Effect of single-pass friction stir processing parameters on the microstructure and properties of 2 mm thick AA2524

Jiangmei He, Yijie Hu, Youping Sun, Wangzhen Li and Guojian Luo

School of Mechanical and Automotive Engineering, Guangxi University of Science and Technology, Guangxi Liuzhou 545006, People’s Republic of China

E-mail: hyj1476182318@163.com

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Abstract

Friction stir processing (FSP) is an important method for obtaining fine grains. To determine the effects of FSP and processing parameters on the microstructure and mechanical properties of rolled sheets, we performed single-pass FSP of a 2 mm thick 2524 aluminium alloy (AA2524) rolled sheet by comparing the combination of different processing parameters. The results show that lamellar grains (rolled state) are replaced by fine dynamic recrystallisation in the stir zone (SZ), and more Al2CuMg phases are precipitated simultaneously. As the rotation speed increases, the grain size and width of the pin stir zone (PSZ) increase, the microhardness first decreases and then increases; with the traverse speed increase, the grain size first decreases and then increases, and the width of the PSZ and microhardness decrease. The SZ has the smallest grain size, highest high-angle grain boundaries (HAGBs), with misorientation angles ($\theta$) > 15° ratio, and largest ultimate tensile strength (UTS), when the rotation and traverse speed were 1000 r·min$^{-1}$ and 125 mm·min$^{-1}$, are 1.59 ± 0.82 $\mu$m, 0.91 and 451.23 ± 0.52 MPa, respectively, and the elongation to fracture is 13%. The UTS and elongation were only 95.12% and 98.48% of those of the base metals (BM), respectively, because of the significant decrease in the dislocation density. Fracture analysis revealed ductile fracture of the joint due to the large number of dimples and fine second-phase particles.

1. Introduction

AA2524 is widely used in aircraft structural parts and skin owing to its high strength, low density, high damage tolerance, and fracture toughness [1–5]. Conventional high-strength AA2524 plates are typically prepared using rolling and heating treatments [5, 6]. The strength of the plate can be improved by the substructure, high-density dislocation entanglement, and a diffuse and fine precipitated phase [6]. However, a high-density substructure leads to a decrease in ductility, and the high-density texture generated during rolling is not conducive to anisotropy [1, 6]. Grain refinement is an important method for improving the alloy strength. FSP is an important method for the preparation of fine-grained materials. Currently, FSP is mainly used for material modification [7] and preparation of composite materials [8] because strong friction heat, plastic deformation, and material mixing occur during processing. Relevant studies have shown that the temperature range can reach 0.6–0.9 Tm (Tm = melting temperature), and the strain rate can reach 10 s$^{-1}$ and 1000 s$^{-1}$ in FSP [9, 10]; however, this cannot be achieved via other preparation methods. Therefore, complete dynamic recrystallization usually occurs in the SZ and forms fine HAGBs which is conducive to improving the strength, and random grain orientation is also conducive to reducing anisotropy [10, 11].

Existing research indicates that the main factors determining the structure and performance of an FSW/FSP include process parameters (rotation and traverse speeds), tool geometry [12, 13], and cooling medium [14]. Some studies have shown that a suitable combination of process parameters is a prerequisite for obtaining good structure and performance. Li et al [15] discussed the effect of traverse speed on the grains and properties of Al-Mg alloys. It was found that as the traverse speed increased, the grain size first decreased and then increased, the
tensile strength first increased and then decreased, and a HAGBs ratio exceeding 90% was found in the SZ. Moshwan et al. [16] discussed the effect of rotating speed on a 5052–O alloy and found that an appropriate increase in rotational speed is beneficial to second-phase refinement and dispersion distribution, which plays an important role in strength improvement. Zhou et al. [17] observed that a low rotating speed led to a low welding temperature, grooves on the joint surface and flashes, and pores at the edge of the SZ when the rotation speed was too high. All the above studies show that a suitable combination of rotation and traverse speed plays an important role in obtaining defect-free, uniform plates and fine grains, higher mechanical strength, and ductility.

At present, there are few reports on the FSP of 2 mm thick AA2524 sheets. To determine the effect of FSP and different processing parameters on rolling sheets, we performed single-pass FSP on a 2 mm thick AA2524 rolled sheet to discuss the influence of different parameter combinations (rotation speed and traverse speed) and to obtain the evolution of the microstructure and mechanical properties.

2. Materials and methods

2.1. Materials

Table 1 lists the nominal chemical compositions of AA2524 prepared via metal die casting. The ingots were homogenised at 485 °C for 10 h, rolled from 14 mm to 2 mm thickness in four passes at a strain rate of 10 s⁻¹, solution-treated at 495 °C for 1 h, and aged at 150 °C for 4 h. The final mechanical properties are listed in Table 1.

Table 1. Nominal chemical composition and mechanical properties of the AA2524 (mass fraction, wt%).

| Element | Mass Fraction, wt% | Ultimate Tensile Strength | Elongation | Microhardness |
|---------|--------------------|---------------------------|------------|---------------|
| Cu      | 4.5                | 474.37 MPa                | 13.2%      | 138.86 HV     |
| Mg      | 1.5                |                           |            |               |
| Mn      | 0.6                |                           |            |               |
| Zr      | 0.5                |                           |            |               |
| Ti      | 0.2                |                           |            |               |
| Al      | balance            |                           |            |               |

Figure 1 shows the optical metallographic structure and x-ray diffraction (XRD) pattern of the base metal (BM). Lamellar grains were observed along the rolling direction (RD). The TD and ND represent the transverse and normal directions, respectively. The grain size of the rolled sheets exceeded 100 μm. AA2524 has a medium Cu/Mg ratio, and the precipitation phase is Al₂CuMg [18], which is consistent with the XRD results (Figure 1(d)).

2.2. Experimental method

Figure 2(a) illustrates the processing tool. The shaft shoulder has a diameter of 10 mm. The tool has a conical pin with a 1.8 mm length and a diameter of 3 mm at the end, and a right-hand thread. The conical stir pin and screw thread are beneficial to the flow of the metal though the circumferential and axial directions [19]. Figure 2(b) shows the processing method and the tensile samples. The FSP was performed on a rolled plate. The oxide layer on the sheet surface was removed using a steel brush and cleaned with acetone prior to processing. FSP experiments were performed using a welding machine. Figure 2(c) shows the specifications of the tensile test samples, in which four samples were cut for each parameter set.

Table 2 lists the processing parameters, and all combinations of rotation and traverse speeds were tested in this experiment. The changes in the rolled structure after FSP and the effects of processing with different parameters were discussed. The macrostructure, grain, phase, microhardness and tensile strength of the SZ are the characteristics be concerned.

Metallographic samples were cut along the TD. A mixed acid solution (1 ml HF + 1.5 ml HCl + 2.5 ml HNO₃ + 95 ml H₂O) was used for corrosion. A Leica DMI 3000 M optical microscope was used to observe the microstructure. A smart-lab x-ray diffractometer was used for phase analysis. An ETM 105D electronic testing machine was used for the tensile test at a tensile speed of 2 mm-min⁻¹. The microhardness, tested by taking ten points in the SZ and averaging them, was tested using an HVS-1000Z machine with a load of 9.8 N, and loading time of 10 s. Tensile fractures were observed using a SIGMA field-emission scanning electron microscope (SEM). Electron backscatter diffraction (EBSD) samples were prepared by electrolytic polishing in a mixed solution (70% CH₃OH + 30% HNO₃) with a polishing voltage of −35 °C for 35 s at a scanning voltage of 20 kV.

3. Results and discussion

3.1. Macrostructure

Figure 3 shows the distribution of the different zones for different parameters. It can be seen that the lamellar grains (Figure 1) are replaced by fine grains because of dynamic recrystallization. Figure 3(b) shows the shoulder stir zone (SSZ), pin stir zone (PSZ), thermomechanically affected zone (TMAZ), and heat-affected zone (HAZ).
The width of the PSZ cannot be accurately determined because the PSZ and TMAZ have unclear boundaries, but the width has an increasing tendency as the rotation speed increases from 400 r·min⁻¹ to 1300 r·min⁻¹ (figures 3(a), (b), (e), (f)) and a decreasing tendency as the traverse speed increases from 25 mm·min⁻¹ to 150 mm·min⁻¹ (figures 3(c)–(e)). As the rotational speed increases, the strain rate and heat generated by the
friction between the tool and metal also increase, which is conducive to an increase in the SZ area [20]. An increase in traverse speed reduces the residence time of the heat source, which leads to a reduction in the area of the SZ [15].

The TMAZ can be divided into the advancing side (AS) and the retreating side (RS) because of the opposite flow directions. AS has the same direction as the rotation of the tool and the traverse direction, and RS has the opposite direction. A hole was observed in the SZ close to the AS, as shown in figure 3(a), because the metal could not fill the processing zone [20]. Holes appear on the AS rather than the RS because the RS metal has a higher strain rate [21]. A hole can be a source of cracks when a plate is stressed; therefore, it is necessary to eliminate hole defects. In this study, holes did not exist when the rotation speed was 700–1300 r·min⁻¹, and the traverse speed was 25–150 mm·min⁻¹.

3.2. Microstructure

Figure 4 shows EBSD analysis of grain size and grain boundary angle in PSZ with different processing parameters. The PSZ can usually represent the entire SZ because it occupies the largest area of the SZ (figure 3). There was no EBSD analysis of 400–125 because of the tunnel defects. As shown in figure 4, dynamic recrystallization occurred in all the SZs, and the ratio of HAGBs exceeded 0.75. When the parameter was 1000–125, the SZ has the minimum grain size and the maximum HAGBs ratio was 1.59 ± 0.82 μm and 0.91, respectively. The grain size decreased significantly on then rolled sheet. The dynamic recrystallization grain size was related to the strain rate and processing temperature. A high strain rate is conducive to reducing the grain size during recrystallization, and a high processing temperature will lead the recrystallized grain growth [15, 20, 22]. These two factors determine the grain characteristics during processing.

Figures 4 (a)–(c) show the grain characteristics when the traverse speed increases from 25 mm·min⁻¹ to 150 mm·min⁻¹ at a rotation speed of 1000 r·min⁻¹. As the traverse speed increases, the grain size first decreased and then increase, and the HAGBs ratio first increased and then decrease. An increase in traverse speed leads to a decrease in the generated heat and strain rate, which can inhibit the endothermic growth of dynamic recrystallization grains, whereas a reduction in the strain rate is not conducive to the refinement of recrystallised grains [15]. The grain size was reduced from 25 mm·min⁻¹ to 125 mm·min⁻¹ showing that grain refinement due to lower heat was dominant. The grain size increased from 125 mm·min⁻¹ to 150 mm·min⁻¹, indicating that dynamic recrystallisation grain growth due to the decrease in strain rate is dominant.
Figures 4 (b) and (d) show the grain characteristics of 1000–125 and 1300–125. As the rotational speed increased from 1000 $\text{r min}^{-1}$ to 1300 $\text{r min}^{-1}$, the grain size increased from 1.59 ± 0.82 $\mu\text{m}$ to 1.85 ± 0.91 $\mu\text{m}$. An increased rotational speed is conducive to increasing the strain rate and heat generation [20]. The grain size increased slightly, indicating that the grain growth caused by the increase in heat was greater than the grain size reduction caused by the increase in deformation. Another explanation is that an excessively high rotation speed and temperature will reduce the viscosity of the metals, which will result in sliding friction between the stir pin and the material, leading to a decrease in the degree of deformation [17, 23].

There are also many changes in the structure compared to the rolled sheet after FSP, except for the SZ, which has been reported in many studies. EBSD analysis was performed for these regions below. The SZ had the smallest average grain size at 1000–125; therefore, EBSD analysis was conducted on other zones of this parameter. Figure 5(a) shows the characteristics of the SSZ, which underwent complete dynamic recrystallization, the average size and the ratio of HAGBs were 3.02 ± 4.42 $\mu\text{m}$ and 0.22, respectively. The grain size is larger than that of the PSZ (figure 4(b)) and has an uneven distribution because the heat generated by the friction between the shoulder and the materials is higher than that generated by the stirring pin, which leads to the growth of recrystallised grains [24]. Figure 5(b) shows discontinuous dynamic recrystallization in the TMAZ,
where the grains were distributed along the direction of the organisation flow. The TMAZ is usually subjected to heat and extrusion from the SZ. The grains in the upper right had complete dynamic recrystallisation close to the SZ, whereas the grains in the lower left did not undergo dynamic recrystallisation but were broken, indicating that heat and strain transfer was gradually lost away from the SZ, and recrystallisation did not occur sufficiently. The final average grain size is only 1.69 ± 2.16 μm because many fine grains are formed after dynamic recrystallisation. The distribution of subgrain recrystallisation along the flow microstructure explains why the ratio of HAGBs was only 0.46. Figure 5 shows the microstructure of the HAZ. The metals in this zone are only affected by high temperatures during processing, which leads to grain recovery and growth. The average grain sizes and ratios of HAGBs are 11.42 ± 7.95 μm and 0.62, respectively. The grain orientation in this zone is typically close to that of the BM.

3.3. XRD analysis

Figure 6 shows the XRD phase analysis for different processing parameters. As a precipitation-strengthening alloy, the state of the precipitation phase in AA2524 significantly influences its mechanical properties. Therefore, the characteristics of the precipitated phase in the SZ were tested using XRD after the FSP. Some reach shows that peak temperature achieves the range of 0.6–0.9 Tm during FSP, which is higher than the solution temperature of many aluminium alloys [25]. Such high temperatures lead to precipitated-phase dissolution or precipitation [26, 27]. In figure 6, the diffraction peak intensity is higher than that of the BM (figure 1(d)), which indicates precipitation of the Al2CuMg phase during FSP. In figure (a), there are apparent diffraction peaks of the Al2CuMg phase at 400 r·min⁻¹ to 1000 r·min⁻¹, which gradually decreased in intensity, while the diffraction peaks disappeared at 1300 r·min⁻¹. In figure (b), as the traverse speed increases from 25 mm·min⁻¹ to 125 mm·min⁻¹, the diffraction peak intensity of the Al2CuMg phase increases gradually but disappears at 150 mm·min⁻¹. This is consistent with the law that an increase in rotational speed and a decrease in traverse speed.
will lead to an increase in temperature and facilitate the precipitation of the phase, while excessively high processing heat may lead to the dissolution of the phase \[26, 27\]. Combined with figures (a) and (b), the higher diffraction peak intensity for the Al2CuMg phase appeared at 1000–125.

Dislocation density is an important factor that affects the mechanical strength. The dislocation density and microstrain of the alloy were measured using XRD profile analysis \(\varepsilon_X\), and was calculated by XRD peak broadening using the Williamson-Hall method. It is assumed that the broadening is caused by particle broadening and microstrain \[28–30\].

\[
\frac{2\beta \cos \theta}{\lambda} = \frac{0.9}{d} + \frac{2\varepsilon_X \sin \theta}{\lambda}
\]

where \(\beta\) is the width of the half-peak at the maximum of the XRD diffraction peak, \(\theta\) is the Bragg angle, \(2\theta\) is the peak position of each diffraction peak, \(\lambda\) is the wavelength of the Cu K\(\alpha\) radiation (\(\lambda = 0.15418\) nm), \(d\) is the size of the XRD coherent diffraction zone, and \(\varepsilon_X\) is the microstrain. The broadening effect caused by the grain size was only effective when the grain size was less than 100 nm. This can be ignored in alloys, and the dislocation density \(\rho\) can be calculated as follows \[31, 32\]:

\[
\rho = \frac{k\varepsilon_X}{Fb^2}
\]

where \(b\) is the Burgers vector, which is 0.286 nm, \(k = 16.1\) and \(F = 1\) \[30\]. Table 3 presents the results of the final calculations. The dislocations were calculated and are listed in table 3. The results showed that the dislocation density after FSP was lower than that after BM because the dislocations were consumed by dynamic recrystallisation during processing. The maximum dislocation density is at 1000–125.

### 3.4. Mechanical property

Figure 7 shows the microhardness distribution in the SZ for different parameters. The results show the microhardness of BM (rolled state) is 138.86 \(\pm\) 4.88, 150.04 \(\pm\) 2.64 at 1000–125, and 141.08 \(\pm\) 1.27 at 1300–125. The microhardness declined slightly after FSP compared with the BM, and gradually decreased with the increase in traverse speed; with the increase in rotation speed, the microhardness first decreased and then increased. The microhardness usually depends on the grain size, dislocation density, and distribution of the precipitated phase. A trace precipitated phase exists after FSP (in figure 1(d) and figure 6), and the grain is significantly refined (in figure 4), which is conducive to the increase in microhardness. However, a significant decrease in the dislocation density (in figure 3) will lead to a decrease in microhardness. In figure 7, the microhardness decreases but is not significant.

Figure 8 shows the tensile properties for different processing parameters. The UTS first increases and then decreases as the rotational and traverse speeds increase. The UTS reaches to a maximum of 1000–125, which is

### Table 3. The dislocation density in different processes.

| States     | BM   | 400–125 | 700–125 | 1000–25 | 1000–75 | 1000–125 | 1000–150 | 1300–125 |
|------------|------|---------|---------|---------|---------|----------|----------|----------|
| Dislocation density \(\rho\) \(\times 10^{13}/\text{m}^{-2}\) | 32.8 | 4.59    | 3.13    | 5.65    | 1.19    | 17       | 1.89     | 4.67     |
451.23 ± 0.52 MPa, because of both the dislocation strengthening and fine grain strengthening, as it has the smallest grain size (figure 4(b)) and the largest dislocation density (table 2) compared to other parameters.

Figure 5(b) shows the elongation, but there is no obvious trend as the rotating and traverse speeds increase, with a maximum value of 14.25% at 700–25 and 13% at 1000–125. Figures 5(c) and (d) show the tensile stress-strain curves for different processing parameters.

At 1000–125, the strength and elongation reached 95.12% and 98.48% of the BM (table 1), respectively. The strength and elongation are close to those of the BM because the processing zone is strengthened by grain
refinement (figure 4) and the precipitation phase (figure 6). In contrast, the strength was slightly reduced because of the dislocation density (table 2), and the microhardness (figure 7) was significantly reduced.

3.5. Tensile fracture
Figure 9 shows the tensile fractures for different parameters. There was little difference in the fracture morphologies under different processing parameters. All the fractures had many fine and uniform dimples. Many fine second-phase particles can be observed at the bottom of the dimples, indicating the ductile fracture characteristics of the BM and the processing sheet.

Figure 10 shows the relationship between the grain size, tensile strength, and elongation for AA2524 prepared by different processing methods and FSP/FSW of different Al alloys. Owing to the lack of studies on FSP/FSW of AA2524, other grades of Al alloys have been studied. Compared with AA2524 prepared by rolling [1–5], the plate prepared by this method had the smallest average grain size and moderate strength and elongation. Compared with other aluminium alloys, such as FSP/FSW [15, 20, 33–42], the plate prepared by this process has a fine grain size and high strength.

4. Conclusions
FSP was performed on 2 mm thick rolled AA2524 by comparing the combinations of different rotation and traverse speeds, The results show that:
(1) Compared with the BM, dynamic recrystallisation occurred in the SZ after the FSP, and the ratio of HAGBs was greater than 0.75. A large amount of the Al2CuMg phase precipitated during processing; however, the dislocation density decreased because of the consumption of dislocations caused by recrystallisation.

(2) With an increase in the rotational speed, the area of the SZ increased, the dynamic recrystallisation increased, the intensity of the diffraction peak of the Al2CuMg phase gradually decreased, the microhardness first decreased and then increased, and the tensile strength first increased and then decreased.

(3) As the traverse speed increases, the area of the SZ decreases gradually, the grain size decreases first and then increases, the intensity of the diffraction peak of the Al2CuMg phase increases first and then decreases, the microhardness decreases gradually, and the tensile strength first increases and then decreases.

(4) The maximum UTS at 1000–125 is 451.23 ± 0.52 MPa, and the elongation to fracture is 13%, because it has the smallest average grain size, the largest dislocation density and HAGBs ratio. There were only 95.12% and 98.48% of the BM, respectively, because of the significant reduction in dislocation density and microhardness, and the difference in the tissue between the pin and SSZ.

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Data availability statement

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

Conflict of interest

The authors declare that they have no conflict of interest.

ORCID iDs

Yijie Hu https://orcid.org/0000-0002-1687-8649

References

[1] Chen Y, Xiong C, Liu W, Pan S, Song Y, Liu Y and Zhu B 2021 Texture evolution and control of 2524 aluminum alloy and its effect on fatigue crack propagation behavior Appl. Sci. 11 5550
[2] Li F D, Liu Z Y, Wu W T, Xia P, Ying P Y, Zhao Q, Li J L, Bai S and Ye C W 2016 On the role of texture in governing fatigue crack propagation behavior of 2524 Aluminum Alloy Mater. Sci. Eng. A 669 367–78
[3] Li F D, Liu Z Y, Wu W T, Xia P, Ying P Y, Zhou Y R, Liu W J, Lu L Q and An W 2017 Enhanced fatigue crack propagation resistance of Al-Cu-Mg alloy by intensifying Goss texture and refining Goss grains Mater. Sci. Eng. A 679 204–14
[4] Shou W B, Yi D Q, Liu H Q, Tang C, Shen F H and Wang B 2016 Effect of grain size on the fatigue crack growth behavior of 2524–T3 aluminum alloy Arch Civ Mech Eng. 16 304–12
[5] Ying P, Liu Z, Bai S, Wang J, Li J, Liu M and Xia L 2017 Effect of artificial aging on the Cu-Mg co-clustering and mechanical behavior in a pre-strained Al-Cu-Mg alloy Mater. Sci. Eng. A 707 412–8
[6] Sun Y P, Hu Y J, Wang S H, He J M, Yang C Y and Zhai C T 2022 Evolution of subgrains, dislocations and mechanical properties in a 2524Al alloy during the high-strain-rate rolling J. Mater. Eng. Perform 31 2321–6
[7] Arora H S, Singh H and Dhindaw B K 2012 Composite fabrication using friction stir processing—a review Int. J. Adv. Manuf. Technol. 61 1043–53
[8] Luo Z A, Xie G M, Ma Z Y, Wang G L and Wang G D 2013 Effect of yttrium addition on microstructural characteristics and superplastic behavior of friction stir processed ZK60 alloy J. Mater. Sci. Technol. 29 1116–22
[9] Hu Y J, Sun Y P, He J M, Yang C Y, Wan S Y and Zhai C T 2022 Effect of friction stir processing parameters on microstructure and properties of ZK60 magnesium alloy Mater. Res. Express 9 016508
[10] Mansoor B and Ghosh A K 2012 Microstructure and tensile behavior of a friction stir processed magnesium alloy Acta Mater. 60 3079–88
[11] Yang Q, Feng A H, Xiao B L and Ma Z Y 2012 Influence of texture on superplastic behavior of friction stir processed ZK60 magnesium alloy Mater. Sci. Eng. A 556 671–7
[12] De Giorgi M, Scalpi A, Panella F W and De Filippis L A C 2009 Effect of shoulder geometry on residual stress and fatigue properties of AA6082 fsw joints J. Mater. Sci. Technol. 23 26–35
[13] Wang G Q, Zhao Y H and Hao Y F 2018 Friction stir welding of high-strength aerospace aluminum Alloy and application in rocket tank manufacturing J. Mater. Sci. Technol. 34 73–91
14. Heidazadeh A et al 2021 Friction stir welding/processing of metals and alloys: A comprehensive review on microstructural evolution Prog. Mater. Sci. 117 100752
15. Li Y L, Yan H G, Chen J H, Xia W J, Su B, Ding T and Li X Y 2020 Influences of welding speed on microstructure and mechanical properties of friction stir welded Al–Mg alloy with high Mg content Mater. Res. Express 7 076506
16. Moshwani R, Yusof F, Hassan M A and Rahmat S M 2015 Effect of tool rotational speed on force generation, microstructure and mechanical properties of friction stir welded Al–Mg–Cr–Mn (AA 3052-O) alloy Mater. Des. 66 118–28
17. Zhou L, Li G H, Zhu G D, Shi F Y, Liu H J and Feng F C 2018 Effect of rotation speed on microstructure and mechanical properties of bobbin tool friction stir welded AZ61 magnesium alloy Sci. Technol. Weld. Joining 23 596–605
18. Quan L W, Zhao G, Gao S and Muddle B C 2011 Effect of pre-stretching on microstructure of aged 2524 aluminium alloy Trans. Nonferrous Met. Soc. China 21 1957–62
19. Reza-E-Rabby M, Tang W and Reynolds A P 2018 Effects of thread interruptions on tool pins in friction stir welding of AA6061 Sci. Technol. Weld. Joining 23 114–24
20. Li Y L, Xia W J, Yan H G, Chen J H, Ding T, Sun Y P and Li X Y 2021 Microstructure and mechanical properties of friction-stir-welded high-Mg alloyed Al–Mg alloy plates at different rotating rates Rare Met. 40 2167–78
21. Zhao Y H, Lin S B, Wu L and Qu F X 2005 The influence of pin geometry on bonding and mechanical properties in friction stir weld 2014 Al alloy Mater. Lett. 59 2948–52
22. Shen J L, Liu H J and Cai F 2010 Effect of welding speed on microstructure and mechanical properties of friction stir welded copper Mater. Des. 31 9397–42
23. Arora K S, Pandey S, Schaper M and Kumar R 2010 Effect of process parameters on friction stir welding of aluminum alloy 2219-T87 Int. J. Adv. Manuf. Technol. 50 941–52
24. Rai R, De A, Bhadadhi H K D H and DeBroy T 2011 Review: friction stir welding tools Sci. Technol. Weld. Joining 16 325–42
25. Padhy G K, Wu C S and Gao S 2018 Friction stir base welding and processing technologies - processes, parameters, microstructures and applications: A review Int. Mater. Sci. Technol. 34 1–38
26. Hou J C, Liu H J and Zhao Y Q 2014 Influences of rotation speed on microstructures and mechanical properties of 6061–T6 aluminum alloy joints fabricated by self-reaction friction stir welding tool Int. J. Adv. Manuf. Technol. 73 1073–9
27. Chu Q, Li W Y, Yang X W, Shen J J, Vairis A, Feng W Y and Wang W B 2018 Microstructure and mechanical optimization of prokale friction stir spot welded joint of an Al–Li alloy J. Mater. Sci. 34 1739–46
28. Ma K, Wen H, Hu T, Topping T D, Isheim D, Seidman D N, Lavernia E J and Schoening J M 2014 Mechanical behavior and strengthening mechanisms in ultrafine grain precipitation-strengthened aluminum alloy Acta Mater. 62 141–55
29. Williamson G, Hall K and H W 1953 X-ray line broadening from alloyed aluminium and wolfram Acta Metall. 1 22–31
30. Williamson G K and Smallman R E III 1956 Dislocation densities in some annealed and cold-worked metals from measurements on the x-ray debye–scherer spectrum Philos. Mag. 1 34–46
31. Li Z et al 2021 Achieving high damping and excellent ductility of Al Mg alloy sheet by the coupling effect of Mg content and fine grain structure Mater. Charact. 174 110974
32. Ma K et al 2014 Mechanical behavior and strengthening mechanisms in ultrafine grain precipitation-strengthened aluminum alloy Acta Mater. 62 141–55
33. Gao S, Wu C S and Padhy G K 2017 Material flow, microstructure and mechanical properties of friction stir welded AA 2024–T3 enhanced by ultrasonic vibrations J. Manuf. Process. 30 385–95
34. Panga Q, Zhang H H, Mohammad J H and Hu Z L 2019 Characterization of microstructure, mechanical properties and formability for thermomechanical treatment of friction stir welded 2024–O alloys Mater. Sci. Eng. A 765 138303
35. Yadav V K, Gaur V and Singh J V 2020 Effect of post-weld heat treatment on mechanical properties and fatigue crack growth rate in welded AA-2024 Mater. Sci. Eng. A 779 139116
36. Dong J H, Gao C, Yao L, Han J, Jiao X D and Zhu Z X 2017 Microstructural characteristics and mechanical properties of bobbin-tool friction stir welded 2024–T3 aluminum alloy Int. J. Miner. Metall. Mater. 24 2226–33
37. Chen Y, Wang H, Wang X Y, Ding H, Zhao J W, Zhang F H and Ren Z H 2019 Influence of tool pin eccentricity on microstructural evolution and mechanical properties of friction stir processed Al-5052 alloy Mater. Sci. Eng. A 739 272–6
38. 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
39. Yang C et al 2020 Microstructure and mechanical properties of double-side friction stir welded 6082Al ultra-thick plates J. Mater. Sci. Technol. 41 105–16
40. Chen Y, Li H Y, Wang X Y, Ding H and Zhang F H 2020 A Comparative Study on Stationary–Shoulderand Conventional Friction-Stir-Processed Al-6061 Alloy J. Mater. Eng. Perform. 29 1185–93
41. Yang W J, Ding H and Li J Z 2021 Parametric optimization for friction stir processing in Al–Zn–Mg–Cu alloy Mater. Manuf. Process. 37 1–10
42. Chen Y, Jiang F F, Ding H, Zhao J W and Li J Z 2018 Effects of friction-stir processing with water cooling on the properties of an Al–Zn–Mg–Cu Alloy Mater. Sci. Technol. 34 153–60