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EFFECT OF WELDING PARAMETERS ON THE MECHANICAL PROPERTIES OF FRICTION-STIR-WELDED HEAT-TREATABLE AA6061-T6

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Abstract. The effect of welding parameters on the mechanical properties of the friction stir welding of heat-treatable 6061-T6 was experimentally investigated. The influence of the welding rates on the hardness, tensile strength, bending strength, and the impact energy of the welding was investigated. The alloy 6061 could be welded with free defects. The mechanical properties were sensitive to the welding regimes and the location in and around the welded zone. Both the tensile and bending strengths of the joint were quite low compared to those of the base alloy 6061. The bending ductility of the joints was improved significantly. While the impact resistance around the welded zone was higher than that of the base alloy, the impact resistance at the weld center was remarkably low.

Keywords: friction stir welding AA6061-T6, hardness, tensile strength, bending strength, impact energy.

Classification numbers: 2.9.1, 5.1.4.

1. INTRODUCTION

With high specific strength, aluminum alloys have been applied spreadly in high-speed industry. One of the obstacles in using the high strength aluminum alloys associating with joining them by welding [1]. Friction stir welding (FSW), invented by The Welding Institute (TWI) in 1991, has been emerging as a key technology for welding alloys previously regarded as unweldable [2 - 3]. In the friction stir welding process, the material in the welded zone is heated and plasticized by friction process induced by the kinetic friction at the contact surface between the rotated non-consumable tool and the workpieces. The friction stir welding process is a thermo-mechanical plastic deformation in which the microstructure is dramatically recrystallized. As a result, the welded zone possesses several microstructure features and mechanical properties [4 - 9]. Aluminum alloy 6061 (named AA6061) is a heat-treatable aluminum alloy and is widely applied for transportation facilities. The mechanical properties of the welded joints of this aluminum alloys need to be explored clearly to expand the application. Recently, the friction stir welding of both the similar AA6061 and dissimilar AA6061 with other aluminum alloys are addressed [10 - 11]. This work aim is to investigate the effect of the welding rate (at a constant rotation speed) of the tool on the mechanical properties of the FSW butt-joint of AA6061-T6 plate 5.0 mm thickness.

2. MATERIALS AND EXPERIMENTS

The 5.0 mm AA6061-T6 plates were joined by friction stir welding technique in the Friction Welding Lab of Nha Trang University. Table 1&2 showed the properties of the aluminum alloy 6061. The tool geometry used in this FSW is a 20 mm shoulder diameter, a truncated cone pin with the screw pitch of 1.0 mm in which the pin diameter at the middle pin length is 5 mm. The tool shoulder is 20.0 mm in diameter. The pin is aligned at a tilt angle of 2.0^o. The FSW joints were fabricated with several welding speed rates (denoted *WSR*). The attention was put on the effect of the tool welding speed. The tool rotation was kept constant at 600 rpm, and other parameters were kept constant. After being fabricated, the cross-section of the welding was polished and etched to observe the defects and grain microstructure with a solution of 150 ml H_2O, 3 ml HNO_3, 6 ml HCl and 6 ml HF. The defects and microstructure were observed by a high magnification microscope, using a microscope combined with a magnification computer connector. The hardness was measured by a diamond indentation with 50 g loading with 10 seconds of hold time. The tensile and bending strengths of the FSW 6061-T6 were measured by the 5.0 mm thickness plate specimens. The specimens were machined in which the loading direction was perpendicular to the weld direction of the FSW plate as shown in Figure 1. The tensile and bending specimen geometries were determined by ASTM- E08 and ASTM-E290, respectively. The tensile and bending tests were performed by the Instron 3366 machine at 10^{-3}/s constant strain rate. The impact tests were performed by the impact-machine IT406M. The impact specimen geometry was determined by ASTM-E023.

Table 1. The chemical composition of AA6061 aluminum alloy [12].

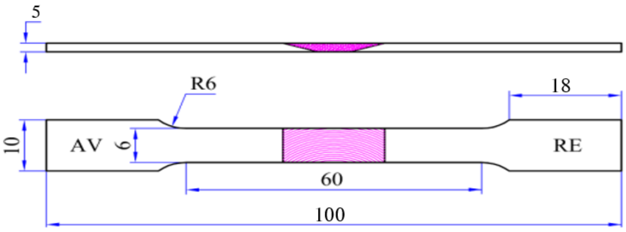
Element	Al	Mg	Cr	Cu	Si	Zn	Mn	Ti
Percentage (%)	Bal.	0.85	0.06	0.22	0.68	0.07	0.32	0.05

3. RESULTS AND DISCUSSION

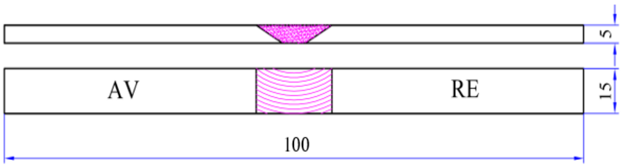
Many welding speed rates were performed for fabricating the joints to study the effect of the welding regimes on the mechanical properties of the FSW joint of aluminum 6061-T6. The welding process and the fabricated plate of FSW AA6061-T6 are shown in Figure 1(d). Figure 2 showed a typical microstructure of the FSW 6061-T6 (fabricated at *WSR* = 2.0 rev/mm). Here the microstructure in the welded zone was recrystallized dramatically. In general, the grain sizes in the stirred zone (about 20 μm) was quite fine in comparison to that of the base alloy (about 80 μm), see region III and region I in Figure 2.

The hardness distributions measured at the middle-line in the cross-sections are shown in Figure 3 as a function of the welding parameter, *WSR*. In general, a significantly softened feature in and around the welded zone is observed in all FSWs. The softening appearing in and around the welded zone could be related to the dissolution and/or coarsening of precipitates in this alloy [1]. It was also found that, in all cases, the lowest hardness in the cross-section of the FSW is placed on the heat-affected zone (HAZ) in the advancing side and/or retreating side, outside the stirred zone (see Figure 3). The fact that the hardness in the stirred zone is higher than that in HAZ might be associated with a high density of grain boundaries in the stirred zone or Hall Petch effect [13].

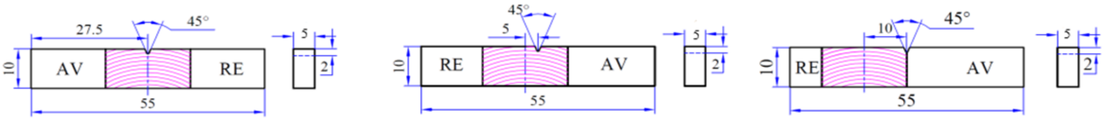
The measurement of the tensile strength of the FSW 6061-T6 was carried out by the Instron 3366 machine at a constant strain rate of 10^{-3}/s using of the specimen shown in Figure 1.



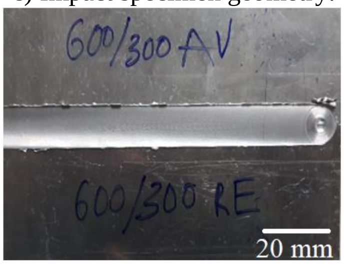
a) Tensile specimen geometry.



b) Bending specimen geometry.



c) Impact specimen geometry.



d) The fabricated FSW plate AA6061.

Figure 1. Geometries of the experimental specimens used in the work and the FSW 6061 plate.

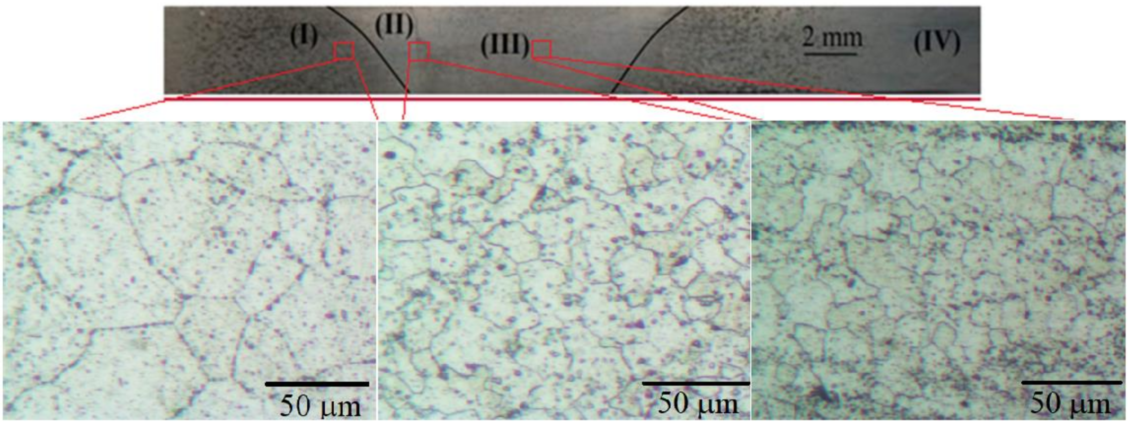


Figure 2. Microstructure in the cross-section of FSW fabricated at *WSR* of 2.0 rev/mm.

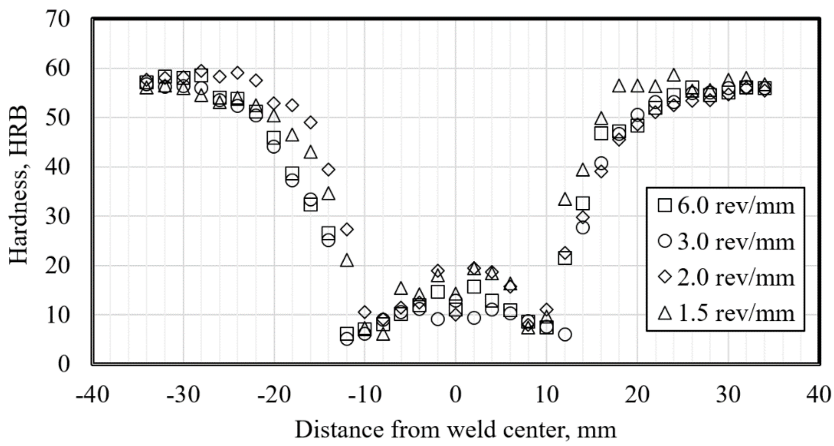


Figure 3. Hardness distribution across the welding cross-section (measured at the middle line).

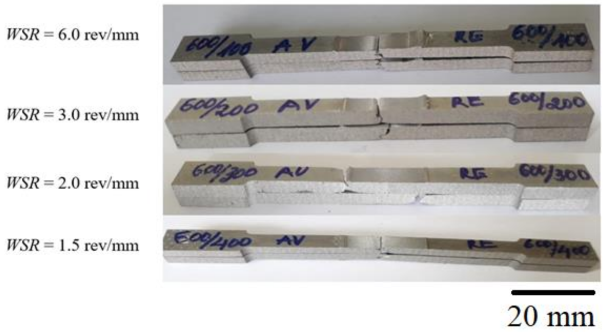


Figure 4. Tensile failures in the FSW under various welding regimes.

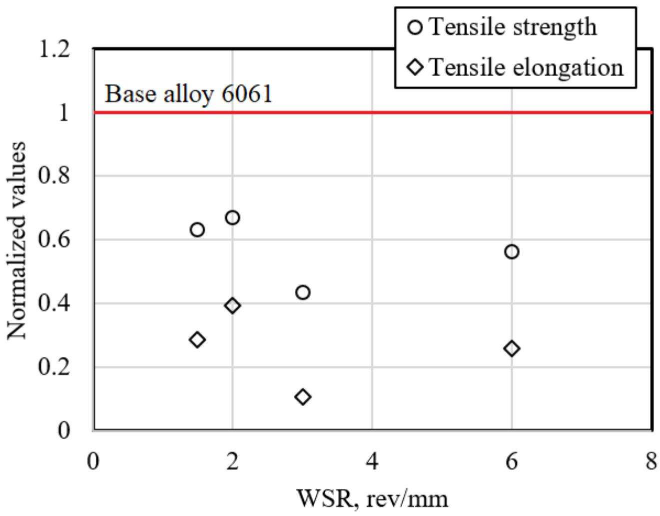


Figure 5. Tensile properties of the FSW under various welding regimes
(the tensile strength of the joint was normalized to that of base alloy 6061).

The tensile failures of all FSW specimens took place in the stirred zone or in the HAZ (on the advancing side or on the retreating side) as seen in Figure 4. All specimens fractured in the stirred zone were induced by the tunnel defects there. The tensile strength of the joint was presented in Figure 5. In the regime, *WSR* of 2.0 rev/mm, the defects were eliminated and the tensile specimens were fractured outside the stirred zone, in the HAZ. It can be seen in Figures 3&4 that the tensile fracture locations were taken place in the HAZ in the advancing (AV) side where the lowest hardness in the joint. The lowest hardness location and the lowest tensile strength in the joint is well agreed and reasonable in this case.

The results of the bending test for both the base alloy and the welded specimens were shown in Figure 6. Almost all the bending specimens were cracked and initiated at the bottom line defects of the joint as seen in Figure 6. The joint seems to be successfully fabricated at *WSR* = 2.0 rev/mm, here the joint was bent with no crack (Figure 6). The bending strength of the joint was lower than that of the base alloy. The maximum strength of the welding is about 75 % of that of base alloy 6061 (Figure 7). The reduction of the bending strength might concern the low hardness in the welded zone. However, interestingly, the bending ductility of the welded joint was improved significantly compared to that of base alloy 6061 (Figure 7). This enhanced ductility of bending might associate with the refined microstructure in the welded zone.

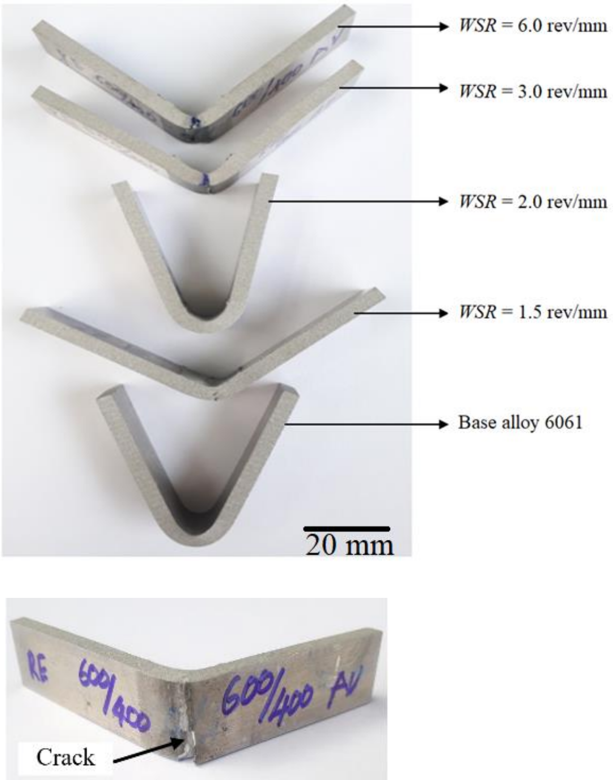


Figure 6. Bending failures in the FSW under various welding regimes.

The impact resistance of the joint was quite sensitive to the location in the welding as seen in Figure 8. Here, at the weld center location of the joint, the impact resistance of the welding was remarkably low in comparison to that of the base alloy. In the heat-affected zone and the thermo-mechanical zone (5.0 mm away from the weld center), the impact resistance of the joint was remarkably higher than that of the base alloy 6061 (Figure 8). The fluctuation of the impact resistance at different locations across the welding might associate with the change of ductility across the joint. The lower impact energy took place at the weld center with all welding regimes might concern the tunnel defects and kissing bond in this area. However, at the welding regime with 2.0 rev/mm, where the defects seem completely eliminated, the impact energy at the weld center still lower than that of base alloy 6061. This strange phenomenon will be clarified in the next works.

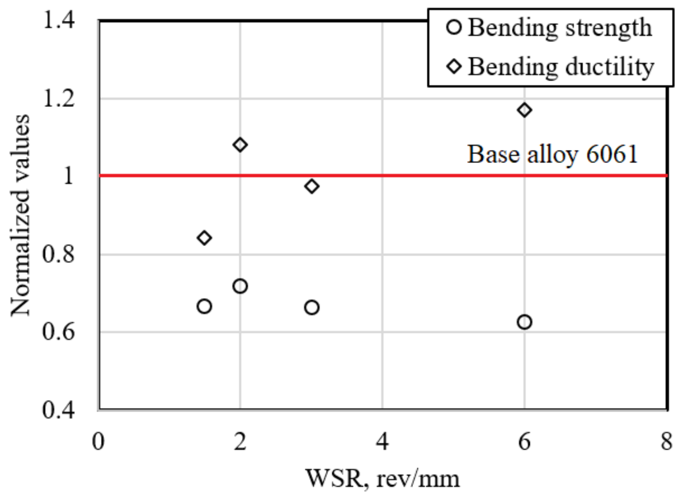


Figure 7. Bending properties of the FSW under various welding regimes
(the bending strength of the joint was normalized to that of base alloy 6061).

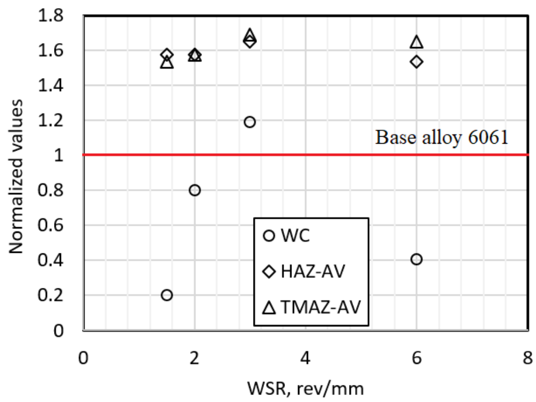


Figure 8. Impact energy at various locations in the FSW (at weld center (WC), at 5 mm away from weld center (TMAZ-AV), at 10 mm away from weld center (HAZ-AV).

4. CONCLUSIONS

The FSW of aluminum alloy 6061-T6 was fabricated and the effect of welding rates on its hardness, tensile strength, bending strength, and impact resistance of the joint were evaluated. The joint was softened significantly in and around the welded zone. In tensile and bending tests, almost all of the joints were fractured in the welded zone. Only at the welding regime, *WSR* = 2.0 rev/mm, the joint was fractured outside the welded zone for both tensile and bending tests. Both tensile and bending strength of the joint in all welding regimes were quite lower than those of the base alloy 6061. The highest tensile strength and bending strength of the joint were about 65 % and 72 % of those of base alloy. The impact resistance was significantly sensitive to the location across the welding. Generally, the impact resistance of the joint was higher than that of the base alloy. At the weld center, the impact resistance of the welding was quite low compared to that of the base alloy.

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