Effects of Post-weld Heat Treatment on Microstructure and Mechanical Behavior of Friction Stir Welded Thick Section Al–Zn–Mg–Cu Alloy

T. Ramakrishna, S. Srinivasa Rao and G. Swami Naidu

Abstract Friction stir welding is considered to be a promising solution to successfully join high strength 7000 series aluminum alloys. However, questions related to a decrease in weld mechanical properties with an increase in plate thickness still remain unanswered. In this study, 16 mm thick AA7075–T651 aluminum alloy plates were successfully joined by friction stir welding. The welds were heat treated using a special solutionizing method called cyclic solution treatment (CST). The effects of CST on mechanical behavior and microstructures of the welds were studied using hardness, tensile, and impact tests and optical microscopy. The post-weld heat treatment significantly improves the hardness of the joint and homogenizes the hardness distribution across the welded joint. However, the tensile properties and impact toughness of the welds were not found to be beneficially affected. A significant grain growth in the weld nugget was observed after CST.

Keywords Friction stir welding · Thick sectional Al alloy · Post-weld heat treatment · Mechanical properties · Microstructures

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A. Prasad et al. (eds.), *Advances in Engineering Design*,
Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-13-6469-3_3

1 Introduction

Heat-treatable aluminum alloys such as alloy 7075 with favorable strength to weight ratios are widely used in aerospace industries [1]. However, the structural applications of these alloys inevitably include welding and it is considered difficult using conventional fusion welding processes. Friction stir welding (FSW), a solid-state process invented at The Welding Institute (TWI), is an alternate solution for joining aluminum alloys [2] since it offers many benefits over conventional joining methods. It is involved with lower heat during the process, no melting, low defects, and low distortion [3–5]. Though there is a quite a bit of research already reported on joining of AA7075 using friction stir welding in the literature [6–10], many questions on the poor mechanical behavior of the welded joint still remain unanswered [11, 12].

In the recent past, there have been some efforts made to improve the mechanical properties of friction stir welded joints by changing tool geometry and welding parameters [13, 14]. Among the various techniques, post-weld heat treatment (PWHT) is found to be the most appropriate method for restoring degraded mechanical properties of the welds [15, 16]. Feng et al. [15] investigated the effect of solutionizing temperature on the tensile strength of the weld. Priya et al. [16] reported that direct aging of friction stir welded 2219 and 6061-T6 alloys at 165 °C for 18 h without solution treatment improves the hardness of weld nugget while it does not cause hardness recovery in the other zones of weld region.

There are very few works reported on PWHT of friction stir welded AA7075 [17–21]. Barcelona et al. [17] reported that PWHT leads to a uniform distribution of precipitate particles in various zones of the weld. The PWHT was also found to cause a recovery in the strength of the joint and abnormal grain growth (AGG) in the weld region [18]. However, Mahoney et al. [19] realized that direct post-weld aging without solution treatment does not exhibit a useful effect on the yield strength of 7075-T651 weld. The solution treatment followed by aging was found to marginally improve the tensile properties of the welds [20]. Yeni et al. [21] also concluded that the post-weld aging increases the hardness across the weld. More recently, a new technique for heat treating high strength aluminum alloys has been devised based on cyclic solution treatment (CST) followed by artificial aging [22]. The beneficial effect of CST on mechanical properties of 7075 aluminum alloys has been earlier reported [23]. Furthermore, the effects of CST and artificial aging on mechanical properties of friction stir welded joints have been studied by Bayazid et al. [24].

Most of the above studies have been carried out on the plates with a thickness ranging from 3 to 8 mm and in the majority of the cases positive effect of PWHT on friction stir welded Al alloy plates is very well established. However, the same has not been investigated on the welds with a plate thickness 10 mm and more. An unpublished work carried out very recently by the present authors on 10 mm thick friction stir welds revealed that the rightly selected post-weld heat treatments improve mechanical properties of the friction stir weld. In fact, as the thickness of the plates to be welded increases, the reductions in mechanical properties increase. Hence, it is of prime interest to investigate that the loss in mechanical properties of friction stir welded thick section AA7075–T651 Al alloy can be recovered by PWHT. In this study, the possibility of restoring mechanical properties of 16 mm thick AA7075–T651 friction stir welds using cyclic solution treatment has been investigated.

2 Experimental Procedure

Friction stir welding trials were carried out on 16 mm thick plates of AA7075–T651 aluminum alloy. The chemical composition of the alloy is presented in Table 1. The plates were cut and machined to 110 mm width and 250 mm length coupons. The plates were longitudinally butt-welded using a friction stir welding machine. In one of the previous studies carried out on friction stir welding of 10 and 16 mm thick AA7075 plates, the 16 mm thick friction stir welded joints were developed using the process parameters given in Table 2 and they were found to be defect free [10]. Thus, the same was used in this work to produce the welds.

The post-weld heat treatments were carried out using a special solutionizing method called cyclic solution treatment (CST), a repeated heating between 400 and 480 °C for 1.5 h (0.25 h for each cycle) and water quenching (Fig. 1).

Microhardness surveys were conducted using a Vickers hardness testing machine under a load of 200 g applied for 15 s. The hardness measurements were made across the weld and at the mid-thickness of the weld cross-section with a spacing of 1 mm between adjacent indentations. Tensile specimens transverse to the welding direction were made according to ASTM B557 standard. Tensile tests were performed at room temperature using a computer-controlled universal testing machine. Weld microstructures were examined using stereo and optical microscopy. The samples were carefully prepared to the required sizes from the weld and then polished using emery papers of various grades. Final polishing was done using diamond compound (1 Âμm particle size) in a disk polishing machine. The polished samples were etched using standard Keller's reagent (5 ml HNO3, 2 ml HF, 3 ml HCL, and 190 ml distilled water) to understand the macro and microstructures of the weld.

Table 1 Chemical composition of 7075–T651 in wt%

Zn	Mg	Cu	Si	Fe	Cr	Ti	Mn	Al
6.0	2.5	1.4	0.03	0.08	0.20	0.05	0.01	Bal

Table 2 Friction stir welding process parameters

Nomenclature	Process parameter
Tool geometry	M2 tool steel Taper threaded pin (left-hand metric threads, 1.5 mm pitch) Pin diameter: 10 mm (shoulder end) and 8 mm (tip end) Pin length: 15.5 mm Shoulder diameter: 30 mm Flat shoulder
Tool rotational speed	500 rpm
Welding speed	25 mm/min
Tool tilt	1.5°

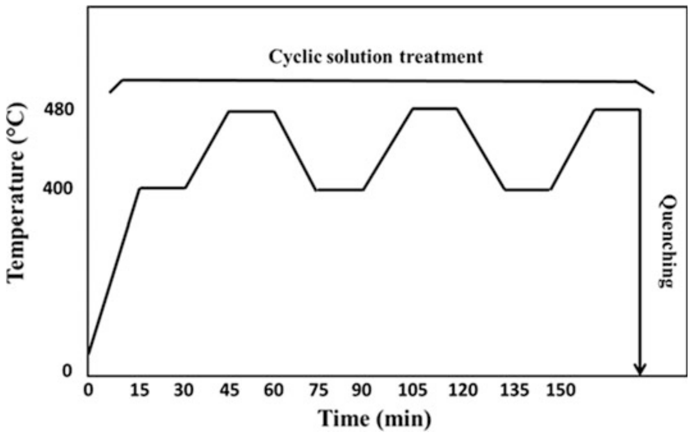

Fig. 1 Schematic illustration of cyclic solution treatment

3 Results and Discussion

3.1 Hardness Profiles

The hardness profiles of AA7075–T651 Al alloy friction stir welded joints in as-welded and cyclic solution treated (CS-treated) conditions are presented in Fig. 2. As it can be seen, the hardness of the weld region was found to be much lower across the weld zones such as weld nugget (WN), thermo-mechanically affected zone (TAMZ), and heat-affected zone (HAZ) than that of the base material. Also, the hardness measurements across the weld were found to be not homogenized exhibiting lower hardness values in the heat-affected zone and higher hardness values in the weld nugget. This happens to be a much disturbing issue in the

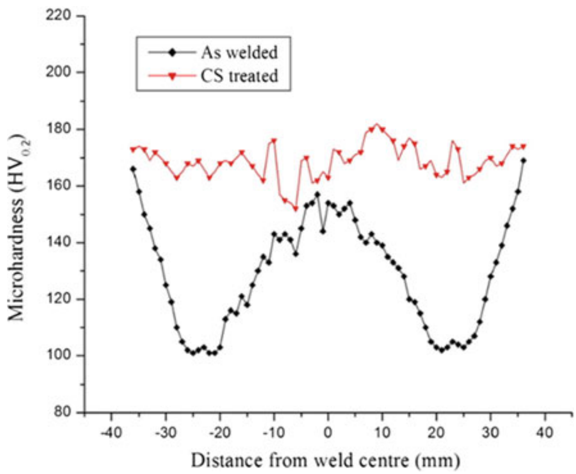

Fig. 2 Microhardness profiles of the welds in as-welded and CS-treated conditions

thick section friction stir welded high strength aluminum alloys such as AA7075–T651, as the same was also reported in previous studies [10].

The cyclic solution treatment carried out on friction stir welds was found to significantly improve the hardness across the weld. Interestingly, the CST was also found to enhance the homogeneity in hardness values across various zones of friction stir welded joint.

3.2 Tensile Properties

The results of tensile tests performed on the base material and friction stir welds, both in as-welded and cyclic solution treated condition, are presented in Table 3. Friction stir welding was found to cause reductions in the strength and elongation of the base material. Tensile fractures occurred in the heat-affected zone of the welded joint and this could be due to marginal grain growth and formation of precipitated free zones taking place in the HAZ during friction stir welding, as the same was also reported by the previous researchers [10].

The post-weld heat treatment conducted, intending to recover strength values, on the welds did not show beneficial effects on tensile properties of the joint. Particularly, the percent of elongation was adversely affected. This low elongation displayed by the welds after cyclic solution treatment can be attributed to the hardness increase in various zones of combined weld region, which do not plastically deform during the testing, thus reducing the overall elongation of the specimens. Similar statements were also made for thin section 7075 Al alloy plates in T6 condition [18]. The CS treated welds were found to fracture in WN–TMAZ interface (Fig. 3).

Table 3 Tensile properties of friction stir welds before and after post-weld heat treatment

Material	Yield strength (0.2% proof) (MPa)	Tensile strength (MPa)	% El	Joint efficiency in terms of YS	Fracture location	Impact toughness (J)
Base material	563	610	10	–	–	6.67
As-Welded	192	330	8	35	HAZ	5.5
CS treated	178	253	4	32	WN-TMAZ	5.33

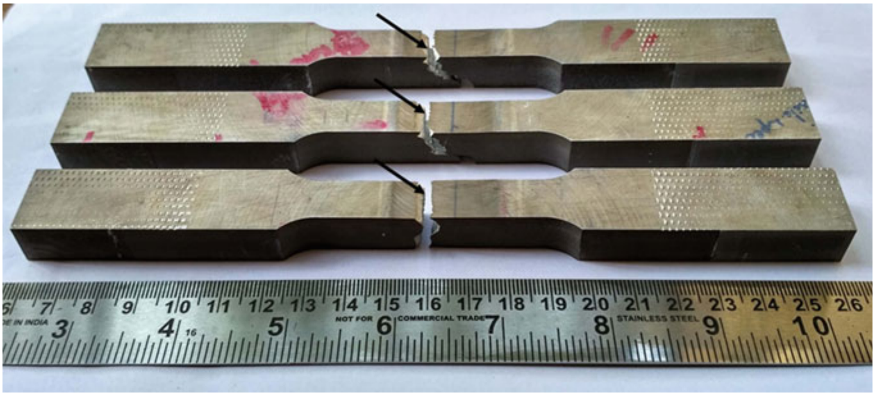

Fig. 3 Tensile-tested specimens showing fractures in WN-TMAZ interface (arrows show fracture location)

3.3 Impact Toughness

The results of the impact tests conducted on base material and the welds before and after post-weld heat treatment are presented in Table 3. The base material exhibited better impact toughness compared to the welds. The cyclic solution treatment caused a further decrease in the impact toughness of the welds. Failed impact test specimens are shown in Fig. 4.

3.4 Microstructure

The results of optical microscopy are presented in Figs. 5 and 6. The base material microstructure was characterized by pancake shaped large elongated grains, a type of hot-rolled structure (Fig. 5a). The typical TMAZ and HAZ zones of friction stir weld are shown in Fig. 5b and c. As can be observed, the transition zone between the base material and weld nugget was characterized by a highly deformed structure

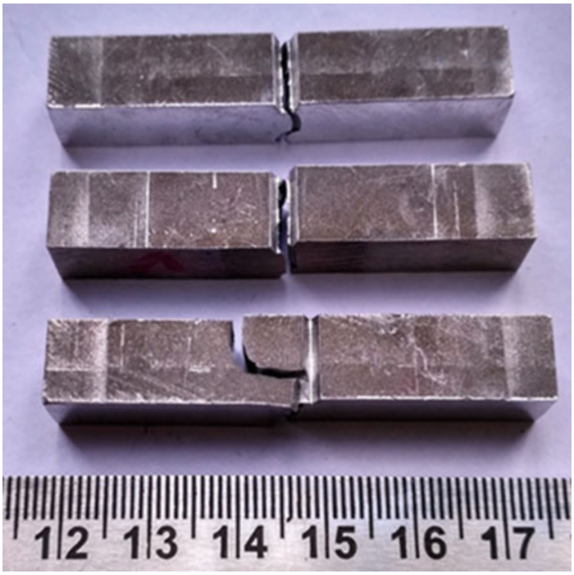

Fig. 4 Impact tested specimens of CS treated welds

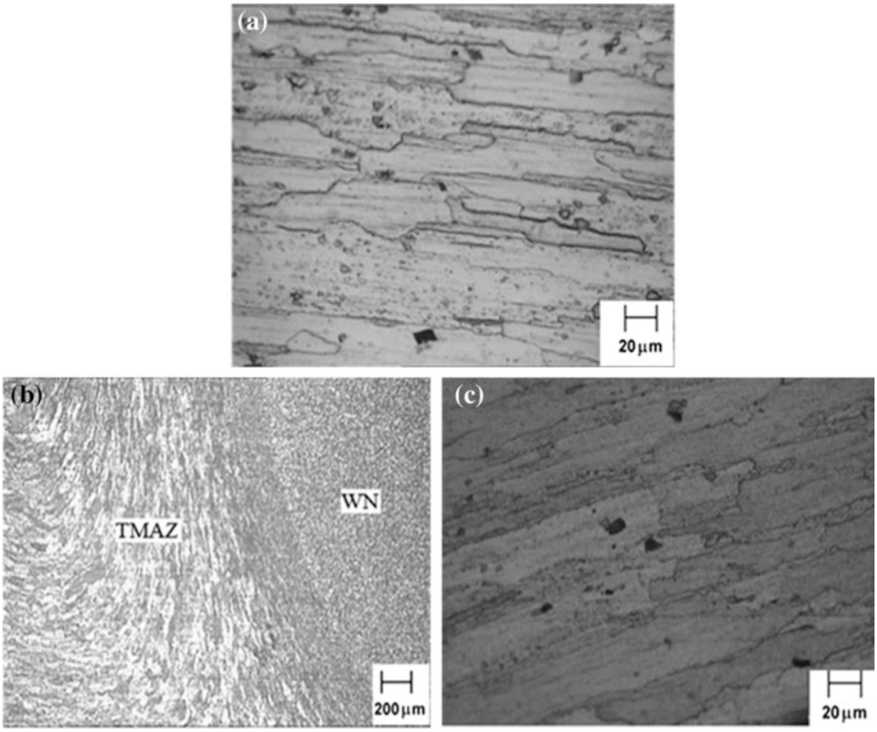

Fig. 5 Microstructures of base material and typical TMAZ and HAZ: **a** base material, **b** TMAZ, and **c** HAZ

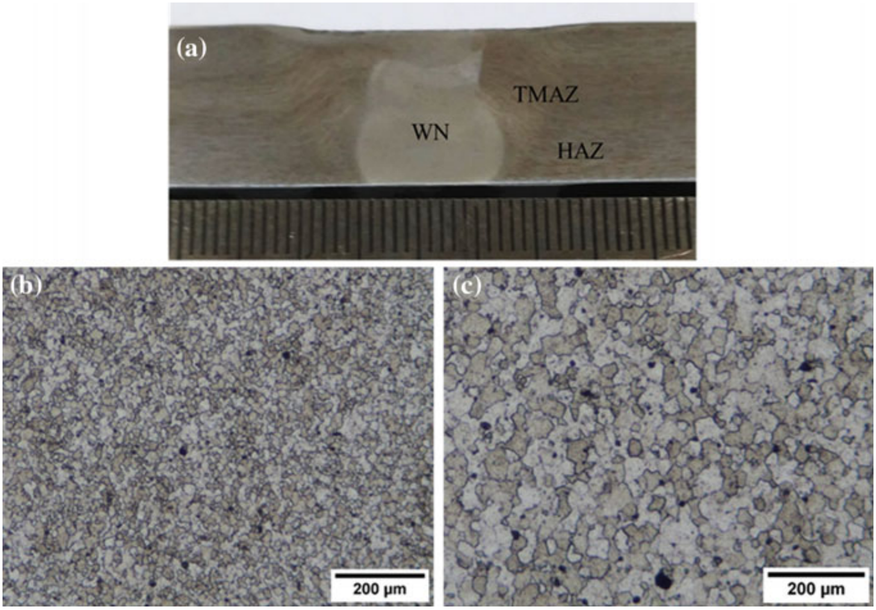

Fig. 6 Weld cross-section and weld nugget microstuctures: **a** typical macrostructure, **b** as-welded, and **c** CS-treated weld

(Fig. 5b) and the HAZ retained the same grain structure as the parent material excepting noticeable grain growth. The typical cross-sectional appearance of the friction stir weld is shown in Fig. 6a. The weld nugget microstructure of the friction stir welded joint exhibited very fine equiaxed grains (Fig. 6b) resulted from dynamic recrystallization phenomenon, that usually takes place during friction stir welding, due to severe plastic deformation and temperature rise of the welding area. The post-weld cyclic solution treatment was found to cause noticeable grain grown in the nugget zone of the weld region (Fig. 6c), usually known as (AGG) abnormal grain growth. This is likely to occur during the conventional solution treatment and the same has also been reported by several authors [21, 25].

4 Conclusions

- Friction stir welding can produce full penetration sound welds on 16 mm thick AA7075–T651 plates. However, it causes reductions in strength and hardness values.
- The post-weld cyclic solution treatment significantly improves the hardness of the joint and homogenized the hardness distribution across the welded joint.

- The cyclic solution treatment does not exhibit beneficial effects on tensile properties and impact toughness of the welded joint.

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