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Microstructure and mechanical properties of dissimilar friction stir welding of 6061-to-7050 aluminum alloys

R.I. Rodriguez [a], J.B. Jordon [a,*], P.G. Allison [a], T. Rushing [b], L. Garcia [b]

[a] The University of Alabama, Dept. of Mechanical Engineering, Tuscaloosa, AL 35487, USA
[b] Engineering Research and Development Center, Army Corp of Engineers, Vicksburg, MS 39180, USA

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ABSTRACT

In this work, the microstructure and mechanical properties of friction stir welded dissimilar butt joints of 6061-to-7050 aluminum alloys were evaluated. Microstructure analysis of the cross-section of the joints revealed distinct lamellar bands and various degrees of intermixing that were correlated with tool rotational speed. Due to the distinct mechanical properties of the two alloys, microhardness measurements showed a consistent asymmetric hardness distribution profile across the weld nugget, regardless of tool rotational speed. Under monotonic tensile loading, an increase in the joint strength was observed with the increase in the tool rotational speed. Regarding fracture, the joints consistently failed on the 6061 aluminum alloy side. Furthermore, two modes of failure were observed, one through the stir zone and the other through the heat-affected zone. Inspection of the fracture surfaces suggested that inadequate material intermixing produced at low tool rotational speeds was the cause for the low mechanical strength and failure through the stir zone. On the other hand, the failure observed through the heat-affected zone at high rotational speeds was produced due to the material softening as confirmed by the microhardness measurements.

1. Introduction

Due to their high strength-to-weight ratio, good machinability, and high resistance to corrosion [1], aluminum alloys are an attractive lightweight metals for structural applications in the aerospace, automotive, and naval industry. However, the joining of Al alloys by conventional fusion welding techniques is known to be problematic [2], where some of these issues include the formation of secondary brittle phases, cracking during solidification, high distortion, and residual stresses [2].

Among aluminum alloys, the heat treatable 6XXX Al–Mg–Si and 7XXX Al–Mg–Zn systems [1] are some of the most widely advanced and used alloys. The AA6061 class have been extensively employed in marine frames, pipelines, storage tanks and aircrafts [3]. On the other hand, the AA7050 alloy is widely used in the aerospace industry and is known to have an improved toughness and corrosion resistance when compared to other alloys from 7XXX series [4]. The strengthening of these alloys is achieved by producing hard nanosized Mg-rich precipitates via solution heat treatment, and subsequent artificial aging [5–9]. Although the AA6061 alloy can be joined by conventional fusion welding, the AA7050 alloy is considered to be "unweldable" by these methods [9]. However, multiple studies have demonstrated the effectiveness of friction stir welding (FSW) for the joining of the AA6061 [7,10–13] and the AA7050 [14–17].

While FSW has been successfully demonstrated for joining similar aluminum alloys [18–21], particular interest has been established on the research and development of joining dissimilar metals [22,23]. Recent studies have been conducted in the dissimilar FSW of AA6061-to-AA7075 [24], AA2024-to-AA6061 Al alloys [25] and others [25–30], however, to the best of the authors' knowledge, this is the first study to investigate the joining of AA6061-to-AA7050 aluminum alloy with FSW.

2. Materials and methods

Butt friction stir welds were produced using 5 mm thick rolled plates of AA6061-T6 and AA7050-T7451. The nominal composition and mechanical properties for each material is summarized in Table 1. The aluminum alloys were welded at three different tool rotational speeds were evaluated (270, 340, and 410 rpm), while the welding transverse speed was fixed to 114 mm/min. It is noted that the welding parameters chosen in this study were similar to studies reported elsewhere [23,24,31–33]. A cylindrical threaded

* Corresponding author.
E-mail address: bjordon@eng.ua.edu (J.B. Jordon).

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Table 1
Nominal composition and mechanical properties for AA6061-T6 and AA7050-T7451 plates.

Material	Al	Si	Cu	Mg	Cr	Zn	UTS (MPa)	YS (MPa)	Elongation (%)
AA6061-T6	Bal.	0.6	0.3	1.0	0.2	–	310	275	15
AA7050-T7451	Bal.	–	2.3	2.2	–	6.2	524	469	11

tool, having a pin and shoulder diameter of 10 mm and 18 mm respectively, was used for this study. The butt friction stir welding was performed parallel to the rolling direction of the plates, and by placing the AA7050-T7451 on the advancing side. After the welding was completed, the top and bottom surfaces of the welded plates were machined down to a 4 mm of thickness. This was done to eliminate the stress raisers produced due to the flash material at the top of the weld. Flash material is produced on top of the welded plates due to the direct interaction of the tool shoulder and the underneath material that is been extruded and stirred around the pin. Afterwards, specimens for microstructural and mechanical characterization were cut perpendicular to the welding direction by using a water jet cutting. A schematic representation of the preparation of the samples is presented in Fig. 1. Microstructural characterization of the welds was carried out using optical (OM) and scanning electron microscopy (SEM), and energy dispersive X-ray spectrometry (EDS). The transverse and longitudinal sections of the welds were prepared using conventional metallographic techniques. All samples were etched for 60 s in a solution consisting of 1 g NaCl and 50 mL H_3PO_4 dissolved in 125 mL of ethanol, followed by a 5 s step using Wecks's tint (4 g of $KMnO_4$ and 1 g of NaOH dissolved in 100 ml of distilled water). Vickers microhardness measurements were performed in the transverse cross section of the FSWed samples using 0.5 mm spacing, a load of 100 gf and a dwell time of 5 s.

To characterize the mechanical properties of the welds, monotonic tensile testing was performed on the FSWed coupons at room temperature using a servo-hydraulic load frame. The testing was performed in displacement control mode at a rate of 1 mm/min using a 25.4 mm extensometer. Samples were prepared following the ASTM E8, having a width of 6 mm and a gage length of 50.8 mm, the overall dimensions of the samples are specified on Fig. 1. A total of 9 samples, 3 per condition, were tested.

3. Results and discussion

The transverse (X–Y) sections of the joints produced at different tool rotational speeds are shown on Fig. 2. As stated earlier, the AA7050 was positioned on the advancing side (right hand side), while the AA6061 was placed on the opposite or rather the retreating side. Due to the differences in etching response, AA6061 is shown as the bright colored regions, whereas the AA7050 is shown as the dark colored regions. No void defects were noticeable from the traverse sections in any of the tested parameters. Three main regions can be distinguished on the transverse sections, corresponding to the stir zone (SZ), the thermo mechanical affected zone (TMAZ), and the heat affected zone (HAZ). The SZ features vortex structures, that consists of alternate lamella of material corresponding to the base alloys and a mixture of both. Further examination using EDS confirmed the presence of three (3) distinct layers (Fig. 3). Locations A and B consisted of the nominal composition for the AA6061 and AA7050 respectively, while location C consisted of a combination of both materials. Similar results have been demonstrated on dissimilar AA6061-AA7075 FSW [24]. The formation of the bands corresponding to the composition of Location C, have been attributed to the plasticized material constrained in the features associated with the tool geometry. As such, a fraction of the material is trapped in the features of the tool and subjected to extended deformation periods, allowing the material to be intermixed before being deposited in the SZ.

The formation of vortex structures or "onion rings" is typical of FSW, but is exaggerated in the welding of dissimilar metals [22]. These lamellar structures are attributed to the stirring action of the threaded tool, the in-situ extrusion, and to the transverse motion in the welding direction [23]. In fact, the thickness of the bands of unmixed material was also modified as the tool rotational speed was increased in the dissimilar welding of AA6061-to-AA7050. Microstructural examination of the longitudinal sections revealed that the spacing between the material bands decreased with the increasing tool rotational speed. Average values for the material bands interspacing of 460, 350 and 300 μm were obtained for a tool speed of 270, 340 and 410 rpm respectively. This implies that a more uniform mechanical mixing was achieved at higher tool rotational speeds.

For the current study, the aim was to demonstrate the effectiveness of FSW on the joining of AA6061 to AA7050, therefore, the location of the materials with respect to the tool rotation was not investigated. While not the aim of this study, several studies

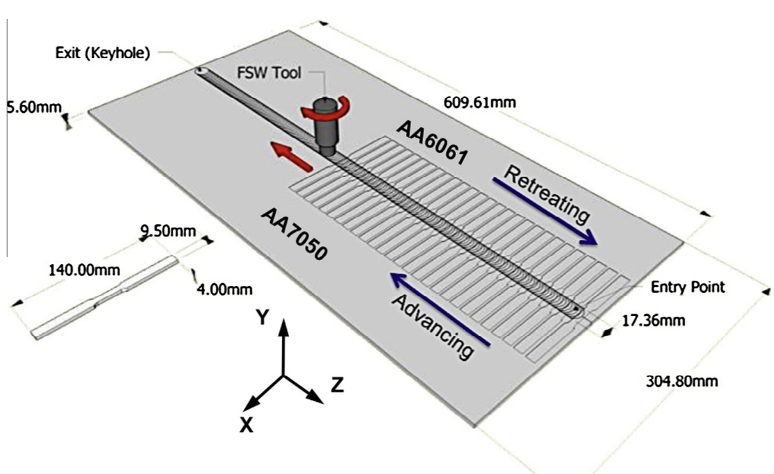

Fig. 1. Schematic representation of the dissimilar AA6061-AA7050 FSW. The welds were carried out parallel to the rolling direction of the plates, and by placing the AA7050 alloy on the advancing side. Tensile test coupons were cut perpendicular to the welding direction.