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A comparative research on bobbin tool and conventional friction stir welding of Al-Mg-Si alloy plates

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ABSTRACT

In our work, Al-Mg-Si (6061Al -T4) plates of 6 mm thickness were subjected to bobbin tool friction stir welding (BT-FSW) and conventional friction stir welding (C-FSW) for comparison. How the welding process affects the microstructure and mechanical properties was investigated at various rotation rates and welding speeds. The results showed that butt FSW joints with high quality could be produced at the selected parameters. The joint strength rose with enhanced welding speed and was nearly independent of the rotation rate in both the welding processes. The strength of the joints produced with BT-FSW reached the same level as that of the C-FSW. The maximum joint strength of 229 MPa was 93% of the base material (BM), which is superior to the reported results of 60–80% for the T4 condition. The fracture position of most of the joints was in the heat-affected zone (HAZ), which is the lowest hardness zone.

1. Introduction

6061 Al alloy, which is typical of the 6xxx (Al-Mg-Si) series, has outstanding mechanical properties, good corrosion resistance and weldability, which renders it useful in various applications in many fields such as aerospace, automotive, shipbuilding, and other industries [1,2]. Welding, as an essential joining method, furthers its applications in many industrial fields. However, fusion welding can cause many welding defects and disadvantages during the welding of precipitation-strengthened aluminium alloys.

Friction stir welding (FSW) [3], which is a solid-state joining process, has been invented to join aluminium alloys while overcoming the problems faced in fusion welding. FSW has great advantages over fusion welding in joining light alloys such as magnesium and aluminium alloys [3,4]. Besides, high quality joints of aluminium matrix composites [5–7] and dissimilar alloys [8–10] can be acquired by FSW or its derivative process [11,12]. However, conventional friction stir welding (C-FSW) has a high demand for clamping and also a backing anvil; besides, there is a risk of root defects, like kissing bonds and lack of penetration, and non-uniform heat input can occur in the process [13–15].

Bobbin tool friction stir welding (BT-FSW), also called self-support friction stir welding (SS-FSW) [16,17], has remarkable potential to overcome the above problems encountered in the C-FSW process. The so-called bobbin tool consists of two shoulders, namely the upper shoulder and the lower shoulder, connected by a pin between them. The process is performed with the two shoulders in contact with the surface of the workpiece and it enables a balanced axial force and uniform temperature gradient through the thickness direction of the weld. Additionally, the two-shoulder feature enables it to join hollow extrusion profiles, expanding its applications greatly [4,16,17].

To date, there have been systemic reports on FSW of 6061Al [18–24], but studies on BT-FSW of 6xxx series aluminium alloys [25–28] are still insufficient, and many less than C-FSW. As mentioned above, root flaws, especially kissing bonds and a lack of penetration, are inclined to be generated for medium thick plate in the C-FSW process when the parameters are unsuitable [13,29–31]. BT-FSW has the potential to avoid these root defects due to its unique features.

The limited process window and wider softened area of the joint are the main problems currently faced in BT-FSW. Usually, the as-welded joints produced by BT-FSW have lower strength than those of C-FSW. Lafly et al. [32] reported that the BT-FSW joint strength was lower than

Abbreviations: FSW, friction stir welding; BT-FSW, bobbin tool friction stir welding; C-FSW, conventional friction stir welding; NZ, nugget zone; TMAZ, thermo-mechanically affected zone; HAZ, heat-affected zone; BM, base material; JLR, joint line remnants; LHZ, lowest hardness zone; UTS, ultra tensile strength; EBSD, electron backscattered diffraction; TEM, transmission electron microscopy; SEM, scanning electron microscopy; T4, natural aging after solid solution heat-treatment

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that of a C-FSW joint for 6056 alloy. Zhang et al. [33] conducted the BT-FSW/C-FSW of AA2219-T4 alloy and also acquired lower joint strengths by BT-FSW compared with C-FSW. Esmaily [25] compared the microstructure and properties of the BT-FSW and C-FSW processes for 6005-T6 plates of 10 mm thickness, and although a high strength joint by BT-FSW was acquired, it was conducted under only one parameter combination (900–1200), and the process window was very limited.

The present work is aimed at illuminating the weldability of 6061-T4 Al alloy subjected to the BT-/C-FSW processes, and identifying the different effects of the two welding processes on the evolution of microstructure and its relationship with the mechanical properties of the welds.

2. Experiment

The base material (BM) for butt welding was 6.35 mm thick 6061Al-T4 plates (T4 treatment: natural aging after solid solution heat-treatment) with dimensions of 320 mm × 80 mm. The chemical composition of the BM is 1.0 Mg, 0.6 Si, 0.25 Zn, 0.25 Cu, 0.7 Fe, 0.15 Mn, 0.08 Cr, 0.15 Ti, and balance Al (wt%).

The welding processes (BT-FSW and C-FSW) were both carried out using a numerically controlled FSW machine (FSW-5LM-020) and the welding was conducted in a parallel direction to the rolling direction of the BM. The tilt angle of the tool was 2.75° and 0° in the C-FSW and BT-FSW processes, respectively. The bobbin tool used in the experiment consisted of symmetrical upper and lower shoulders with a scrolled groove feature 22 mm in diameter, and was connected by a cylindrical pin with a mixed thread 8 mm in diameter and 6 mm in length. The C-FSW tool consisted of a 22 mm diameter concave shoulder and a cylindrical right-threaded pin 8 mm in diameter and 6 mm in length. The figures of the welding tools were presented in Fig. 1. To demonstrate the effect of the rotation rate, the welding speed was kept constant at 100 mm/min while the plates were subjected to BT-FSW and C-FSW processes at three rotation rates of 300, 400 and 600 rpm for comparison. A constant rotation rate was then maintained at 600 rpm while four welding speeds of 50, 100, 150 and 300 mm/min were conducted to demonstrate the effect of the traversing speed. The variable rotation rate groups of the corresponding joints were respectively defined as BT-300-100, BT-400-100, BT-600-100, C-300-100, C-400-100, and C-600-100; the variable traversing parameters of the corresponding joints were defined as BT-600-50, BT-600-150, BT-600-300, C-600-50, C-600-150 and C-600-300.

Microstructural observations were conducted using optical microscopy (OM), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and electron backscattered diffraction (EBSD). OM observation was carried out with the samples prepared by grinding, polishing, and etching with Keller's reagent (NHO_3: HCl: HF: H_2O = 2.5: 1.5: 1: 95 vol%). The fracture morphology of failed tensile samples was observed by SEM after tensile tests. Twin-jet electro-polishing was used to prepare samples for TEM observation with a 30% nitric acid and 70% methanol solution (temperature: −30 °C; voltage: 15 V). Grain structure and mean size were ascertained by EBSD. Samples for EBSD were prepared by grinding and mechanical polishing, followed by electro-polishing in a solution of 10% perchloric acid and 90% alcohol solution at −25 °C and 15 V for 1 min.

An auto testing machine (Leco, LM-247AT) was used for hardness measurement on the cross-section along the centre line across the weld under a load of 300 g, holding for 15 s. Tensile specimens with a gauge 50 mm in length and 10 mm in width were machined perpendicular to the welding direction. Room-temperature tensile tests were conducted at a constant strain rate of $1 \times 10^{-3}\,s^{-1}$, and each parameter was tested at least three times for accurate results. All the FSW samples were kept 1 month before examinations of the microstructure and mechanical properties after FSW.

3. Results and Discussion

3.1. Microstructure Evolution

Cross-sectional microstructures of the joints at various rotation rates are presented in Fig. 2. Fig. 2a–c shows the BT-FSW joints and Fig. 2d–f the C-FSW joints. Defect-free joints were generated during welding, and all the BT/C-FSW joints exhibited four microstructural zones: nugget zone (NZ), thermo-mechanically affected zone (TMAZ), heat-affected zone (HAZ), and base material (BM). Unlike the C-FSW joints, the NZ in BT-FSW joints has an hour-glass shape. This is attributed to the contact and friction heat produced from both the upper and lower shoulders. An apparently sharp boundary between the NZ and TMAZ could be found on the advancing side (AS) in both the BT/C-FSW joints. This phenomenon is attributed to the intense plastic deformation and material flow during welding [3,25]. It is noticed that zig-zag lines (“S” lines) or joint line remnants (JLR) are quite evident in the centre of the joints, especially for BT-FSW joints. For the C-FSW joints, they are inclined to the AS.

The cross-sectional microstructures of the BT-FSW and C-FSW joints at various welding speeds are presented in Fig. 3. Fig. 3a–d shows the changing tendency when increasing the welding speed of the BT-FSW joints, and Fig. 3e–h shows the C-FSW joints. JLRs can also be observed in the centre of the weld, and, with increase of the welding speed, the profiles of the NZ and JLRs become indistinct at high welding speed

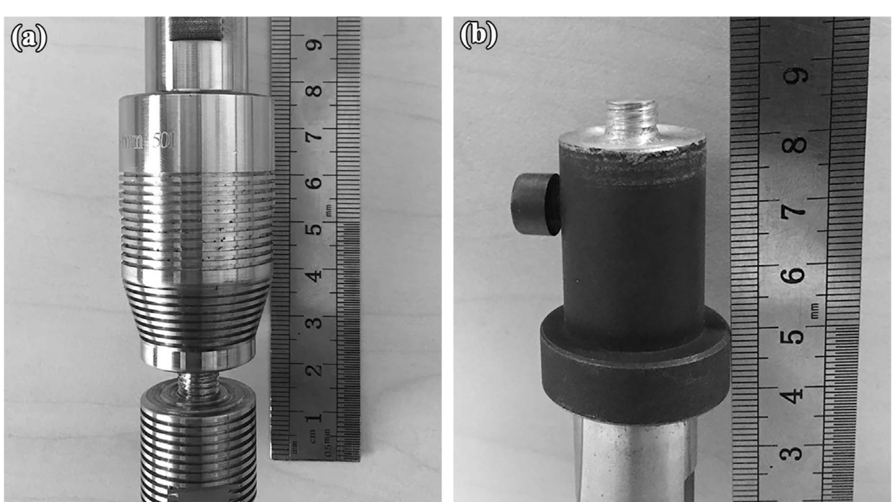

Fig. 1. Picture of weldng tools: (a) bobbin tool; (b) conventional tool.