Improvement of Microstructural and Mechanical Characteristics of Friction Stir Welded AA6061 Aluminium Alloy Joint

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Abstract: To improve mechanical characteristics of friction stir welded joint made of AA6061-T6, AA2024 was used as a filler material due to its high strength and compatibility with AA6061 aluminium alloy. Different filler strip thickness (1, 1.5, and 2 mm) were investigated. Homogenous plastic deformation of the mixture with soft and refined grains was observed in the stir zone due to dynamic recrystallization of the grains. Friction stir welded joints with filler strip showed high hardness and tensile strength compared with filler-free joints. Welded joint with 1 mm filler strip has the highest tensile strength among other joints due to the dynamic recrystallization of the refined grains as a result of heat concentration. In addition, using greater thickness of filler strips makes the joining process more difficult, causes joint defects and reduces the tensile strength of welded joints.

Key words: Friction Stir Welding; dissimilar alloys; AA6061 Aluminum Alloy; Mechanical Characteristics; Microstructure.

1. Introduction
Friction stir welding (FSW) was developed in Cambridge by TWI, UK in 1991 [1]. As a solid-state welding method, it has several advantages over traditional fusion welding techniques, such as high joint strength, lack of cracks, less distortion, clean and save power [2-4]. FSW is widely applied for various alloys in comparison with traditional welding techniques. FSW can be used for similar or dissimilar materials like aluminium alloys, titanium and copper alloys. As well as, a lot of application use FSW technique via various types of FSW machines like horizontal, vertical and longitudinal in the industrial range such as the floor panel of recent ships or train [5]. Nowadays, FSW has many worldwide applications, for example, fabrication of aluminium components, manufacturing of airframe structures for commercial and military aircraft, recent automotive manufacturing and space shuttle external tanks. The main idea of FSW is very simple, a revolving tool of non-consumable material has three main functions, heating of the workpiece, material stirring to produce the joint, and...
restraint of the soft metal under the shoulder of the tool and causes plastic deformation in the metal which leads to solid-state joining in the surrounding area [6]. The strength of FSW joints depends on many parameters such as tool rotation, traverse speed, tool tilt angle, plunge depth and flow of material. The flow of material through FSW has important role which controls the formation of joints without defects and the microstructural characteristics during the weld, therefore. Joining of dissimilar materials is difficult when compared to joining similar materials, due to the difference in chemical composition and mechanical characteristics of the base materials [7-9]. Lap joints which consisted of AA6061–AA 5052 alloys and AA6061 alloy above it, had high Mechanical strength [10] due to the change of joint strength using different thicknesses of plates. For dissimilar lap joining of AA2024 and AA7075 aluminium alloys, increasing in hook size was observed when the AA7075 alloy was located above the joint [11]. Enhanced mechanical properties are achieved when a stronger material is involved in the advancing (AS) side and softer material in the retreating side (RS) [12-14]. AA6061 and 2024 aluminium alloys were selected in this study because they are used in many fields such as aerospace, marine manufacturing and storage tanks [15]. Much effort has been made to improve the mechanical properties of FSW joints by computational [16, 17] and practical methods [18-20].

Herein, the microstructural and mechanical properties of friction stir welded AA6061-T6 aluminium alloy joint have been improved where strips of AA2024 with different thickness were added vertically in between the base metal of the joints. AA2024 strips were used as a filler material which has high strength and good compatibility with AA6061. Traditional FSW tool was used, mechanical and microstructural characteristics of all joints were investigated. The main objective of this work is to increase the strength of AA6061 aluminium alloy joints using high strength material such as AA2024 by FSW process.

2. Materials and Methods

In the present investigation, AA6061-T6 aluminium alloy was used as a base metal and the AA2024 aluminium alloy was used as a filler metal. The chemical compositions of AA6061-T6 and AA2024 aluminium alloys were presented in Table 1. Two plates (120 ×50×8) mm were prepared for the formation of a butt joint, while three AA2024 filler strips with the same length and different thickness (1, 1.5, 2) mm were inserted vertically between the base metal plates, as well as AA6061-T6 joint was welded without filler strip for comparison purpose. FSW was carried out using computer numerical control (CNC) milling machine. FSW was performed using H13 steel tool with 20 mm shoulder diameter and a cylindrical threaded pin with 6 mm diameter and 3 mm length.

Table 1. Chemical composition of AA6061 and AA2024 aluminum alloys (wt. %).

| Alloy    | Si    | Fe | Cu     | Mn     | Mg     | Zn     | Cr    | Ti    | Al    |
|----------|-------|----|--------|--------|--------|--------|-------|-------|-------|
| AA6061   | 0.543 | 0.0009 | 0.237  | 0.00551 | 1.07   | 0.00549 | 0.221 | 0.047 | 97.86 |
| AA2024   | 0.0516 | 0.131 | 6.35   | 0.475  | 1.85   | 0.0648  | 0.0001 | 0.0554 | 91.02 |

AA6061/AA2024/AA6061 butt joints were welded using tool rotational speed of 2000 rpm, welding speed of 25 mm/min, and zero tilt angle. welding was performed perpendicular to rolling direction. A schematic illustration of the FSW technique with filler strip was shown in Figure 1.
3. Results and discussion

3.1 Microstructural Investigations

Figure 2 shows a micrograph of the microstructure of AA6061 base alloy. The microstructure consists of coarser elongated α-Al grains in which the grains are oriented along the rolling direction, and black spots attributed to over etching during microscope investigation. Figure 3 shows typical micrographs of the microstructure at the center of the SZs developed using a different AA2024 strip thicknesses. SZs exhibited finer grains compared to the base alloy. This may be due to the concentration of heat that causes excessive fine grains in equiaxed shape in the SZ, where higher plastic deformation of the material occurs in this region due to dynamic recrystallization [21]. Highly refined grains may enhance the strength of the welded joint [22]. The results revealed that when using a strip with thickness of 1 mm or 1.5 mm, SZs show a lower average grain size when compared to SZs developed without a filler strip, while SZ developed using 2 mm strip shows the largest average grain size. Consequently, it is evidence of a direct relationship between grain size and strip thickness, as the heat generated from the tool shoulder is insufficient to soften and refine the filler material grains.

Figure 2. The microstructure of AA6061-T6 base alloy.
3.2 Mechanical Characteristics

3.2.1 Hardness of welded joints. The Hardness of welded regions developed using AA2024 filler strips is higher than that developed without filler strip. The peak hardness of SZ at the joint without filler strip was about 49 VH. The SZ developed using 1 mm strip showed higher peak hardness, compared to that developed using 2mm and 1.5mm strips. The peak hardness of welded regions developed using 1, 1.5, and 2mm filler strip were 106, 94 and 101 VH, respectively, as shown in Figure 4(a). Thus, a proportional relation between hardness and strip thickness was observed. The increased hardness of welded regions developed using AA2024 filler strips may be attributed to higher hardness of AA2024 alloy which contains Cu particles as well as interference between AA6061 and AA2024 grains with homogenous distribution which increases hardness of the joints [23].

3.2.2 Tensile Characteristics. Tensile test was performed for FS AA6061 specimens with and without AA2024 filler strips, and it was observed that all tensile failures occurred outside the SZ, which was attributed to the fact that the SZ strength was higher than other zones, moreover, specimens with 1 mm AA2024 filler strip has the highest tensile strength. A gradual decreasing in the tensile strength was detected for specimens with 1.5 and 2 mm filler strip, respectively, while a joint without filler strip has less tensile strength compared to other joints, as shown in Figure 4(b). Small thickness of the filler strip resulted in sufficient contact surface of the revolving pin between the workpiece and the filler strip, making an adequate blend and improved plastic flow. Results show that maximum ultimate tensile strength (UTS) value for the joint with 1 mm strip is 215 MPa, while the UTS for the as received base metal is 175 MPa, this may be attributed to deep dimples that enhance ductility and strength.
4. Conclusions

In order to improve the mechanical characteristics of AA6061-T6 joint, AA2024 strips were used as a filler material between the joint plates with a suitable process parameter. The following conclusions can be drawn:

- Homogenous plastic deformation of the mixture was observed in the stir zone, soft and refined grains were also detected due to the dynamic recrystallization of the grains as a result of heat concentration, especially for the joint with lower filler strip thickness.
- Increasing the thickness of AA2024 filler strip results in joint defects and reduces the tensile strength of welded joints.
- FSW joints with filler strip showed high hardness and tensile strength at the SZ compared to joints without AA2024 filler strip.

References

[1] W.M. Thomas, E.D.N., J.C. Needham, M.G. Murch, P. Templesmith, C.J. Dawes, G.B. Patent Application No. 9125978.8 (December 1991).
[2] Wan, L., et al., Effect of self-support friction stir welding on microstructure and microhardness of 6082-T6 aluminum alloy joint. Materials & Design, 2014. 55: p. 197-203.
[3] Zhang, L., et al., Friction stir welding of Al alloy thin plate by rotational tool without pin. Journal of Materials Science & Technology, 2011. 27(7): p. 647-652.
[4] Nandan, R., T. DebRoy, and H. Bhadeshia, Recent advances in friction-stir welding-process, weldment structure and properties. Progress in materials science, 2008. 53(6): p. 980-1023.
[5] Zargar, O.A., Friction Stir Welding Aluminum Alloy H20-H20 Conventional and Overlap Joints Mechanical Properties. Manufacturing Science and Technology, 2014. 2(2): p. 27-33.
[6] Cam, G. and S. Mistikoglu, Recent developments in friction stir welding of Al-alloys. Journal of Materials Engineering and Performance, 2014. 23(6): p. 1936-1953.
[7] Heidarzadeh, A., et al., Tensile behavior of friction stir welded AA 6061-T4 aluminum alloy joints. Materials & Design, 2012. 37: p. 166-173.
[8] Amancio-Filho, S., et al., Preliminary study on the microstructure and mechanical properties of dissimilar friction stir welds in aircraft aluminium alloys 2024-T351 and 6056-T4. Journal of materials processing technology, 2008. 206(1-3): p. 132-142.
[9] Babu, S., et al., Microstructure and mechanical properties of friction stir lap welded aluminum alloy AA2014. Journal of Materials Science & Technology, 2012. 28(5): p. 414-426.
[10] Soundararajan, V., E. Yarrapareddy, and R. Kovacevic, Investigation of the friction stir lap welding of aluminum alloys AA 5182 and AA 6022. Journal of Materials Engineering and Performance, 2007. 16(4): p. 477-484.
[11] Song, Y., et al., *Defect features and mechanical properties of friction stir lap welded dissimilar AA2024–AA7075 aluminium alloy sheets*. Materials & Design, 2014. 55: p. 9-18.

[12] Xue, P., et al., *Effect of friction stir welding parameters on the microstructure and mechanical properties of the dissimilar Al–Cu joints*. Materials science and engineering: A, 2011. 528(13-14): p. 4683-4689.

[13] Padmanaban, G. and V. Balasubramanian, *Selection of FSW tool pin profile, shoulder diameter and material for joining AZ31B magnesium alloy—an experimental approach*. Materials & Design, 2009. 30(7): p. 2647-2656.

[14] Kwon, Y., I. Shigematsu, and N. Saito, *Dissimilar friction stir welding between magnesium and aluminium alloys*. Materials Letters, 2008. 62(23): p. 3827-3829.

[15] Sadeesh, P., et al., *Studies on friction stir welding of AA 2024 and AA 6061 dissimilar metals*. Procedia Engineering, 2014. 75: p. 145-149.

[16] Shehabeldeen, T.A., et al., *Modeling of friction stir welding process using adaptive neuro-fuzzy inference system integrated with harris hawks optimizer*. 2019.

[17] Okuyucu, H., et al., *Artificial neural network application to the friction stir welding of aluminium plates*. 2007. 28(1): p. 78-84.

[18] Ma, H., et al., *Gap-tolerance control for friction stir butt welding of 2A14 aluminium alloy*. 2019. 148: p. 106915.

[19] Rajakumar, S., et al., *Influence of friction stir welding process and tool parameters on strength properties of AA7075-T6 aluminium alloy joints*. 2011. 32(2): p. 535-549.

[20] Costa, M., et al., *Dissimilar friction stir lap welding of AA 5754-H22/AA 6082-T6 aluminium alloys: Influence of material properties and tool geometry on weld strength*. 2015. 87: p. 721-731.

[21] Babu, S.R., et al., *Microstructural changes and mechanical properties of friction stir processed extruded AZ31B alloy*. Procedia Engineering, 2012. 38: p. 2956-2966.

[22] El-Hafez, H.A., *Mechanical properties and welding power of friction stirred AA2024-T35 joints*. Journal of materials engineering and performance, 2011. 20(6): p. 839-845.

[23] Kalaiselvan, K., I. Dinaharan, and N. Murugan, *Characterization of friction stir welded boron carbide particulate reinforced AA6061 aluminium alloy stir cast composite*. Materials & Design, 2014. 55: p. 176-182.