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Effect of Welding Parameters on Microstructure and Tensile Properties of Friction Stir Welded 6061 AL Joints

A.H. Feng[1], D.L. Chen[1,a] and Z.Y. Ma[2]

[1] Department of Mechanical and Industrial Engineering, Ryerson University, 350 Victoria Street, Toronto, Ontario M5B 2K3, Canada

[2] Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, 72 Wenhua Road, Shenyang 110016, China

[a] dchen@ryerson.ca

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Abstract

The present investigation is aimed at evaluating the influence of tool rotation rate and welding speed on the microstructure, tensile properties, and fracture mode of 6061 Al-T651 alloy after friction stir welding (FSW). TEM results revealed that in the nugget zone (NZ), FSW resulted in the dissolution of fine needle-shaped precipitates that previously existed in the base metal. At a given rotation rate of 1400rpm, the yield strength (YS) and ultimate tensile strength (UTS) of the welded joints increased with increasing welding speed from 200 to 600mm/min. However, the UTS of the joints was nearly independent of the rotation rate. Furthermore, the relationship between the hardness distribution and fracture location has also been identified.

Introduction

FSW, invented at The Welding Institute (TWI) of the UK in 1991 [1], is a relatively new solid state joining process capable of welding lightweight materials, such as Al and Mg alloys which are relatively difficult to weld using conventional fusion welding techniques [2]. A lot of studies on the FSW of Al alloys have been reported, with emphasis on the effect of FSW parameters on the precipitation sequence [3,4], texture [5], and mechanical properties [6-8]. In the precipitation-hardened Al alloys, FSW results in a softened region in the heat-affected zone (HAZ), which is basically characterized by the dissolution/coarsening of precipitates during the FSW thermal cycle [4,5,9]. It was also reported that the tensile fracture path of the welds corresponds to the lowest hardness zones [7,8]. However, some inconsistent results were reported in the literature. For example, the FSW parameters have been reported to have a significant effect on the tensile properties and fracture locations, while others presented that the yield and ultimate tensile strength were affected only to a significantly lesser degree. Further studies on the effect of the FSW parameters on the deformation characteristics and fracture mechanisms are needed.

Experimental Procedure

Commercial 6061Al-T651 plates (400mm long, 80mm wide, and 6.2mm thick) were FSWed along the rolling direction using a FSW machine (China FSW Center). A steel tool with a shoulder of Φ16 mm and a threaded pin of Φ6mm was used. The tool rotation rates were from 600 to 1400rpm, and the welding speeds were from 200 to 600mm/min.

The microstructure was examined using transmission electron microscopy (TEM). Φ3 mm TEM foils were prepared by twin-jet electropolishing using a solution of 70pct methanol and 30pct nitric at -35°C and 19V. Vickers microhardness distribution maps were measured on the cross-section perpendicular to the welding direction using an computerized Buehler hardness testing under a load of 300g for 15s. A total of seven test lines was measured through the cross section at an interval of 0.5mm. Subsized tensile specimens following ASTM E8 standard, with a gauge section of 25mm ×

6mm × 5mm, were machined perpendicular to the FSW direction. Room temperature tensile tests were carried out at a strain rate of 1×10^{-3} s^{-1} on a computerized United tensile testing machine.

Results and Discussion

As-received 6061Al-T651 base metal (BM) consisted of large, elongated, pancake-shaped grains typical of a hot-rolled structure [6]. A considerable amount of coarse dispersoids was randomly distributed both within grains and at grain boundaries (Figure 1(a)). A high density of fine needle-shaped precipitates (Mg_2Si, β'') were observed in the BM under a high magnification (Figure 1(b)). After FSW, the NZ is characterized by fine and equiaxed recrystallized grain structure (Figure 1(c)). No fine needle-shaped precipitates (β'') were observed via TEM examinations even under high magnifications. Thus FSW resulted in the dissolution of β'' precipitates. Similar results have also been observed in FSWed 6063Al joints [9,10]. However, the coarse dispersoids were still seen in the NZ.

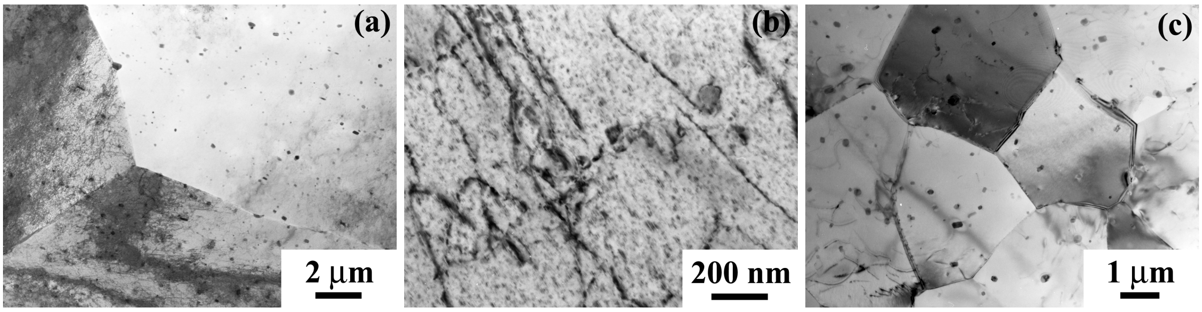

Figure 1. TEM images of FSWed 6061Al-T651 alloy (1400 rpm-600 mm/min): (a) and (b) BM, (c) NZ.

As shown in the hardness maps (Figure 2), two issues are worth noting. First, two low hardness zones (LHZs), located at the boundary between the thermomechanically affected zone (TMAZ) and HAZ, were obviously observed due to precipitate overaging [6], crystallographic texture [10], and grain/subgrain structure [11]. The location of LHZs changed and the width of the LHZs increased with decreasing welding speed from 600 to 200mm/min. The asymmetry of the weld was noticeable between the advancing side (AS) and retreating side (RS). A similar result has also been observed in FSWed 2519Al-T87 alloy [11]. Second, the hardness profile greatly depended on the precipitate distribution and only slightly on the grain size (Figures 1 and 2), as also reported in [9]. The precipitate distribution was strongly influenced by the thermal hysteresis [9]. It is known that the precipitation sequence of the Al-Mg-Si alloys is clusters of Si atoms $\rightarrow$ GP−Ⅰ zones $\rightarrow$ GP−Ⅱ zones/needle-shaped precipitate (β'') $\rightarrow$ rod-shaped precipitates (β') $\rightarrow \beta$-Mg_2Si [12]. The β'' precipitate is associated with the peak-aged condition. Based on the DSC results, the β'' and β' dissolution/precipitation peaks were identified to be ~250°C and ~300°C, respectively [13,14]. Therefore, the thermal cycle above 250°C resulted in the dissolution of the needle-shaped precipitates in the Al-Mg-Si alloy [9]. LHZs, characterized by a low density of β' precipitates, experienced approximately the same peak temperature of 360°C to 370°C with various durations [6]. Indeed, the highest temperature occurred at the center of the NZ [15]. While the high temperature in the NZ led to the dissolution of β'', the stronger solid solution strengthening and smaller grain size due to dynamic recrystallization during FSW gave rise to the slightly higher hardness in the NZ, compared with the LHZs.

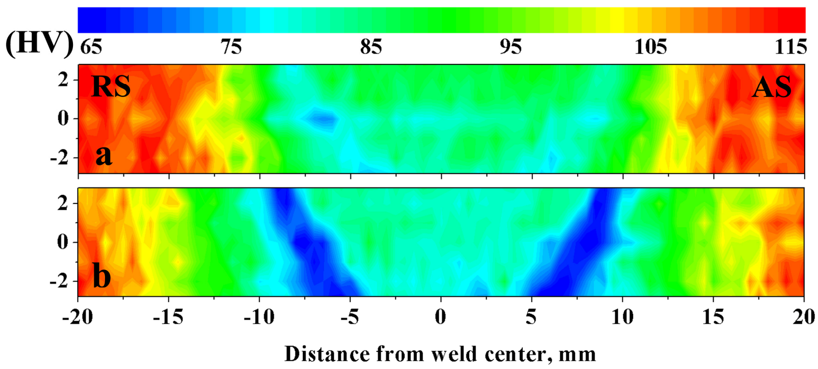

Figure 2. Microhardness contour maps for the FSWed 6061Al-T651 joints: (a) 1400 rpm-600 mm/min, (b) 1400 rpm-200 mm/min.

As shown Figure 3, at a given rotation rate of 1400rpm, YS and UTS increased with increasing welding speed from 200 to 600mm/min (Figure 3(a)). However, the tensile strength was nearly independent of the rotation rate (Figure 3(b)). The obtained results are in good agreement with those reported in the literature [6,8]. Figure 4 shows the failed tensile specimens. The shear fracture paths after FSW were about 52° and 58° to the tensile axis, respectively (Figure 4(b) and 4(c)). The results indicated that the FSWed 6061Al-T651 joints failed roughly along the LHZs.

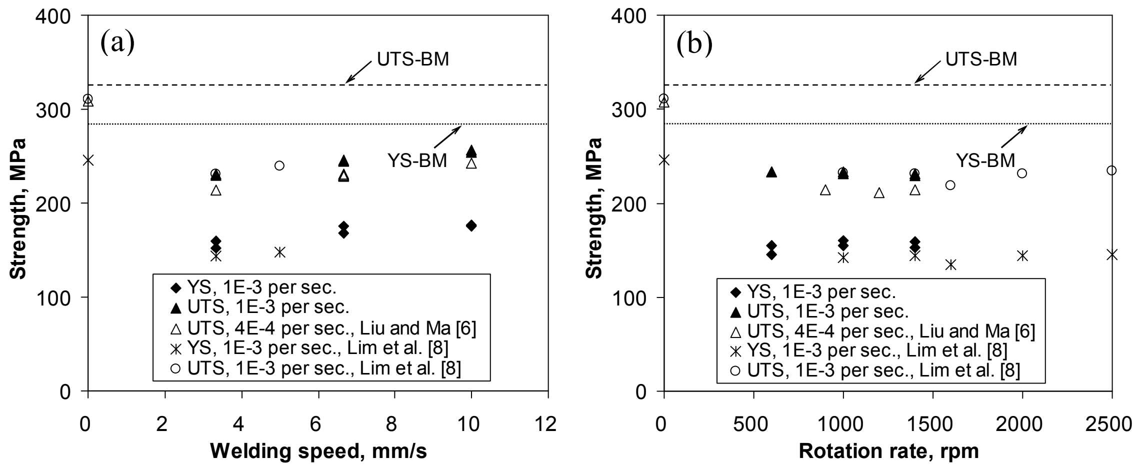

Figure 3. Tensile strength of FSWed 6061Al-T651 joints: (a) strength vs. welding speed, (b) strength vs. rotation rate.

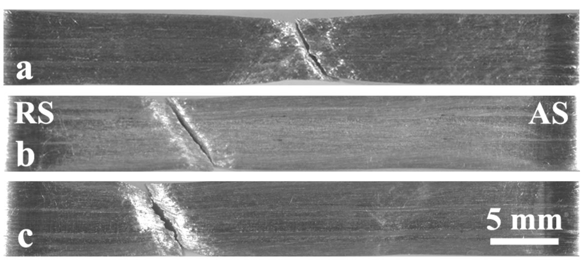

Figure 4. Appearance of failed FSWed 6061Al-T651 joints: (a) BM, (b) 1400 rpm-600 mm/min, (c) 1400 rpm-200 mm/min.

Conclusions

The NZ was characterized by fine and equiaxed recrystallized grains and uniformly-distributed coarse dispersoids. FSW resulted in the dissolution of the fine needle-shaped precipitates that previously existed in the BM. The tensile strength of the FSWed 6061Al-T651 joints increased with increasing welding speed, while it was basically independent of the rotation rate. The hardness contour results indicated that the tensile fracture path of the joints corresponded to the LHZs.

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