Effect of water cooling on microstructure and mechanical properties of friction stir welded dissimilar 2A12/6061 aluminum alloys

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Abstract

In-process cooling has been reported beneficial to some friction stir welded (FSW) aluminum alloys. But the effect of water cooling (WC) on the performance of dissimilar joints is still unclear. This work studies the effects of process parameters and water cooling on the microstructure and mechanical properties of the dissimilar 2A12-T6/6061-T6 FSW joints. Two rotational speeds (1200 and 1500 rpm) and one welding speed (80 mm min⁻¹) were adopted. The macro/micro structural characteristics, microhardness distribution, tensile properties and fracture morphology have been investigated. The results show 2A12 on advancing side shows the higher plasticizing degree than 6061 during FSW. Cracks and tunnels are found in nugget zone (NZ) of 1200-80WC joint due to the poor fluidity of metals. The average grain size of NZ increases with the rotational speed and can be decreased by water cooling. For all of the joints, the lowest hardness positions locate in the heat affected zone of 6061. The effect of water cooling on hardness is found related to the nature of material and the rotational speed. The 1200-80 joint shows the best mechanical properties. Water cooling damages the mechanical properties of the 1200-80 joint by inducing void and crack defects. However, it enhances the strength of 1500-80 joint. The 1200-80WC joint fractures in NZ while others fracture in the positions with the lowest hardness. The fracture locations and morphology accord well with the microstructure, microhardness and tensile properties.

1. Introduction

Aluminum alloy is widely used in automobile, ship, aircraft and rail vehicle manufacturing industry due to its high specific strength, corrosion resistance and good plasticity. Dissimilar aluminum alloy welding parts can maximize the advantages of various aluminum alloys and have attracted much attention [1]. For now, arc welding is widely used in high-speed railway body welding, but the coarse joint microstructure and large deformation limit the enhancement of joint strength which is critical to the safety of products [2, 3]. The differences in physical, chemical, metallurgical and mechanical properties among dissimilar aluminum alloys, as well as the high thermal conductivity, making the weld joints are prone to defects which deteriorate the welding quality [4, 5]. Therefore, it is still a great challenge to achieve good joint performance, especially for the heat treatable aluminum alloys (2-series, 6-series and 7-series) which are sensitive to temperature [6].

As one of the solid-state joining techniques, friction stir welding (FSW) shows advantages over fusion welding in the applicability of materials and the operability of microstructural control [2, 7]. Some welding defects like deformation, cracking and porosity can be avoided due to the low operating temperature of FSW [8]. The material flow in advancing side (AS) and retreating side (RS) of nugget zone (NZ) is asymmetric, which is an intrinsic characteristic of FSW. Hence, for dissimilar joints, the base material location has a significant impact on the temperature field, material composition of NZ and plastic metal flow behavior [9]. In another aspect, the welding heat which determined by the process parameters has a great influence on the coarsening and dissolution of precipitated phase due to the differences in performance of the materials, indicating the welding
parameters are crucial for the properties of welds. It was revealed by Zhang et al. that the joining material direction affected the mechanical properties of joints by influencing material flow behavior and microstructure. The maximum tensile strength was acquired for the RD [10]–TD AA2024/7075 joint due to the proper heat input and sufficient material flow [10]. Cavaliere et al. investigated the 6082/2024 FSW joints and found that 2024 should be placed on the AS to reduce the axial pressure of the stirring tool [11]. Kumar et al. reported that the ultimate tensile strength and hardness increased with the increasing rotational speed (1200 to 1400 rpm) at the lower welding speed (30 to 50 mm min⁻¹) in FSW 2024/6082 joints [12]. Zhang et al. gave a quantitative analysis of grain structure and texture evolution of dissimilar friction stir welded 2024/7075 joints, in which it was found that the average grain size and recrystallization degree were reduced with the increase in welding speed [13]. It was reported by Mehdi that the grain size is decreases by increasing the tool rotational speed [14].

For the heat treatable aluminum alloys, FSW with large heat input would lead to the noticeable decrease of strength in the heat affected zone (HAZ) or thermo-mechanical affected zone (TMAZ) where the fracture always occurs, which can be attributed to the dissolution of the precipitated phases, the decrease of dislocation density and grain coarsening [15]. Rapid cooling FSW could reduce the peak temperature and increase the cooling rate, which was conductive to overcome the above mentioned adverse effects caused by high temperature [16]. It was reported that the strength and ductility of AA2029 FSW joint was enhanced by in-process cooling [17]. The lower precipitate coarsening level and the narrower precipitate free zone contributed to the hardness improvement of underwater joint [18]. The major reasons for enhanced tensile properties of cooling assisted FSW was generalized by Singh et al. [19] as the lesser precipitate deterioration, controlled temperature profiles, refined grain microstructure, solid solution strengthening and higher density dislocation. However, it was reported the mechanical properties of normal weld joints was superior than the in-process cooled ones due to intense natural aging response of AA7039 after FSW [20]. It is noticed that the effects of in-process cooling on FSW joints are associated with the nature of base materials and the process parameters, thus could lead to different results. For dissimilar aluminum alloys, the effects of in-process cooling on the performance of FSW joints should be more complicated. Although water cooling is convenience and efficiency, researches with regard to the correlation between water cooling and process parameters are still inadequate, their effect mechanism on performance of dissimilar aluminum alloy FSW joints need to be investigated.

In the present work, the precipitation hardening Al–Cu–Mg alloy 2A12–T6 (similar to AA2024) and Al–Mg–Si alloy 6061–T6 are selected as the base materials (BMs). Water cooling has been applied to the FSW process with different parameters to make a comparison with the conventional FSW. The macro/micro structural characteristics, microhardness distribution, tensile properties and fracture morphology have been investigated. The relationship among process parameters, microstructures and mechanical properties has been discussed. It is attempted to reveal the effect of water cooling on microstructure and mechanical properties of dissimilar weld joints.

### 2. Experimental procedure

5 mm thick 6061–T6 and 2A12–T6 rolling plates—260 mm long and 80 mm wide—were selected as base alloys for the friction stir welding experiment. The chemical compositions of base alloys are listed in Table 1. Friction stir welding was carried out on a vertical numerical control machine FSW–LM–BM16. The stirring tool was made of H13 steel with the diameter of 16 mm, 5 mm for shoulder and stirring pin, respectively. The length of the cylindrical stirring pin is 4.6 mm. As shown in the schematic diagram of figure 1, 2A12–T6 and 6061–T6 was placed on the AS and the RS, respectively. The welding direction was parallel to the rolling direction (RD) of 6061 and perpendicular to that of 2A12. FSW was performed at rotational speed of 1200 and 1500 rpm with constant welding speed of 80 mm min⁻¹. The tilt angle was 2.5° and the plunge depth was kept within 0 ~ 0.2 mm during FSW. For comparison, continuous water cooling through a nozzle with a flow rate of 0.5 L min⁻¹ was applied to another set of joints during FSW (figure 1). The nozzle was placed 30 mm behind the FSW tool. There are brief expressions for samples, for example, 1200–80WC represents for the sample welded at 1200 rpm and 80 mm min⁻¹ with water cooling.

Samples for microstructure observation were taken from the center of the weld joints, the vertical plane was ground and polished, then corroded by Keller reagent. A ZEISS optical microscope (OM) and ZEISS Sigma 500

| Alloy   | Mg  | Cu  | Si  | Cr  | Mn  | Fe  | Al   |
|---------|-----|-----|-----|-----|-----|-----|------|
| 2A12    | 1.28| 4.90| 0.43| 0.01| 0.63| 0.44| Bal. |
| 6061    | 0.87| 0.21| 0.61| 0.10| 0.06| 0.39| Bal. |

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**Table 1. Chemical compositions of base alloys (wt%).**
scanning electron microscope (SEM) were used to observe the microstructure of cross-section. The average grain size was measured by the linear intercept method with the aid of ImageJ software. At least five straight lines were adopted to count the number of intercepted grains, so as to calculated the average grain size. Specimen for TEM were taken from the center of 6061-HAZ. They were mechanically polished to about 50 μm and subjected to twin-jet electropolishing. A Tecnai G2 20 TEM was used. The Micro-hardness was measured along the horizontal line of cross-section by applying a load of 100 g and a dwell time of 15 s on an HVS-1000A Vickers microhardness tester, with an interval of 0.5 mm for adjacent measuring points. Planar tensile samples were prepared under the guidance of the ASTM-E8M standard with outline dimensions shown in figure 1. The tensile properties were tested at a loading speed of 1 mm min \(^{-1}\) on an electronic universal testing machine. At the end of the test, the ductility of the specimen was determined by measuring the gage length change of failed specimen. Take the three measurements to calculate the average value. The fracture morphology was observed by SEM in secondary electron imaging mode.

3. Results and discussion

3.1. Macrostructures of joints

The transverse section macrographs of joints welded by different processes are shown in figure 2. Due to the difference in corrosion resistance between 2A12 and 6061, the two kinds of base materials can be roughly recognized by the color shading of the macrograph. The deformation of TMAZ on AS is found more serious than that on RS, which could be associated with fact that the linear speed on the AS is much larger than that on the RS \([21]\). 2A12 appears black while 6061 appears grey in NZ. In the NZ of each weld joint, the content of 2A12 is found higher than that of 6061, representing the net material input from AS to RS. The higher plasticizing degree of 2A12 can be explained by its lower melting point and the higher temperature of AS \([22]\).

The mixing and distribution of the two materials shows different characteristics. Figure 2(a) (1200-80) shows that 2A12 flows into the RS from the top and bottom of the rolled plate while 6061 flows into the AS from the middle part. The welding centerline in figure 2(b) is fully covered by 2A12-dominant composition, indicating the uneven material flow under 1200-80WC. The flow mode of materials in NZ is controlled by the rotational friction of the shoulder and the stirring pin. 2A12 in AS flows forward and enters into RS until the outer edge of the stirring pin. 6061 in RS flows backward, most of which terminates in RS and a small part enters into AS. It is observed from figures 2(c) and (d) that the interflow between two materials reduces when the rotational speed increases to 1500 rpm. The possible reason is the viscosity of materials markedly decreases with the increasing temperature. There is no ‘onion ring’ structure in NZ of the joints, the sharp interface between two materials instead. It indicates the plastic flow of materials is insufficient, which is related to the low friction force by the smooth appearance of stirring pin. Due to the poor fluidity of metals during FSW, the voids are prone to generate in NZ and TMAZ, especially for the water cooled joints as shown in figures 2(b) and (d).

3.2. Microstructures of joints

The micrographs of the marked areas in figure 2 are shown in figure 3. The microstructure of HAZ on AS and RS is displayed in figures 3(A) and (E), in which the coarse grains along the rolling direction and the transverse direction are displayed, respectively. HAZ is affected by the friction heat and the heat dissipation of the metal.
flow during the welding process, the rolling characteristics in this area are weakened and the grain size is close to that of BM [23]. The microstructures of TMAZ on AS are given in figures 3(B) and (H), which show the bent and distorted grains with inconsistent size and shape, resulting from the combined influence of low stress and high temperature during FSW. For one thing, the rotational friction and shear deformation of the stirring tool lead to insufficient plastic deformation of grains in TMAZ, and a few grains undergo dynamic recovery and dynamic recrystallization. For another, the temperature gradient and the strain rate result in the elongation of grains along the rotating direction [24]. The black and coarse second phase particles with different size and quantity can be seen in each zone of figure 3. The particle size of the second phase in HAZ is larger than that in NZ.

Figures 3(C) and (D), (F), (G), (I), (J) and (K) give the micrographs of NZ for different joints. It is well-known that the severe plastic deformation and the dynamic recrystallization takes place under the action of mechanical stir and friction heat, leading to the fine equiaxed grains in NZ [25]. By comparing figures 3(C), (D), (I) and (J), it is observed that the grains of 2A12 on AS is relatively finer than those of 6061 on RS. In addition, the grain size in NZ-RS is not uniform, indicating the inadequate dynamic recrystallization. The reason could be complicated owing to the fact that factors such as temperature, strain and nature of metals affect the dynamic recrystallization [26]. Figures 3(F) and (G) are taken from the NZ of joint (1200-80WC), in which the defects like tunnels, cracks and voids are found prevalent. Tunnels locate in AS near the bottom edge of NZ. This is because the AS (especially the edge of stirring pin) is subjected to greater shear force and friction during welding, and water cooling significantly reduces the heat required for material flow, resulting in poor plastic flow of the material and the formation of tunnels. Cracks can be ascribed to low plastic brittle cracks, which form when the ductility is less than the strain, due to the hardening effect of metals caused by water cooling during FSW. Defects observed in joint of 1200-80WC will inevitably deteriorate the bonding force of NZ, which affects the mechanical properties of weld joint.

Microstructures of NZ (2A12 AS) under different process parameters have been given in figure 4 to study the effect of rotational speed and water cooling on grains. The average grain size is 6.0, 5.8, 7.3 and 6.8 um for figures 4(a)–(d), respectively. It reveals that the grain size is decreased by water cooling. In another aspect, the grain size in NZ increases with the rotational speed, both for the FSW and WC-FSW joints. The coarsening of
grains with the increasing rotational speed is attributed to the increase of heat input which facilitates the growth of recrystallized grains [27]. In-process cooling reduces the peak temperature and duration at high temperatures. Besides the effect of grain refinement, it lessens the precipitate deterioration and increases the dislocation density, which has been reported in literature [28].

Figure 5 presents the TEM bright-field images in 6061-HAZ of 1200-80 and 1200-80WC joint. HAZ of the precipitation hardening aluminum alloys is characterized by the coarser and lesser precipitates compared to the BM [18]. The 6061-T6 base material contains a high density of fine needle-shaped $\beta''$ precipitates, which is the main strengthening phase [29]. Besides the needle-shaped precipitates, figure 5(a) also shows the rod-shaped precipitates which has been reported to be $\beta$ and few dot-shaped precipitates [30]. The $\beta''$ phase partly dissolves and transforms to $\beta$ under the heat effect, thus leads to the softening of HAZ. Compared to figures 5(a), (b) shows the higher density precipitates with smaller size, indicating water cooling helps to reduce the adverse effects of heat to the precipitates. It would probably enhance the hardness and strength of HAZ, which will be discuss in the next section.

3.3. Microhardness profiles of joints

Figure 6 gives the hardness profiles along the cross-section of joints under different process parameters, which were taken along the upper and lower layers of the cross-section. The left and right parts of the curve show the hardness distribution of 2A12 and 6061 respectively, and the hardness changes sharply at the interface of the two materials. It is found that the hardness distribution of the both layers match well with the macrostructural characteristic of each feature area. The fluctuation of microhardness values indicates the inhomogeneity of microstructure. The hardness for base material of 2A12-T6 and 6061-T6 is about 131 HV and 80 HV,
respectively. It is obvious that the hardness values of TMAZ and HAZ are lower than that of the corresponding BM, especially for HAZ. It is noteworthy that the hardness distribution on the upper layer of AS (figure 5(b)) is abnormal, in which the hardness of NZ is quite low. It indicates the weld nugget zone of the 1200-80 joint has been soften by in-process water cooling. Considering the defects observed there, the effect of water cooling is questionable. For all of the joints, the lowest hardness positions locate in the HAZ of 6061, with the hardness around 50 HV. It has been reported that the precipitated phases are partly dissolved or coarsened resulting in the lowest hardness in HAZ [31, 32]. The area with the lowest hardness is prone to fracture during tensile test [33].

The comparison of hardness profiles along the upper layer of joints under different processes is show in figure 7. Observing the hardness of NZ-AS, only joint of 1200-80 shows average hardness which is slightly higher than that of BM, indicating the suitable heat and force on NZ under this process parameter. It is noteworthy that for all joints, the hardness of NZ-RS is slightly lower than that of the corresponding 6061-BM. The hardness of NZ tends to decrease when the hardening effect of grain refinement is not enough to offset the adverse effect of β′′ precipitates dissolution and transformation caused by overheating and rapid cooling. It is known that the peak temperature and the high temperature exposure time of the weld can be remarkably reduced by in-process cooling. Water cooling is found to decrease the hardness of AS and increase the hardness of RS at rotational
speed of 1200 rpm. However, it helps to enhance the hardness of AS at rotational speed of 1500 rpm. It implies the effect of rapid cooling on hardness is related to the nature of material and the quantity of heat generated from the certain rotational speed. When the joint undergoes overheating (such as 1500-80 joint), rapid cooling helps to lessen the dissolution of precipitates, increase dislocation density and refine grains \[34\]. In addition, the hardness of AS decreases with the increase of rotational speed, which proves the over temperature is detrimental to hardness.

**Figure 6.** Hardness profiles along the cross-section of joints under different processes, 1200-80 (a), 1200-80WC (b), 1500-80 (c) and 1500-80WC (d).

**Figure 7.** Comparison of the hardness profiles along the upper layer of joints under different processes.
3.4. Tensile properties and fractography

Figures 8(a) and (b) presents the typical stress-strain curves and the tensile properties of weld joints under different processes. The detailed data are summarized in table 2. The ultimate tensile strength (UTS) is 204.3 and 190.2 MPa for joint of 1200-80 and 1500-80, respectively. The UTS decreases and the elongation (EL) slightly increases (from 3.50% to 3.72%) with the increase of rotational speed. The joint is softened at the higher rotational speed on account of the higher peak temperature. The rule of tensile properties with respect to heat input has been reported by Guo [35] for the 6061/7075 joint. The dissolution of some precipitates reduces the strength but enhances the plasticity. In this work, 1200-80 is considered the preferred parameters for conventional FSW.

With the aid of water cooling, it is noticed the UTS and the EL decreases to 166.7 MPa and 1.50% respectively, for joint of 1200-80WC. As a comparison, the UTS increases to 204.8 MPa for joint of 1500-80WC. This influencing rule is similar to that of the microhardness. For underwater FSW, joint with low rotational speed tends to show poor tensile strength due to insufficient stirring action [36]. The tensile properties can be improved by increasing the rotational speed within limits due to the increase in strain hardening [37]. The result reveals that the rotational speed of 1500 rpm is higher for conventional FSW but proper for water cooled FSW in the current experiments. However, in-process water cooling to joint of 1200-80 severely damage the performance of the joint. Associating with the aforementioned microstructural analysis, it can be deduced when the heat input is moderate or shortage, the additional cooling will damage the mechanical properties of the joint by inducing void and crack defects. As has been proposed by Duan [38], defects due to the insufficient heat input and the redissolution of precipitates due to the overmuch heat input have negative effects on joint performance. In this work, the 1200-80 joint shows the best mechanical properties, followed by the 1500-80WC joint. The strength efficiency and elongation efficiency of the best joint reaches 62% and 33% of 6061-T6, respectively.

The fracture locations of the FSW joints usually found in the lower hardness zone, i.e. TMAZ or HAZ. Sometimes, fracture occurs in the location where significant defects are found [37]. Figure 9 displays the typical fracture locations of different joints. Based on the macrographs in figure 2 and the hardness profiles in figure 6, it is confirmed that the fracture location of the 1200-80WC joint is NZ (figure 9(b)) in which the low hardness and a large number of cracks and voids are shown. The other three types of joints (figures 9(a), (c) and (d)) fracture at HAZ near 6061-BM, where is located the minimum hardness region. HAZ of FSW joint of precipitation
strengthening aluminum alloys is characterized by the lessened and coarsened precipitates \cite{18, 32}. These fracture locations are same as those of the 6061/7075 FSW joints in literature \cite{35}.

The inclined fracture surface and limited necking can be observed in figures 9(a), (c) and (d). While, only figure 9(b) shows the flat fracture surface without necking. Considering the above and the elongation, it is deduced that figures 9(a), (c) and (d) belong to ductile fracture, while figure 9(b) (1200-80WC) belongs to brittle fracture. Figure 10 gives the SEM images of fracture surface. For the natural-cooled joints (figures 10(a), (c)), there are a large number of small and large dimples distributed along grain boundaries, indicating the characteristic of intergranular fracture. Since the grain boundaries are the crack initiation sites during the fracture, the size of dimples should be related to the grain structure. Besides the small and shallow dimples, the fracture surface of the 1200-80WC joint (figure 10(b)) is characterized by some cracks and cleavage facets, indicating a mixed fracture mode of ductile-brittle. This indicates that no obvious plastic deformation has occurred during the tensile test, which is consistent with the low elongation. Some pull-out zone can also be observed on the fractured surface of the 1500-80WC joint (figure 10(d)), indicating that grains on the fracture surface are separated during the tensile test. The above observations are in agreement with the tensile results.

Figure 9. The typical fracture locations of different joints, 1200-80 (a), 1200-80WC (b), 1500-80 (c) and 1500-80WC (d).

Figure 10. SEM images of fracture surface for joints, 1200-80 (a), 1200-80WC (b), 1500-80 (c) and 1500-80WC (d).
4. Conclusions

This work studies the effects of process parameters and water cooling on the microstructure and mechanical properties of the dissimilar 2A12-T6/6061-T6 FSW joints. The main conclusions are listed as follows.

1. The results show 2A12 on advancing side shows the higher plasticizing degree than 6061 during FSW. Cracks and tunnels are found in nugget zone (NZ) of 1200–80WC joint due to the poor fluidity of metals. The average grain size of NZ increases with the rotational speed and can be decreased by water cooling.

2. For all of the joints, the lowest hardness positions locate in the heat affected zone of 6061. The effect of water cooling on hardness is found related to the nature of material and the quantity of heat generated from the certain rotational speed.

3. The 1200-80 joint shows the best mechanical properties. Water cooling damages the mechanical properties of the 1200-80 joint by inducing void and crack defects. However, it enhances the strength of 1500-80 joint.

4. The 1200-80WC joint fractures in NZ while others fracture in the positions with the lowest hardness. The fracture locations and morphology accord well with the microstructure, microhardness and tensile properties.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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