shear strength of the FSSWed joint. Similarly, Babu et al. [11] found that the mechanical performance of FSSWed joints was mainly governed by the geometrical features of hook. For the fatigue behavior, Rao et al. [19] found that the HD was mainly determined by the process conditions and significantly affected the fatigue behavior of the joint. In addition, Xu et al. [20] pronounced the existence of HD was the key factor to reduce the

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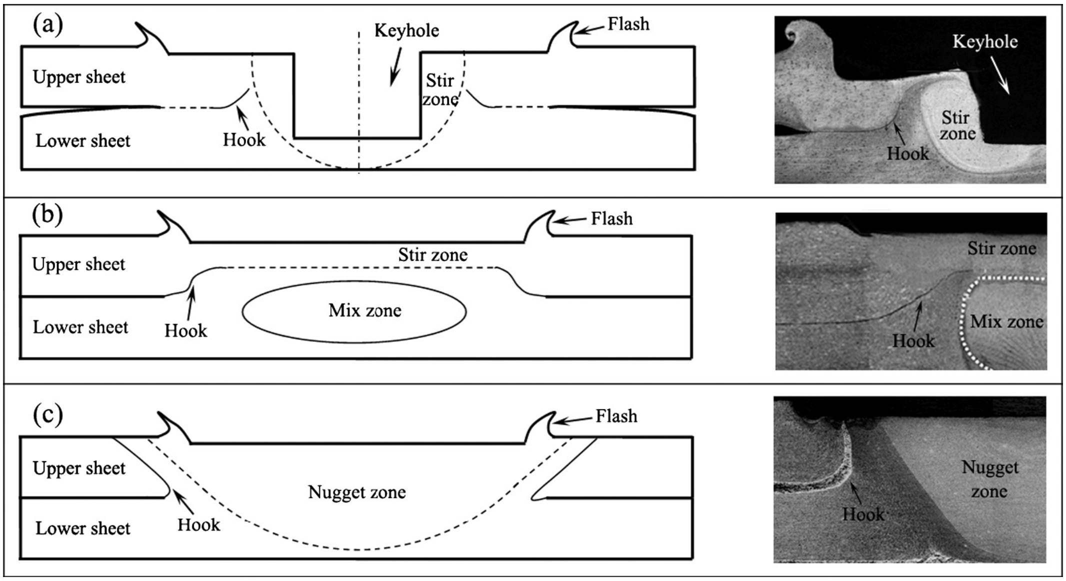

Fig. 1. Schematic diagram of the hook defect in: (a) pin FSSW joint [11, 12], (b) re-filling FSSW joint [14] and (c) pinless FSSW joint (present work).

fatigue strength since fracture can occur along the hook when the weld is subjected to external loading. Yuan et al. [18] prophesied that a higher fracture load can be expected by suppressing the HD. However, to date all efforts have not achieved on the lofty goal to eliminate the HD. This work, therefore, aims to eliminate or control the HD for superior joints.

2. Experimental procedures

1.5 mm thick AA2024-T3 sheets, with 50 mm in length by 40 mm in width, were friction stir spot welded in an overlapped configuration on a FSW machine (FSW-RL31-010, Beijing FSW Technology Co., Ltd., PR China). The detailed chemical composition of the material used is summarized in Table 1. The configuration of the welding tool employed in this study is presented in Fig. 2. The tool is made of H13 steel and has a shoulder of 15 mm diameter, but without pin. Shoulder surface have three involute grooves of 0.3 mm depth.

The cross-section morphology of the joints was analyzed by optical microscope (OM, OLYMPUS GX71, Japan). The room temperature tensile–shear tests were performed at a cross-head speed of 1 mm/min using a computer-controlled testing machine (SHIMADZU AG-X). The tensile–shear load of each joint was evaluated using three tensile specimens. After the tensile–shear test, the fracture features of the samples were analyzed by scanning electron microscope (SEM, Tescan Mira3, Czech). In addition, the composition of the joint was analyzed by energy dispersive X-ray spectroscopy (EDS) attached with the SEM.

3. Welding processes

The pinless FSSW process, as shown in Fig. 3, is greatly different with the conventional FSSW process because the flow of weld metal completely depends on the grooves on the tool shoulder. During the pinless FSSW process, the formation of HD is intimately connected to welding parameters such as the tool rotating speed, plunge rate, plunge depth and dwell time. Hence, the first trial was made to eliminate the HD by varying the welding parameters. These welding parameters are summarized in Table 2.

Based on lots of preliminary experiments, an innovative method that is the FSSW plus subsequent FSW (FSSW-FSW) is at the first time proposed to eliminate the HD. The FSSW-FSW aims at repairing the HD by a secondary nugget zone. The process is divided into three steps as shown in Fig. 4. In step I, a pinless FSSWed joint with the HD was achieved. In step II, the pinless tool was moved on to the HD. In step III, a circular weld was produced by FSW using the pinless tool, achieving a shallow nugget zone which covers the HD. During the step I, in this study, the welding parameters were selected as rotating speed of 950 rpm, plunge rate of 30 mm/min, plunge depth of 0.3 mm and dwell time of 15s using a pinless tool with the diameter of 15 mm. In such a joint, the HD, which is presented by the red dashed line, appears 6.5 mm away from the weld center. During the step III, the welding speed is also believed as an important welding parameter. A new HD may be formed in the weld periphery when the heat input is too large based on our preliminary study. On the other hand, if heat input is insufficient the HD can be partly covered instead of being fully repaired. After a number of experiments, the optimal welding parameters in step III were determined as: rotating speed of 600 rpm, plunge depth of 0.1 mm, plunge rate of 30 mm/min and welding speed of 30 mm/min using the pinless tool with the diameter of 10 mm. In order to distinguish from the FSSW-FSW process, the pinless FSSW process was defined as conventional FSSW process (C-FSSW).

The nugget zone (NZ) in the FSSW-FSW joint is larger than that in the C-FSSW joint, which may lead to the higher mechanical properties. In order to confirm that the improvement of mechanical properties of the FSSW-FSW joints is due to eliminating HD instead of increasing the nugget zone, the C-FSSW joints were made using a tool with 23 mm in diameter because the diameter of FSSW-FSW joint was calculated as 23 mm.

Table 1
Chemical composition (wt.%) of 2024-T3 aluminum alloy.

Cu	Mg	Mn	Si	Fe	Cr	Zn	Ti	Al
3.8–4.9	1.2–1.8	0.3–0.9	0.5	0.5	0.1	0.25	0.15	Bal.

4. Results and discussion

4.1. Macrostructure

Fig. 5 shows the top view and cross-section morphology of the C-FSSW and FSSW-FSW joints. It is clear that the C-FSSW weld has