Effect of a cooling method on the structural and mechanical properties of friction stir spot welding with a 2524 aluminum alloy

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Abstract

Friction stir spot welding (FSSW) is a clean, environmentally-friendly and cost-effective welding technology. To weld joints with improved mechanical properties, an FSSW experiment with a 2 mm-thick 2524 aluminum alloy sheet was performed to explore the influence of ambient cooling (AC), forced air cooling (FAC), waterfall cooling (WC), and an increasing rotational speed under WC, and to evaluate the welding method with regard to the resulting structural and tensile properties of the joint. The results showed that cooling-assisted welding reduced the width of the heat-affected zone (HAZ) and marginally increased the microhardness of the welding nugget zone (WNZ). The maximum tensile shear load (L) and effective width (W) values were 4673 N and 1958 μm at FAC, respectively, which were higher than the values of 4296 N and 1763 μm found with AC, respectively; in addition, the minimum values were 2946 N and 948 μm with WC, respectively. These results are not consistent with the idea that the joint strength can typically be improved with WC, because water absorbs a large amount of welding heat and reduces the plastic deformation capacity of the structure, thereby decreasing the W and L of the joint. Increasing the rotation speed of the welding tool can increase the heat input, which requires increasing the rotation speed along with WC. L and W reach their maximum values of 7652 N and 3320 μm, respectively, at 2500 r-min⁻¹. As the rotation speed increases, L and W decrease. All joints underwent ductile fracturing, and the dispersion distribution of the second-phase particles at the bottom of the dimple exhibited good performance.

1. Introduction

FSSW is a spot-welding technology developed for friction stir welding (FSW) [1]. Dynamically recrystallized metal rather than melted metal occurs in joints when FSSW is used; thus, FSSW is suitable for aged aluminum alloys and other heat-sensitive alloys [2, 3]. FSSW has many more advantages than fusion welding [4–6] or riveting [7] in terms of low energy consumption and environmental protection. Due to problems that exist under fusion welding, welding temperatures can be too high, and grains and second-phase particles of the HAZ tend to grow [8, 9]. Materials with a large eutectic temperature range are prone to cracking [7], and high energy consumptions during welding with aluminum alloy is caused by the high melting point of their surface oxide layer [10], alone with their excellent electrical and thermal conductivities [11]. For these reasons, the strength of the joint will decrease with fusion welding, and weight will worsen when riveting, which is not conducive to being lightweight [12].

In FSSW, dynamic recrystallization will occur in the WNZ and the thermal mechanical affected zone (TMAZ); excessive welding heat will cause recrystallization grain growth and second-phase particle dissolution or coarsening; and the strength of the joint will decrease [13].

Zhang et al [14] conducted friction stir processing (FSP) with a 2024-T4 aluminum alloy under a dry ice and ethanol mixed solution (initial temperature is −30 °C), and found that the grain size decreased from 5.10 μm
under ambient cooling to 1.89 μm Zeng et al [15] conducted FSW under WC, and showed that the stir zone of AC was above that of WC, and that the stir zone increased when the rotating speed increased when using the same cooling method. Xue et al [16] obtained FSW joints with strengths near base material using cooling. Wang et al [9, 13] noted that the average grain size of the WNZ decreased from 3.6 μm under AC to 2.7 μm under WC; the tensile strength coefficient of the joint under WC reached 95% higher than 81% at room temperature; and the fatigue limitation increased from 180 MPa for room temperature to 240 MPa with WC, which was equal to the base material. Wang et al [17] conducted FSP for AZ31 magnesium alloy in three different media, including air, circulating water, dry ice and alcohol mixtures, and results showed that the peak temperature and duration of high temperature decreased gradually. Liu et al [18] performed FSW for ME20 M magnesium alloys under different temperatures of cooling water and found that the grain sizes and precipitation phases increased, and the strength of the welding joint decreased when the water temperature increased. Shekhawat et al [19] investigated the influence of WC on the microstructure and mechanical properties in FSSW and found that the average grain size was 44 μm under WC but 58 μm under AC Zhang et al [3] studied the FSSW of AA2024-T3/AA7075-T6 aluminum alloys in ambient and underwater environments, and found that WC can reduce the

| Cu  | Mg  | Mn  | Ti  | Zr  | Fe  | Si  | Al  | Tensile Strength (MPa) | Specific elongation |
|-----|-----|-----|-----|-----|-----|-----|-----|------------------------|---------------------|
| 4.52| 1.52| 0.62| 0.122| 0.41| 0.11| 0.038| balance | 430                      | 12.3%               |

Figure 1. 3D metallographic diagram of 2524 aluminum alloy sheet.

Figure 2. Structure of FSSW welding tool.
width of the stir zone. When the rotational speed of the tool increases, the tensile-shear force of the joint increase in both ambient and underwater environments.

To study the influence of different cooling methods and develop a manufacturing process that produce high-strength welded joints, FSSW is performed in this study with for 2 mm-thick 2524 aluminum alloy plates under the conditions of AC, FAC and WC to investigate the associated changes in the joint’s structural and mechanical performance.

### 2. Materials and methods

#### 2.1. Materials

A 2 mm-thick 2524 aluminum alloy sheet produced via large strain rolling is welded, and the real composition and mechanical properties are shown in table 1. Figure 1 shows the 3D metallographic structure of the experimental material, and there are lamellar grains along the rolling direction (RD). Figure 2 and table 2 show the structure and parameters of the FSSW tool, respectively. The conical pin and screw thread facilitate axial and circumferential movement of the metal [20], and the concave shoulder improves the strength of the weld joint [21].

Figure 3 shows the size of the welded sample and microhardness sampling location. The plate surface was surface with a steel brush to remove oxide, cleaned with acetone, and welded after drying. Six welding samples were taken for each parameter; four of the samples were used for the tensile property test, one was used for metallographic analysis, and one was used for the microhardness test.

#### 2.2. Experimental method

Table 3 shows the welding parameters, which have been used in other studies, and fine joint tensile properties can be obtained with these parameters [22]. Next, the effects of the formability, macrostructure, microstructure, and mechanical properties of the welded joints under AC, FAC and WC are investigated. Forced air is provided by an air compressor. When welded under WC, water can cover the surface of the material during welding, and the flow rate is 10 l min

### Table 2. Parameters of the FSSW tool.

| Shape       | Shaft diameter | Stir pin shape | Plunge depth | Dwell time | Plunge speed | Retract speed |
|-------------|----------------|----------------|--------------|------------|--------------|--------------|
| Concave     | 10 mm          | Conical        | 0.6          | 10         | 5            | 100          |

Table 3. Experimental scheme.

| Rotation speed (r·min$^{-1}$) | Plunge depth (mm) | Dwell time (s) | Plunge speed (mm·min$^{-1}$) | Retract speed (mm·min$^{-1}$) |
|-----------------------------|-------------------|----------------|-----------------------------|-----------------------------|
| 700                         | 0.6               | 10             | 5                           | 100                         |
2.3. Characterization methods
Welding experiments were performed on a JK-5 multifunctional welding machine. An ETM105D electronic universal testing machine was used for the tensile test. Metallographic samples were cut along the rolling direction (RD) by an electric spark cutting machine at the center of the keyhole. The metallographic specimen was ground, and polished and then etched with a mixed acid aqueous solution (1 ml HF + 1.5 ml HCl + 2.5 ml HNO₃ + 95 ml H₂O). Leica DMI3000 M optical microscope (OM) was used for microstructure observation. The microhardness of the welding joint was tested by an HVS-1000Z machine, the load was 9.8 N, the loading time was 10 s, and the microhardness sampling location is shown in figure 3. A tensile fracture was observed via SIGMA field emission scanning electron microscopy (SEM).

3. Results and discussion
3.1. Experiments of different cooling methods
3.1.1. Macroscopic and microstructural features of FSSW joints
Figure 4 shows the microstructure and effective joint width with different cooling methods. Hooking deflects upward when AC is 4(a) and FAC is 4(b), and in the horizontal direction when WC is 4(c); therefore, the angle of the hook is 180° in 4(c). Therefore, the angle of hook decreases from WC to AC (θ₁) to FAC (θ₂). This decrease occurs because the hooking angle decreases when the plastic deformation of the structure is increases [23]; therefore, the plastic deformation capacity under FAC is greater than that under AC and WC. When welded under AC, the temperature is relatively high, and the sliding friction occurs between the stir pin and material during welding, which causes the plastic deformation to decrease. When welded under FAC, heat is taken away via forced air, and viscoplastic flow occurs; therefore, the plastic deformation capacity of the tissue is enhanced, which leads to an increase in the angle from AC to FAC [24, 25]. When welded under WC, the heat is absorbed by the water, the heat loss is faster than that of FAC, and the temperature remains at a low level, which results in the worst plastic deformation capacity of all tested cooling methods. Consequently, the hook of the WC remains

![Figure 4. Macrostructure of different cooling method and effective width (a) Ambient cooling (a1) Shaft shoulder affect zone (a2) Stir pin affected zone (b) Forced air cooling (b1) Shaft shoulder affect zone (b2) stir pin affected zone (c) Waterflow cooling (d) Effective width.](image-url)
horizontal, and the distortion degree of the thermomechanically affected zone (TMAZ) is reduced, which is consistent with the law obtained by Zeng et al [15].

The area from the hook end to the keyhole forms a stable connection during welding, which can connect the upper and lower plates. The width of this area is the effective width (W), as shown in 4(a). Figure 4(d) shows that W equals 1763 μm under AC, 1958 μm under FAC and 948 μm under WC. According on these results, the plastic deformation capacity of the joint is higher under FAC than AC and WC. When the deformation capacity is high, more structure can be mixed to form a connection area. Thus, W under FAC is greater than those under AC and WC.

The microstructure distributions under AC and FAC are shown in figures 4(a1), (a2), (b1) and (b2). Due to stirring, dynamic recrystallization occurred in all areas during welding, and this zone is typically referred to as the WNZ, which can be divided into two areas based on the type of stirring that occurs. The shaft shoulder affect zone (SSAZ) as shown in figures 4(a1) and (b1) is affected by the shaft shoulder, and the friction heat between the shaft shoulder and material is the primary source of the heat in welding [20, 26]. In this case, the grain size in this area are large after welding due to the high welding temperature. The stir pin affected zone (SPAZ) in figures 4(a2) and (b2) is primarily affected by stir pin during welding. In this zone, the heat is low; however, the plastic deformation capacity is higher than that in the SSAZ, due to the stirring by the screw thread. Thus, the grain sizes in this area are smaller than those in the SSAZ after welding. The grain sizes of 4(a1) and 4(b1), 4(a2) and 4(b2) are similar, which indicates that welding under FAC did not markedly reduce recrystallization growth.

3.1.2. Microhardness profile of the joints

Figure 5 shows the microhardness distribution curve for joints under different cooling methods. Primarily related to grain size, dislocation density and the distribution of the precipitation phase [25], microhardness decreased first and then increased far away from the WNZ. In the WNZ, dynamic recrystallization tends to refine the grains and consume dislocations; thus, the dislocation density of the WNZ decreases. Smaller grains can increase the microhardness, while the consumption of dislocations decreases the microhardness [9]. Second-phase particles will be precipitated after redissolution at high temperatures, which will lead to fine and evenly distributed second-phase particles, which improve the joint’s microhardness. Incomplete dynamic recrystallization occurred in the TMAZ because the rate of microstructure deformation was low, and the dislocation density was higher than that in the WNZ [27]. The state of the second-phase particles in the TMAZ is related to its position. When it is near the WNZ, the second-phase particles redissolve at high temperatures and will grow when near the HAZ, decreasing the microhardness in this area. Therefore, the microhardness in the TMAZ is lower than that in the WNZ. The HAZ recovers due to the influence of the welding heat; grains and second-phase particles grow; and the dislocation density decreased, decreasing the microhardness to its minimum value. Moving away from the WNZ, the effects of the heat decrease; therefore, the hardness gradually returns to that of the original base material (BM).

Under AC, the microhardness decreases to its minimum value, then fluctuates continuously, and finally rises slowly, indicating that the joint is significantly affected by the welding heat and that the width of the HAZ is large. Under FAC, forced air removes some of the welding heat; thus, the width of the low-hardness zone is reduced compared to AC. The microhardness distribution curve of WC is similar to that of FAC; however, the width of
the low microhardness is smaller because water absorbs more heat than forced air. Therefore, we can conclude that the HAZ width decreases when more effective cooling methods are used.

W is measured from the dash to the key hole in Figure 5. Because different W’s are used with the different cooling methods, the sizes of each area are unequal. However, the microhardness under FAC and WC in this region is higher than that under AC, which indicates that cooling can improve the strength of the structure in the WNZ because the heat input can be reduced by cooling, which will reduce recrystallization growth. Thus, the grain size of the WNZ under FAC and WC will be finer than that under AC; however, the improvement is relatively small, as shown in Figure 4. Therefore, when welded with cooling, the increase in microhardness is small [15, 17, 18].

3.1.3. Tensile properties of the joints

Figure 6 shows the maximum L of the joint under different cooling methods. The maximum L of the joint is 4296 N under AC, 4673 N under FAC, only 2946 N under WC, while the corresponding values for W/L are 0.41, 0.42, and 0.32, respectively. L is correlated with W in Figure 4(d); W and L are largest under FAC, and smallest under FAC.

In the effective connection area, the microhardness thus increases marginally, and W increases markedly under cooling. L is related to the microhardness and W. Under FAC, both the W and microhardness are high;
thus, L is the largest. under WC, the microhardness is higher than that under AC; however, W is markedly reduced, and the L is the minimized.

3.1.4. Tensile macrofracture morphology of the joint
Table 4 shows the tensile macrofracture morphology of the joint made under different cooling methods. C and d are the fracture dimensions under AC and FAC that are torn along the inclined direction because the joint is subjected to both tensile and shear forces under tensile test; we label this fracture as mode I. Certain metal in the joint remained on the upper plate after fracture, as shows in a and b. When welded under WC, the surface finish of the upper plate decreased after welding, as shown in e. The fracture direction was parallel to the lap surface, as shown in f; we label this fracture as mode II. This phenomenon is likely caused by thermal dissipation, which markedly increases sharply when welded under WC, decreasing the viscosity of the metal and creating a poor surface finish. Hooking also tends to encourage tensile crack propagation in lap joints [28]. In figure 4, AC and FAC exhibit upward hooks, which result in a stripping fracture behind the upper and lower plates on one side of the weld joint. A shear fracture also occurred during the tensile test, which formed the fracture of mode I [29]. Under WC, the hook is horizontal, and the shear fracture occurs under a tensile force, forming mode II, which is along the horizontal direction [23].

3.1.5. Fractography of FSSW joints
Figure 7 shows the SEM morphology of the fracture under different cooling methods. There were many dimples on the fracture surface and second-phase particles at the bottom of the dimples, indicating that all joints underwent ductile fractures under different cooling methods. The dimples are similar in figures 7(a) and (b). Figures 7(a1) and (b1) show the parabolic shear dimple in an area away from the keyhole, which indicates that this area is subjected to shear forces during the tensile test. As shown in figures 7(a2) and (b2), elliptic dimples were present in the area near the keyhole, which indicated that fractures occurred under normal stress, and the dimples were large and unequal in this area. In figure 7(c), the distribution of dimples is similar to that above; however, the size is smaller and equal. In figure 7(c2), the second-phase particles are also smaller, and the small
dimple sizes can explain the small observed rain size. All of these results indicate that the microstructure of the FSSW joint under WC is remarkably refined [30].

3.2. Experimental of high rotation speed with water flow cooling

When FSW is performed under WC, the strength will typically increase due to grain refinement [9, 14, 31]; however, based on previous research of FSSW under WC, L decrease due to the decrease of W. Thus, L increases in the FSSW joint with a fine grain joint and, more importantly, when W increases.

To obtain a larger L, the following tests are performed by optimizing the welding process. However, FSSW is affected by many welding factors, such as rotation speed, plunge depth, dwell time, plunge speed and retreat speed, etc, among which the first three are most influential. As the rotating speed increases, the welding heat input, plastic flow and microhardness of the metal increase [6, 23]. Zeng et al [15] also noted that increasing the rotation speed will lead to an increase in the connection area with the same cooling method. In comparison, an increase in the plunge depth will also improve the plastic deformation and microhardness; however, the thickness of the upper plate reduces concurrently, which reduces L [29]. An excessively long dwell time will result in an increase heat input and a decrease in microhardness and structure coarsening; thus, the increase in L is small [22].

Therefore, we can increase the rotation speed under WC until L reaches its maximum value, and the other parameters remain unchanged. The rotation speed was increased from 700 r·min$^{-1}$ to 2700 r·min$^{-1}$ under WC, and the other parameters were the same as those shown in table 3.

3.2.1. Macroscopic and microstructural features of FSSW joints

Via experimental, the L of the joint reaches its maximum value when the rotating speed is 2500 r·min$^{-1}$. Above this speed, the L and W decrease.

Figure 8 shows the macrostructure and effective width with different rotation speeds under WC. The W is 3320 μm at 2500 r·min$^{-1}$, and 2162 μm at 2700 r·min$^{-1}$. The decreases in W at 2700 r·min$^{-1}$ may occur because the welding temperature is too high and exceeds the endothermic limit under WC, causing the viscosity of metal to decrease, and the flow to change from viscoplastic to sliding friction, which decreases the migration of metal.
and yields weak agitation [25, 32]. Hou et al [8] also found that over speed in FSW decreases the plastic flow of metal.

Figure 9 shows the microstructure of 2500 r·min⁻¹ with water flow cooling (a) Base metal (b) Heat affected zone (c) Shaft shoulder affected zone (d) Stir pin affected zone.

Figure 10. Microhardness profile of the welding joint with different rotating speed and WC.
3.2.2. Microhardness profile of the joints

Figure 10 shows the microhardness profile of the welded joint with different rotating speeds under WC. The microhardness curve in Figure 10 is similar to that of WC in Figure 5, indicating that microhardness is not affected by the increase in the rotating speed under WC. The microhardness of 2500 $r \cdot min^{-1}$ is much higher than that of 2700 $r \cdot min^{-1}$ while the distance from the center of the keyhole is 2 to 4 mm and 6 to 8 mm; the small difference in 4 mm to 6 mm which may be caused by measurement deviations. These phenomena demonstrate a higher microhardness in the joint at 2500 $r \cdot min^{-1}$. When the rotating speed increases, the temperature increase, and the cooling capacity of the water will be insufficient, making the structure grow and coarsen; therefore, the microhardness decreases marginally at 2700 $r \cdot min^{-1}$.

3.2.3. Tensile properties of the joints

Figure 11 shows the maximum L of the joint at different rotation speeds under WC. L is 7652 N at 2500 $r \cdot min^{-1}$, and W/L is 0.43. When the rotating speed rises to 2700 $r \cdot min^{-1}$, L is 5357 N and W/L is 0.40. These results indicated that increase in W lend to the increase in L when the rotation speed is 2500 $r \cdot min^{-1}$; thus, the values of W and L are higher than in the other tests, and the W/L value is nearly equal to that under AC and FAC.
3.2.4. Tensile macro fracture morphology of the joint

Table 5 shows the tensile macrofracture morphology under WC at 2500 r·min⁻¹. When the rotation speed is 2500 r·min⁻¹, the surface finish is poorer than that at 700 r·min⁻¹, and the amount of flash increases because more metal is squeezed out. The fracture of the joint is considered mode II, which is similar to table 4 under AC and FAC [33].

3.2.5. Fractography of FSSW joints

Figure 12 shows the SEM morphology at 2500 r·min⁻¹ under WC. The dimples in figure 12 are small and more evenly distributed than the fractures in figures 7(a) and (b). Many fine second-phase particles are dispersed at the bottom of the dimple, which indicates that the microstructure of the joint is better than that produced with other parameters, which will inevitably lead to an increase in joint strength due to the resulting fine structure.

3.3. Discussion

When the rotation speed is 2500 r·min⁻¹, both L and W reach their maximum values. The values of L and W increase by approximately 88.3% and 80%, respectively, compared to those under AC. Addition, according to the results of these experiment, the joints obtained with this welding parameter have a higher L in their cooling method when the value of W/L is close to 0.42, such as under AC [22] and FAC in figure 6, when the fracture of tensile test is mode I. When the joint is welded with an ineffective welding technology, the fracture is mode II, (e. g., under WC at 700 r·min⁻¹, W/L = 0.3).

4. Conclusion

FSSW of 2 mm-thick 2524 aluminum alloy plates was performed under ambient cooling, forced air cooling, waterflow cooling and increased rotation speed under waterflow cooling. The following conclusions can be drawn from the results of this study:

(1) The maximum tensile shear load grows with increasing of effective width. Under ambient cooling, the load and width are 4296 N and 1763 μm, respectively. Under forced air cooling, the plastic deformation capacity and the microhardness of the welding nugget zone increased, and the load and width were 4673 N and 1958 μm, respectively. Under waterflow cooling the water removes heat effectively and reduces the plastic deformation capacity of the structure. The load and width are reduced to 2946 N and 948 μm, respectively, even if the microhardness increases in the welding nugget zone.

(2) When welded under cooling, the grain size of the welding nugget zone is refined; the width of the heat affected zone and the distortion degree of the thermomechanically affected zone decreases; and water cooling has a strong effect the effective width and a weak effect on the microhardness of the welding nugget zone. All joints underwent are ductile fracture due to the many dimples in the welded joints, and the dimples of the fractures are fine, uniform and dispersed.

(3) With increasing rotation speed under waterflow cooling, the maximum tensile shear load and effective width of the joint reach 7652 N and 3320 μm, respectively, at 2500 r·min⁻¹. When the rotation speed increases insufficient cooling occurs, and the effective width and maximum tensile shear load of the joint decrease due to the change in the plastic deformation mode.

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References

[1] Dourandish S, Mousavizade S M, Eatzpour H R and Ebrahimi G R 2017 Microstructure, mechanical properties and failure behaviour of protrusion friction stir spot welded 2024 aluminium alloy sheets Sci. Technol. Weld. Joining 23 295–307

[2] Yan J, Sutton M A and Reynolds A P 2005 Process–structure–property relationships for nugget and heat affected zone regions of AA2524–T351 friction stir welds Sci. and Technol. Weld Joining 10 725–36
[5] Zhang G J, Xiao C Y and Ojo O O 2020 Dissimilar friction stir spot welding of AA2024-T3/AA7075-T6 aluminium alloys under different welding parameters and media Defense Technology (https://doi.org/10.1016/j.dt.2020.03.008)

[6] Thomas W M, Nicholas E D, Needham J C, Murch M G, Templesmith P and Dawes C J 1991 GB Patent application no. 9125978.8 International Patent Application No. PCT/GB92/02203

[7] Kumar P R et al 2020 Parametric optimization of friction stir spot welded aluminium AA6063 alloys J Mater. Today Proc. (https://doi.org/10.1016/j.jmatpr.2020.08.667)

[8] Kumar A P and Mahapatra S S 2019 Investigation of weld zone obtained by friction stir spot welding (FSSW) of aluminium-6061 alloy Mater. Today: Proceedings 18 4491–500

[9] Pan F S, Xu A L, Deng D A, Ye C H, Jiang X Q, Tang A T and Ran Y 2016 Effects of friction stir welding on microstructure and mechanical properties of magnesium alloy Mg-SAl-3Sn Mater. Des. 110 266–74

[10] Hou J C, Liu H J and Zhao Y Q 2014 Influences of rotation speed on microstructures and mechanical properties of 6061-T6 aluminium alloy joints fabricated by self-reacting friction stir welding tool Inter. J. Adv. Manuf. Technol. 73 1073–9

[11] Wang B B, Chen F F, Liu F, Wang W G, Xue P and Ma Z Y 2017 Enhanced mechanical properties of friction stir welded 5083Al-H19 joints with additional water cooling J. Mater. Sci. Technol. 33 1009–14

[12] Heidarzadeh A, Mironov S, Kaibyshev R, Çam G, Simar A, Gerlich A and Withers P J 2020 Friction stir welding: a numerical and experimental study Progress Mater. Sci. 100752

[13] Fratini L, Buffa G and Shchipurni R 2010 Mechanical and metallurgical effects of in process cooling during friction stir welding of AA7075-T6 butt joints Acta Mater. 58 2056–67

[14] Sekhar S R, Chittaranjandas V, Govardhan D and Karthikeyan R 2018 Effect of tool rotational speed on friction stir spot welded AA5052-H38 aluminium alloy Mater Today: Proceedings 5 5536–43

[15] Wang B B, Xue P, Xiao B L, Wang W G, Liu Y D and Ma Z Y 2020 Achieving equal fatigue strength to base material in a friction stir welded 5083-T19 aluminium alloy joint Sci. Technol. Weld. Joining 25 81–8

[16] Zhang B, Lin X X, Guo Q, Wang W, Zhu L L and Wang K S 2015 Evolution of grain characteristics of forced cooling friction stir processed 2024 aluminium alloy Rare Mater. Engin. 44 1479–84

[17] Zeng X H, Xue P, Wang D, Ni D K, Xiao B L and Ma Z Y 2018 Realising equal strength welding to parent metal in precipitation-hardened Al-Mg-Si alloy via low heat input friction stir welding Sci. Technol. Weld. Joining 23 478–86

[18] Xue P, Xiao B L, Zhang Q and Ma Z Y 2011 Achieving friction stir weld joint of pure copper joints with nearly equal strength to the parent metal via additional rapid cooling Scr. Mater. 64 1051–4

[19] Wang K S, Guo Q, Wang W, Guo W and Wu N 2013 Effect of cooling medium on microstructure and property of AZ31 magnesium alloy in friction stir welding J. Aerom. Mater. 33 35–7

[20] Liu W M, Yan Y F, Sun T, Wu S Y and Shen Y F 2019 Influence of cooling water temperature on ME20M magnesium alloy submerged friction stir welding: a numerical and experimental study Inter. J. Adv. Manuf. Technol. 105 5203–15

[21] Sheikhatv B S, Naladukura V N and Nagamothu K B 2020 Microstructures and mechanical properties of friction stir spot welded Al 6061 alloy lap joint welded in air and water Mater Today: Proceedings (https://doi.org/10.1016/j.jmatpr.2020.06.065)

[22] Rai R, De A, Bhadesia H K R D H and DebRoy T 2011 Review: friction stir welding tools Sci. Technol. Weld. Joining 16 325–42

[23] Hirasawa S, Badarinarayan H, Okamoto K, Tomimura T and Kawanami T 2010 Analysis of effect of tool geometry on plastic flow during friction stir spot welding using particle method J. Mater. Process. Technol. 210 1455–63

[24] Hu Y J, Sun Y P, He J M, Li W Z and Feng X H 2020 Effect of dwell time on microstructure and properties of friction stir spot weld for 2524 aluminium alloy Light Alloy Fabric Techn. 48 53–9

[25] Hu Y J, Sun Y P, He J M and Li W Z 2020 Effect of rotational speed on microstructure and properties of friction stir spot welding for 2524 aluminium alloy Mining Metall Engin. 40 139–43

[26] Mao Y Q, Zhao Y D, Jiang Z M and Ke L M 2018 Effect of assisted preheating temperature on weld formation of FSW of aluminium alloy thick plates Acta Aeron et Astron Sinica 39 422554 (in Chinese)

[27] Zhou L, Li G H, Zha G D, Shu F Y, Liu H J and Feng J C 2018 Effect of rotation speed on microstructure and mechanical properties of bobbin tool friction stir weld AZ61 magnesium alloy Sci. Technol. Weld. Joining. 23 596–605

[28] Akbari R, Mirdamadi S, Khodabande F and Paidar M 2016 A study on mechanical and microstructural properties of dissimilar FSWed joints of AA5251eAA5083 plates Int. J. Mater. Res. 107 752–61

[29] Shen J, Wen L, Luo X, Xu N, Wang L D and Liu M 2014 Development of novel heating tool friction stir spot welding (HT-FSSW) for AZ31 magnesium alloy Sci. Technol. of Weld Joining 19 369–75

[30] Zhou G N, Shen Y F, Li B, Yao L, Wu W X and Hu W Y 2013 Effect of plunge depth on interface distortion in friction stir spot welding Trans. Chin. Weld. Inst. 34 75–8

[31] Hu Y J, Sun Y P, He J M and Li W Z 2020 Effect of plunge depth for shoulder on microstructure and properties of friction stir spot weld joints for 2524 aluminium alloy Ords. Mater. Sci. and Engin. 43 52–6

[32] Devaraju A 2017 Influence of post-weld rapid cooling on grain size and mechanical properties of friction stir welded AA2014 Mater. Today: Proceedings 4 5722–7

[33] Liu X C, Sun Y F, Nagira T, Ushioda K and Fujii H 2019 Experimental evaluation of strain and strain rate during rapid cooling friction stir welding of pure copper Sci. Technol. Weld. Joining 24 352–9

[34] Zhao Y Q, Liu H J, Lin Z, Chen S X and Hou J C 2014 Microstructures and mechanical properties of friction spot welded Al clad 7004 T74 aluminium alloy Sci. Technol. Weld. Joining 19 617–22

[35] Roijink S, Muhayat N and Triyono 2018 Effect of rotation speed on mechanical properties and microstructure of friction stir spot welding (FSSW) Al 5052-steel SS400 Mater. Sci. Eng. 420 012–23