Archives of Materials Science and Engineering

Volume 124
Issue 1
November 2023
Pages 14-24

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

DOI: 10.5604/01.3001.0054.3228

Influence of tool pin profile and welding parameters on microstructure and mechanical properties of dissimilar friction stir welded AA2024 to AA7075 alloys

H.B. Mohammed [a], I.M. Naemah [a], A.J.S. Jomah [b], A.A.A.G. Alrubaiy [b,*]

[a] Department of Mechanical Engineering, University of Diyala, Iraq

[b] Department of Materials Engineering, University of Diyala, Iraq

* Corresponding e-mail address: Ahmed_ali_eng@uodiyala.edu.iq

ORCID identifier: https://orcid.org/0000-0002-3331-321X (A.A.A.G.A.)

ABSTRACT

Purpose: The paper aims to produce aluminium welds in the solid state with good specifications and the least amount of welding defects by using the friction stir welding method (FSW) and different tool pin profiles and welding parameters. The research investigated the mechanical characteristics and microstructure of a friction stir welded dissimilar aluminium alloy (2024-T3 to 7075-0) through thickness produced by varying welding settings and three different FSW tool pin shapes.

Design/methodology/approach: The objective is to obtain the welds with the least amount of welding defects in the solid state by using the friction stir welding method (FSW), designing the tool pin profiles, and changing the rotation speeds.

Findings: According to tensile strength and micro-hardness tests, tool rotation of 2000 rpm and square pin profile were the best compared to other working parameters. The greatest hardness and highest tensile strength of FSWed dissimilar aluminium joints have been 144 HV and 215 MPa, respectively, when using the square pin profile at a tool rotation speed of 2000 rpm. The hardness and tensile strength of FSWed dissimilar aluminium alloy joints increase with the tool rotation speed. Microstructural observations of the FSWed dissimilar aluminium joints using a square pin profile at the tool rotation speed of 2000 rpm exhibited the weld zone's high weld quality. Additionally, there were no defects in the weld zone. The fracture surface of the FSWed joint indicated a ductile fracture type.

Research limitations/implications: With many regions on either side of the weld with varied compositions, microstructures, and characteristics, the resulting welds of dissimilar alloys might result in unsatisfactory weld joints.

Practical implications: The weld zone's exceptional weld quality was demonstrated by microstructural investigations of the FSWed dissimilar aluminium connections utilising a square pin profile at a tool rotation speed of 2000 rpm and feed rate of 20 mm per minute.

Application in aerospace, shipbuilding and marine, railway, construction, electrical industries, and land transportation.

Originality/value: The original value of the paper is the production of welds from dissimilar aluminium alloy (2024-T3 to 7075-0) with the least amount of welding defects by changing the tool pin profiles and tool rotation speeds using the friction stir welding method.

Keywords: Friction stir welding, Aluminium alloys, Tool pin profile, Mechanical properties, Welding parameters

Reference to this paper should be given in the following way:

H.B. Mohammed, I.M. Naemah, A.J.S. Jomah, A.A.A.G. Alrubaiy, Influence of tool pin profile and welding parameters on microstructure and mechanical properties of dissimilar friction stir welded AA2024 to AA7075 alloys, Archives of Materials Science and Engineering 124/1 (2023) 14-24. DOI: https://doi.org/10.5604/01.3001.0054.3228

MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

In the solid-state joining technique known as "friction welding," materials coalesce under compression friction force between workpieces moving or rotating around each other. It generates heat and results in the plastic displacement of the material from the contact surfaces. Under normal conditions, welding does not cause flat surfaces to melt. In the process, shielding gas, flux, and filler metal are unnecessary [1,2]. Compressive forces and friction heat are the two fundamental determinants of the friction welding principle. While frictional heat is created by mechanical energy from the relative movement of the tool or work components, compressive pressures are used to bond [3].

The relative motion of the tool is typically employed in friction welding to join thin layers that are challenging to fuse using conventional friction welding procedures. The two primary friction welding processes, friction stir welding (FSW) and friction crush welding (FCW) are determined by the relative motion of the tool [4]. The UK's Welding Institute (TWI) developed friction stir welding (FSW), a solid-state joining method, to fuse aluminium alloys. FSW has been successfully applied to plenty of metals and alloys, including steel, Cu, Ni, Mg, and Ti alloys, due to the success of the technology in the aluminium sector and the speedy evolution of high-temperature, robust rotation tools [5]. Cast alloys and wrought alloys are the two primary classifications of aluminium alloys. The categories are subdivided further into heat-treatable and non-heat-treatable varieties [6].

When connecting aluminium alloys, fusion state welding causes porosity and welding joint cracking in the state of dissimilar aluminium alloys, resulting in more problems like variation in thermal and mechanical properties having a negative impact on the potency of the disparate joints [6,7]. Aluminium alloys are desirable in the structural sector because of their lightweight, high strength, and corrosion resistance [8]. Aluminium and its alloys have broad applications, such as automobiles, shipbuilding, and aerospace [9]. Copper is a key alloying component in the 2xxx series alloys. The series can be heat-treated and has strong sets with good toughness (at room and high temperatures). The series is often painted or covered in such exposures because they are not resistant to weather corrosion. Due to their excellent strength-to-weight ratio, this type is used widely in the automotive, aerospace, and transportation sectors. The alloy commonly contains magnesium to improve strength and natural ageing [10,11].

The main alloying component in the 7xxx series alloys is zinc. These wrought heat-treatable alloys and the Al-Zn-Mg alloys with Cu additions comprise most of the aluminium alloys utilised in the construction, automotive, marine, aerospace, and military sectors. The alloy system provides the finest balance of strength and durability characteristics [11,12]. Because the 7xxx series is not weldable, the majority of this series is linked with mechanical fasteners [13].

The tool's design is critical to the forming of a good-quality weld. Many researchers have studied the effect of the geometry of the tool on the mechanical properties and microstructure of the welded joint. A. Scialpi et al. study of three shoulder geometries. The tool analysis was performed on 1.5 mm thick AA 6082 T6 sheets. The tool was rotated during the welding operation at a speed of 1810 rpm and a feed rate of 460 mm/min. The quality of the crown and roots has been assessed visually. Tools with varying shoulders generate crowns with extremely diverse qualities. The TFC tool (cavity and fillet) produces a bead with a polished face and low flash, which is generated but eliminated as a continuous chip during the process. When it comes to crown quality, the TFC tool crown is the finest. A thorough optical microscope analysis of the resultant microstructure showed the impact of shoulder shape on nugget size distribution [14]. The friction stir welding of the 2219-T62 aluminium alloy was studied by Weifeng Xu et al. using various welding tools and traverse and rotational speeds. Due to the first tool's three spiral flutes' larger stir and improved plastic flow, the particles and grain size were significantly smaller and more disseminated. The low-hardness plateau is consistent with the geometry of the welding instrument and extends beyond the weld line by more than 10 mm. Compared to the first tool, the hardness decreases slightly when using the second tool. Using the first tool, the ductility and strength increase as the rotating speed decreases from 500 rpm to 300 rpm or the traversing speed increases from (60 to 100) mm/min [15].

R. Hariharan et al. studied the impact of FSW parameters on the mechanical characteristics of welded joints made of different aluminium alloys (Al 6061 & 7075). The tool geometry was carefully chosen and manufactured in order to provide a virtually flat welded interface (cylindrical and tapered) pin profile. For defect-free welded joints, the process parameters 2 and 0 were optimised. As a result of the substantial deformation that occurs at the nugget zone during friction stir welding, it has been found that the joint's mechanical properties are significantly impacted by the evolving microstructure. For ideal welding conditions, a speed of 1250 rpm is preferred [16]. Ranjith et al. show that the effects of the tilt angle (2°–4°) on the mechanical characteristics and microstructure of the welded junction of the dissimilar aluminium alloys AA2014 T651 and AA6063 T651 were investigated. Tool offset and tool pin diameter (5 mm to 7 mm) (0.5 mm towards AS, centre line, and Rs). The outcome demonstrates that a 4-degree tilt angle results in greater material interlocking [17] on joints welded of dissimilar AA6061-T651 and AA7075-T651 alloys; the effect of FSW parameters on rotating and welding speeds with the pin profiles was evaluated, with AA6061-T651 plate on the joint interface. It was shown that the connections between various materials have higher tensile strengths when the heat input decreases. All of the manufactured joints cracked during tensile testing on the AA6061-T651 side in the heat-affected zone where the microhardness rate is low. The joined materials were mixed at a greater spindle speed and a lower welding speed [18]. The thickness of the plates allows for faster cooling, reducing grain formation in the heat-induced HAZ. Hardness was strongest in the base material BM and gradually decreased towards the HAZ [19].

Several research studies [20-23] emphasise the importance of optimising tool pin profile, tilt angle, and rotational speed in friction stir welding processes to achieve high-quality welds with superior mechanical properties.

Kumar et al. [20] investigated the physical, thermal, and mechanical properties of friction stir-welded Al-Cu-Li alloys as a function of tool tilt angle. The results revealed significant differences in mechanical properties depending on tool angle, implying that it is critical in achieving optimal weld properties. The effect of different tool tilt angles (TTA) on the microstructure and mechanical properties of friction stir-welded Al-Cu-Li alloys, which employ five K-type thermocouples to measure the temperature distribution during welding, is investigated in the paper. A defect-free joint is obtained between TTAs of 0° and 2°, and the optimal mechanical properties are obtained at a TTA of 2°, with a tensile strength of 403.2 MPa and a joint efficiency of 75.5%.

Kumar et al. [21] investigated the effect of different tool pin profiles on the friction stir welding of 2050-T84 Al-Cu-Li alloy plates. They concluded that a threaded cylindrical pin profile produced superior weld quality and mechanical properties due to improved material flow and defect formation. In contrast, a flat cylindrical pin profile produced superior weld quality and mechanical properties due to improved material flow and defect formation. The performance of different tool pin profiles (TPP) on friction stir welded 2050-T84 Al-Cu-Li alloy plates, which employ four TPPs: cylindrical, conical, triangular, and square, is investigated in the paper. The triangular TPP produces the finest grain size, hardness, and tensile strength among the four TPPs and the fracture mode shifts from ductile to brittle as the TPP angle increases.

Kumar et al. [22] used friction stir welding to investigate the effect of tool rotational speed on the microstructure and mechanical properties of Al-Li alloys. The results showed that increasing the rotational speed improves mechanical properties due to grain refinement and reduced defect density. The paper investigates the effect of tool rotational speed (TRS) on the microstructure and the mechanical characteristics of an Al-Li alloy welded with FSW. The ideal TRS is 1400 rpm, which results in a fine-grained structure with high hardness, tensile strength, and elongation.

Using artificial neural networks, Kumar et al. [23] predicted the impact of heat generation on force torque and mechanical characteristics in friction stir welding with varying tool rotational speeds. Using a three-layer feed-forward back-propagation ANN model with 10 neurons in the hidden layer, The paper reports that with a high correlation coefficient and a low mean square error (MSE), the ANN model can accurately predict the heat generation influence on force torque and mechanical characteristics at variable TRS in FSW.

The goal of this research was to examine the mechanical characteristic and microstructure of a friction stir welded dissimilar aluminium alloy (2024-T3 to 7075-0) through thickness produced by varying welding settings and three different FSW tool pin profiles (straight cylindrical, triangular, and square).

2. Experimental procedure

FSW experiments were carried out on a vertical milling machine Figure 1. The tools are in the form of three different pin profiles (straight cylindrical, triangular, and square) with dimensions as illustrated in Figure 2; they were fabricated from a drilling machine tool by turning and milling machine. The friction stir welding tools were made of tool steel type X12M before heat treatment to increase hardness.

Fig. 1. Station for making FSW connections

The toolset is used for welding aluminium (7075-0) and aluminium (2024-T3) pleats that are long (120 millimetres), wide (60 millimetres), and thick (3 millimetres). Aluminium alloys AA2024-T3 and AA7075-0 were chosen for friction stir welding due to their wide range of applications in the aerospace, automotive, building, and architecture industries. The chemical composition of these alloys was determined using a spectrometer analysis device from the General Company for Examination and Rehabilitation Engineering in Baghdad, Iraq. The milling machine attached to this toolset has various rotation speeds – Tables 1 and 2 show the plates' chemical composition and mechanical properties, respectively. A clamping mechanism secured the workpieces to the machine table next to each other. The welding was completed after many attempts using tool rotational speeds of 1000, 1410, and 2000 rpm, a feed rate of 20 mm/min, and a tool tilt angle of 2.5º. The aluminium-aluminium plates after welding are illustrated in Figure 3. The future scope of the work is fatigue tests.

The link between welding strength and FSW parameters was expressed by tensile testing on various FSWed dissimilar Al-Al joints. Figure 4 shows a few tensile test samples for different Al-Al joints (Sample 1 at tool rotational speed 1000 and a feed rate of 20 mm/min; Sample 3 at tool rotational speed 1410 and a feed rate of 20 mm/min; and Sample 4 at tool rotational speed 2000 and a feed rate of 20 mm/min).

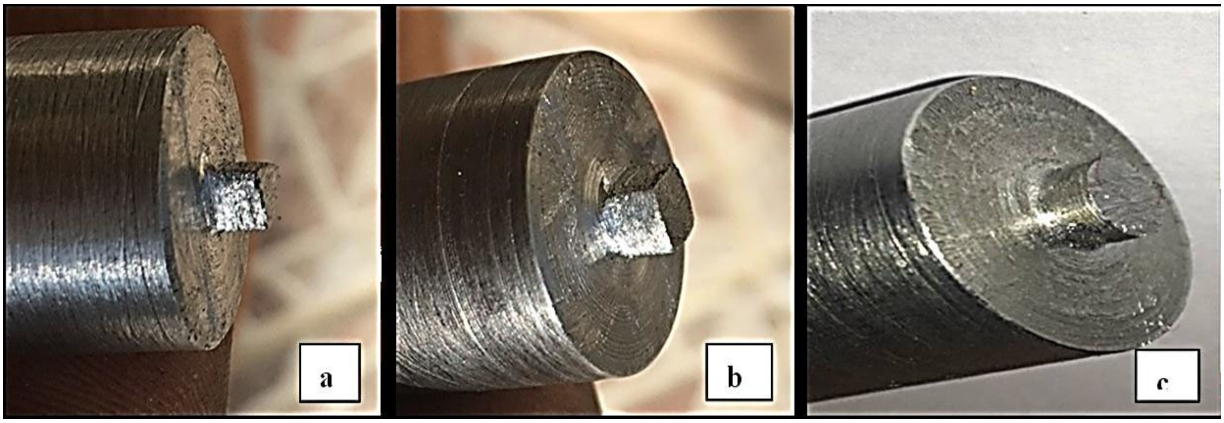

Fig. 2. Tool pin profiles of FSW a - triangular. b - square. c - straight cylindrical.(the shoulder diameter, pin length and rotation diameter are 18, 2.9, 3.8 mm respectively, and its same values to all pin profile)

Table 1.
Chemical composition of aluminium (7075-0) and aluminium (2024-T)

Material type	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	other, total
7075-0	Balance	0.18-0.28	1.2-2	0.5	2.1-9	0.3	0.4	0.2	5.1-6.1	0.15
2024-T3	Balance	0.1	3.8-4.9	0.5	1.2-1.8	0.3-0.9	0.5	0.15	0.25	0.15

Table 2.
Mechanical characteristics of aluminium (7075- 0) and aluminium (2024-T3) [20]

Material type	Tensile strength, MPa	Yield strength, MPa	Elongation, %	Hardness HV
AA 7075-0	Max 276	Max 145	9-10	68
AA 2024-T3	483	289	18	137

Fig. 3. Dissimilar aluminium (7075- 0) to aluminium (2024-T3) plates after welding

Fig. 4. Some dissimilar Al-Al tensile test samples

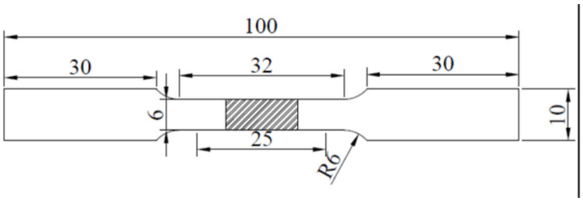

Fig. 5. ASTM- E8 Sub-Size Sample for Tensile Test, all dimensions are in mm [24]

According to ASTM E-8, all tensile test specimens were conducted using the universal testing machine type WDW-200E (Fig. 5. shows the specimen dimensions, the load speed employee equals 1 mm/min, and the strain measurement method from the chart products from the computerised machine after giving specimen dimensions).

After the weld had been conducted, samples were prepared according to analyses that need to be investigated in this work, which are fundamentally microhardness and microstructure tests. Welded samples were polished by polishing papers with a value grade ranging from 150 to 2000, and then cloth polishing was used. The etching process was followed using Keller's Regent (1 ml HF, 1.5 mp HCL, 2.5 mL HNO_3, and 95 mL distilled water). An average of three micro-hardness measurements were conducted with a 0.9806 N load value at different weld joint zones with 20 sec dwelling time. A scanning electron microscope (SEM) of type (FEI 9922650) and an optical microscope of type (Optika-Italy) have both been used to analyse the microstructure and the fracture surface.

3. Results and discussions

Table 2 summarises the mechanical characteristics of the base alloys 2024-T3 and 7075-T3. Figure 6 illustrates how tool pin profiles affect the tensile strength of FSW dissimilar Al-Al joints at different rotation speeds. As a result of the friction stir welding tool penetrating the surface of two different aluminium alloy workpieces on the advancing and retreating sides, it was observed that the strength properties of the welded joints are less than those of the original alloys (2024-T3 and 7075-1). Due to several areas on both sides of the weld with varying compositions, microstructures, and characteristics, the resulting weld of the various alloys could result in weak weld joints.

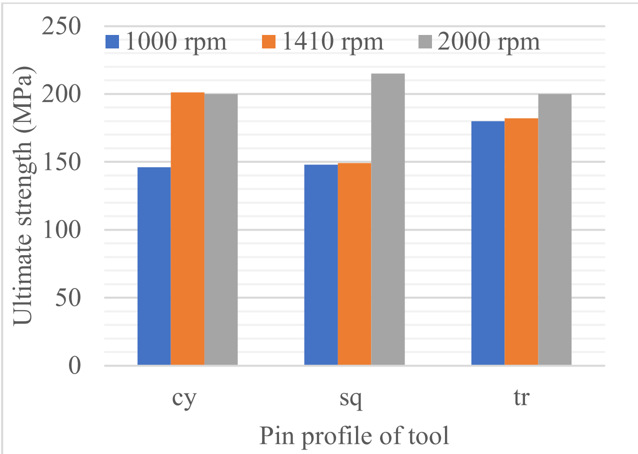

Fig. 6. Impact of tool pin profiles (cylindrical, triangular, and square) on the ultimate strength of FSWed dissimilar aluminium (7075- 0) to aluminium (2024-T3)joints at various rotation speeds (1000, 1410, 2000) rpm

In FSW, the heat input has a significant role in the soundness and in the evaluation of mechanical properties of the weldments, where the input heat affects on all mechanical properties [25]. The findings show that, in the studied range, an increase in tool rotating speed resulted in an increase in tensile strength. In FSW, it is well known that increasing tool rotational speed may promote the dissipation of heat towards the outside of the joints and decrease the heat input necessary for joining. It may lead to a reduction in the size and depth of the welded zone (Thermo Mechanical Affected Zone TMAZ and Heat Affected Zone HAZ), which improves joint effectiveness and tensile strength. As shown in Figure 6, the joint efficiency was 77%, and the dissimilar welds had a tensile strength of 215 MPa at a tool rotation speed of 2000 rpm and a square pin profile. Enhanced tool rotation speed increased heat dissipation in the stir zone, increasing the pin's stirring effect. However, it may also result in fin grins, increasing the material's tensile strength. When compared to the other two pin profiles, the joints formed with a square pin profile had greater tensile strength. It is due to the square pin profile's ability to provide effective material swirling and mixing of different plasticised metals during welding. Due to variations in material flow and the amount of frictional heat produced, tensile strength varies with tool rotation speed and pin shapes.

Figure 6 shows the lowest tensile strength was 145 MPa with joint efficiency (53%) at 1000 rpm tool rotation speed and cylinder pin profile because increased frictional heat decreased tensile strength. The welded joints fabricated using a cylinder pin profile and 1000 rpm tool rotation speed have lower tensile strength.

Figures 7, 8, and 9, respectively, demonstrate the relationship between hardness and distance along the cross-sectional area of the FSW joint at different pin profiles and rotation speeds of the tool. The hardness of welded Al-Al joints is intimately connected to both sides. Figure 7 depicts the relationship between distance and hardness along the cross-sectional area of an FSW joint for various pin profiles and a tool rotation speed of 2000 rpm. The stir zone (SZ) is more hard than the thermomechanically affected zone (TMAZ) and the heat-affected zone (HAZ). The maximum value of hardness was (144 HV) at the square pin profile, (120 HV) at the cylinder pin profile and (115 HV) at the triangle pin profile, respectively. The square pin profile provides superior material stirring quality and allows for mixing dissimilar plasticised metals with small grain sizes. It has a higher hardness than the other two pin profiles. The triangle pin profile has a lower hardness than other pin profiles because of the low material stirring quality of the pin profile. Figures 8 and 9 depict the relation between distance and hardness along the FSWed joint's cross-sectional area for various pin profiles and tool rotation speeds of 1410 rpm and 1000 rpm, respectively. According to the Figures, the hardness decreases with the decreasing tool rotation speed and changes in pin profiles. In FSW, it is well known that increasing tool rotational speed may promote heat dissipation towards the outside of the joints and decrease the heat input. Also, changing the pin profiles may lead to a reduction in the size of the grains and cause increased hardness. Figures 10-12 show the differences in material hardness as a function of rotational speed for each pin shape.

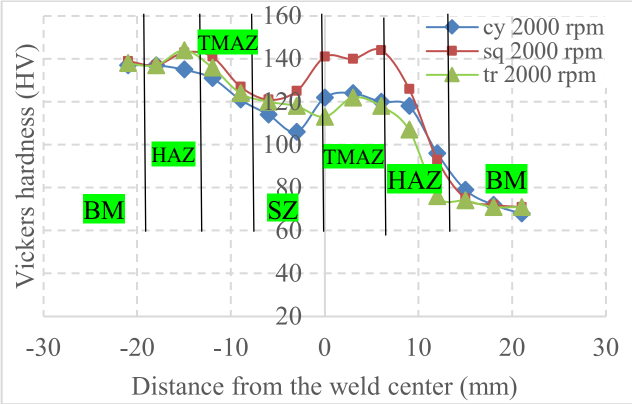

Fig. 7. Hardness distribution over the cross-sectional area of FSW aluminium (7075-0) to aluminium (2024-T3) joints with different pin profiles and tool rotation speed of 2000 rpm, with shoulder diameter of 18 mm

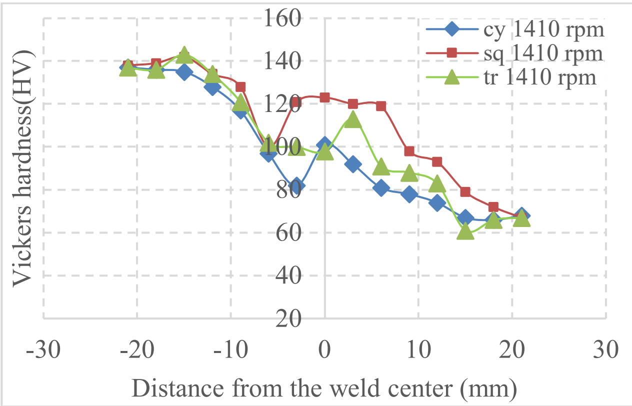

Fig. 8. Hardness distribution over the cross-sectional area of FSW aluminium (7075-0) to aluminium (2024-T3) joints with different pin profiles and tool rotation speed of 1410 rpm, with shoulder diameter of 18 mm

From the results of the tensile strength and micro-hardness tests of dissimilar Al (7075-0) and Al (2024-T3) joints at different tool pin profiles and welding parameters, the optimum tensile strength and microhardness were obtained by using square pin profiles at a rotational speed of the tool of 2000 rpm and a feed rate of 20 mm/min. Figure 13 shows the cross-section FSW joint of the optimal dissimilar Al-Al joint's macro- and microstructural characterisation. The figure shows different zones of grains that were formed during FSW. It can be noticed that there are three distinct regions: the stir zone (SZ), the thermomechanically affected zone (TMAZ), and the heat-affected zone (HAZ). Because there were no defects in the weld zone, which resulted in the total weldability of two alloys in the solid state, the welded joints exhibit high quality.

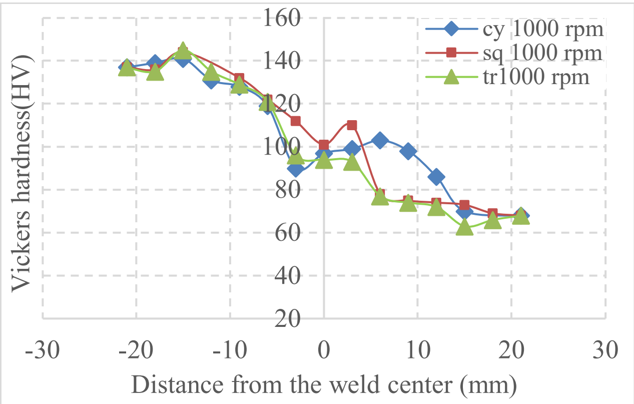

Fig. 9. Hardness distribution over the cross-sectional area of FSW aluminium (7075- 0) to aluminium (2024-T3) joints with different pin profiles and tool rotation speed of 1000 rpm, with shoulder diameter of 18 mm

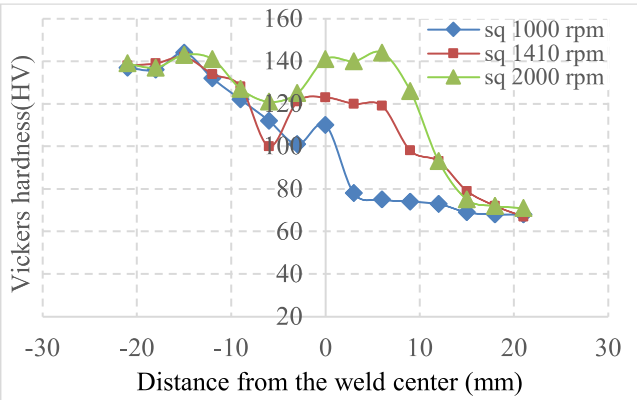

Fig. 10. Hardness distribution over the cross-sectional area of FSW aluminium (7075- 0) to aluminium (2024-T3) joints with different tool rotation speeds and square pin profiles with shoulder diameter of 18 mm

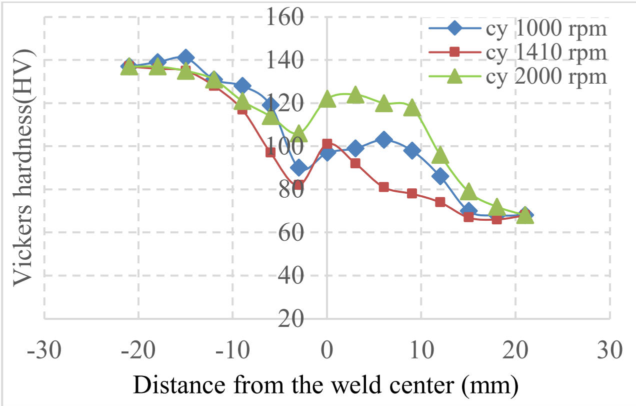

Fig. 11. Hardness distribution over the cross-sectional area of FSW aluminium (7075- 0) to aluminium (2024-T3) joints with different tool rotation speeds and cylindrical pin profiles with shoulder diameter of 18 mm

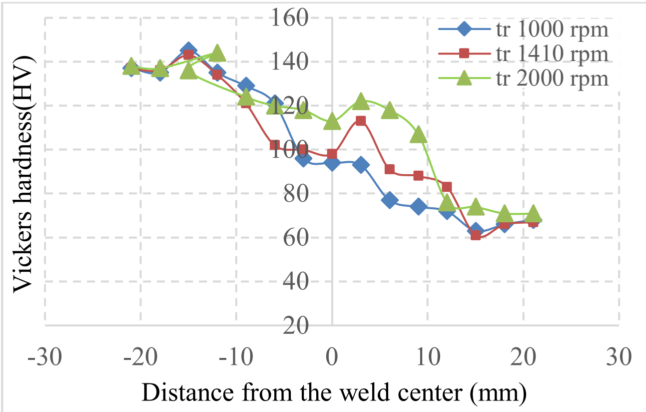

Fig. 12. Hardness distribution over the cross-sectional area of FSW aluminium (7075- 0) to aluminium (2024-T3) joints with different tool rotation speeds and triangle pin profiles with shoulder diameter of 18 mm

The microstructure of BM in both alloys (7075-0 and 2024- 3) is depicted in Figures 13-a and g, and it has elongated grains distributed randomly concerning the rolling direction. Figures 13-b,f show the HAZ microstructure for both alloys; the material in this zone has only gone through the heat cycle. The TMAZ region for both alloys is depicted in Figure 13-c,e. Both alloys are heated and plastically deformed during FSW and are characterised by a distorted structure caused by the mechanical stirring of the tool. As a result, the plastic deformation in TMAZ causes the grains to rotate. The microstructure of the centre SZ is shown in Figure 13-d, and it is composed of two zones made up of crystallisation fines and equiaxed grains of the alloys 7075 and 2024 Al. The region that endures the most strain and goes through recrystallisation is the SZ. The good microstructure is produced by the dynamic recrystallisation of fine equiaxed grain structure caused by low frictional heat and the more extreme plastic deformation that occurs throughout welding in the SZ. All these reasons point back to increasing the tool rotation speed and using square pin profiles.

Figure 14 shows scanning electron microscopy (SEM) of the fracture surface of a tensile-tested dissimilar Al-Al joint to the specimens produced by utilising a square pin profile at a feed rate of 20 mm per minute and a tool rotation speed of 2000 rpm, starting the crack and the fracture obtain in the heat affected zone (HAZ). Small dimples and voids were detected in some parts of the fracture zone of aluminium. Small dimple zones have been mentioned as the final crack-growing regions in the fracture zone due to their coarsest surface with tearing ridge features. Each dimple, mostly on fracture surfaces, represents a void. The void nucleation is related to inclusions inside aluminium; the ductile fracture mechanism is void nucleation, growth and coalescence [26].

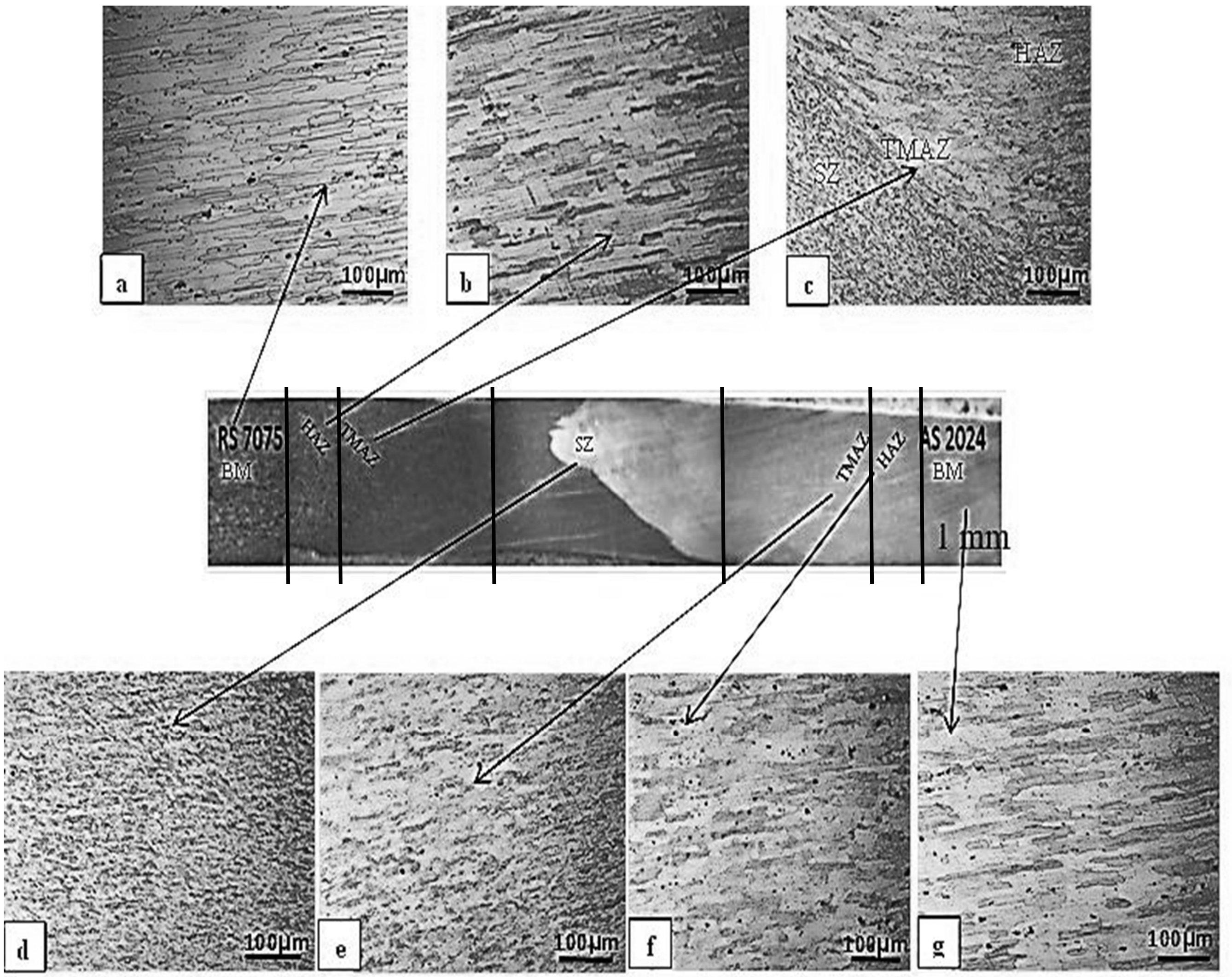

Fig. 13. Macro- and microstructure of an FSW dissimilar aluminium (7075- 0) to aluminium (2024-T3) joint on a square pin profile specimen at a tool rotation speed of 2000 rpm and a feed rate of 20 mm per minute

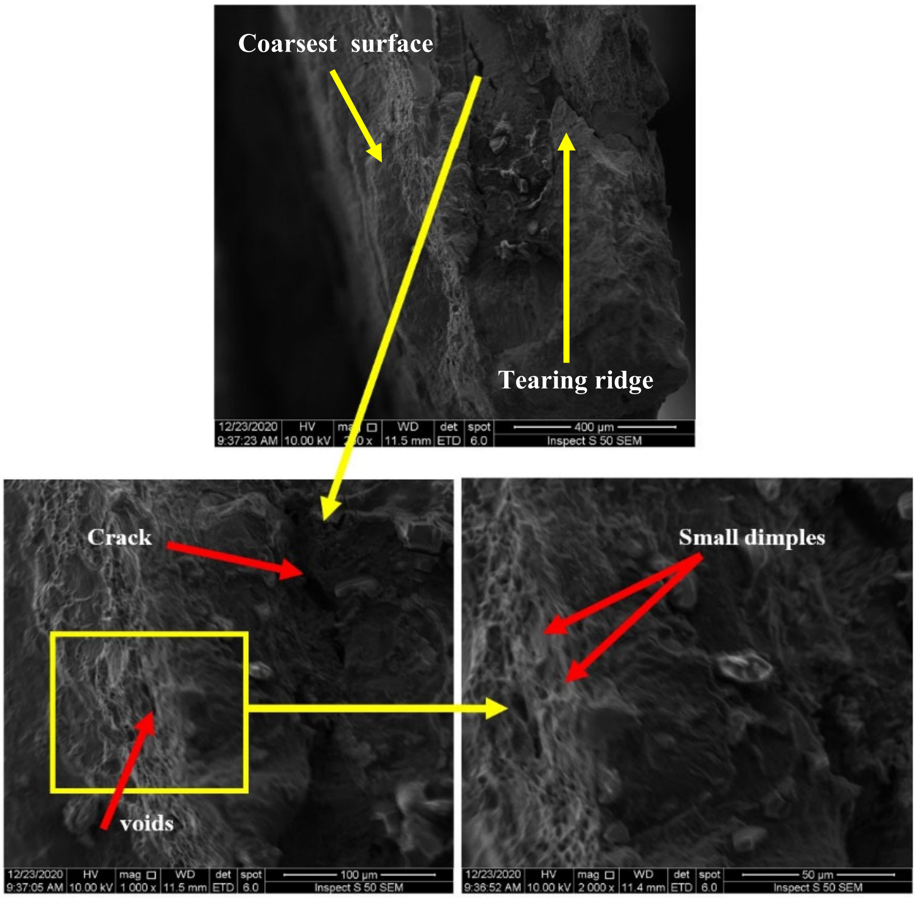

Fig. 14. Scanning electron microscopy (SEM) images of the fracture surface of a tensile tested dissimilar aluminium (7075-0) to aluminium (2024-T3) joint to the specimen by square pin profile at a feed rate of 20 mm/min and a tool rotation speed of 2000 rpm

4. Conclusions

Friction stir welding of 7075-0 and 2024-T3 aluminium alloys was performed using various welding tools and rotating rates. The joint's microstructural features and mechanical characteristics were studied. The following are the key results based on the current experimental work and theoretical analysis:

1. According to tensile strength and microhardness tests, tool rotation of 2000 rpm and square pin profile were the best parameters when compared to other working parameters.
2. The greatest hardness and tensile strength of FSW dissimilar aluminium joints have been 144 HV and 215 MPa, respectively, when using the square pin profile at a tool rotation speed of 2000 rpm and a feed rate of 20 mm per minute.
3. The hardness and tensile strength of FSW dissimilar aluminium alloy joints increase with the increase in tool rotation speed.
4. Microstructural observations of the FSW dissimilar aluminium joints using a square pin profile at a tool rotation speed of 2000 rpm and feed rate of 20 mm per minute exhibited the weld zone's high weld quality. Additionally, there were no defects in the weld zone.
5. The fracture surface of the FSW joint indicated a ductile fracture type.

References

[1] S. Jomah, A.D. Subhi, F.A. Hashim, Effect of friction crush welding parameters on the properties of welded joints of C1020 copper sheet, Journal of Physics:

Conference Series 1973/1 (2021) 012048. DOI: https://doi.org/10.1088/1742-6596/1973/1/012048

[2] H. Mehdi, R.S. Mishra, Mechanical properties and microstructure studies in Friction Stir Welding (FSW) joints of dissimilar alloy – a review, Journal of Achievements of Materials and Manufacturing Engineering 77/1 (2016) 31-40. DOI: https://doi.org/10.5604/17348412.1229666

[3] H.T. Elmetwally, Y.G. Yakoub, M.N. Elsheikh, A.A. Abd-Eltwab, M.E. Abdullah, Influence of Friction Crush Welding Tool Profiles on The weldability of Commercial Aluminum Tubes, International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) 10/3 (2020) 5579-5588.

[4] A.S. Jomah, F.A. Hashim, A.D. Subhi, Metallurgical investigation and mechanical properties of dissimilar friction crush welded Cu-Al sheets with flanged edge, Journal of Physics: Conference Series 1973/1 (2021) 012116. DOI: https://doi.org/10.1088/1742-6596/1973/1/012116

[5] Y.F. Sun, H. Fujii, Investigation of the welding parameter dependent microstructure and mechanical properties of friction stir welded pure copper, Materials Science and Engineering: A 527/26 (2010) 6879-6886. DOI: https://doi.org/10.1016/j.msea.2010.07.030

[6] A.J.S. Jomah, A.F. Hasanm W. Al Azzawi, Microstructure and Mechanical Properties of Friction Crush Welded 1145 Aluminum Sheets with Flanged Edges, Materials Research 26 (2023) e20220419. DOI: https://doi.org/10.1590/1980-5373-MR-2022-0419

[7] D.D. Hao, T.H. Tra, Effects of friction stir welding parameters on the mechanical properties of AA7075-T6, Archives of Materials Science and Engineering 77/2 (2016) 58-64. DOI: https://doi.org/10.5604/18972764.1225594

[8] H. Jamshidi Aval, S. Serajzadeh, A.H. Kokabi, Evolution of microstructures and mechanical properties in similar and dissimilar friction stir welding of AA5086 and AA6061, Materials Science and Engineering: A 528/28 (2011) 8071-8083. DOI: https://doi.org/10.1016/j.msea.2011.07.056

[9] P.K. Sahu, S. Pal, Influence of metallic foil alloying by FSW process on mechanical properties and metallurgical characterization of AM20 Mg alloy, Materials Science and Engineering: A 684 (2017) 442-455. DOI: https://doi.org/10.1016/j.msea.2016.12.081

[10] A.M.A. Mohamed, F.H. Samuel, A review on the heat treatment of Al-Si-Cu/Mg casting alloys, in: F. Czerwinski, Heat Treatment-Conventional and Novel Applications, InTech, Rijeka, Croatia, 2012, 55-72. DOI: https://doi.org/10.5772/50282

[11] N. Kumar, R.S. Mishra, J.A. Baumann, Residual stresses in friction stir welding, Butterworth-Heinemann, Oxford, 2014. DOI: https://doi.org/10.1016/C2013-0-09884-2

[12] T.B. Korkut, E. Armakan, O. Ozaydin, K. Ozdemir, A. Goren, Design and comparative strength analysis of wheel rims of a lightweight electric vehicle using Al6063 T6 and Al5083 aluminium alloys, Journal of Achievements in Materials and Manufacturing Engineering 99/2 (2020) 57-63. DOI: https://doi.org/10.5604/01.3001.0014.1776

[13] F.C. Campbell Jr., Manufacturing technology for aerospace structural materials, Elsevier, Oxford, 2011.

[14] A. Scialpi, L.A.C. de Filippis, P. Cavaliere, Influence of shoulder geometry on microstructure and mechanical properties of friction stir welded 6082 aluminium alloy, Materials and Design 28/4 (2007) 1124-1129. DOI: https://doi.org/10.1016/j.matdes.2006.01.031

[15] W. Xu, J. Liu, H. Zhu, L. Fu, Influence of welding parameters and tool pin profile on microstructure and mechanical properties along the thickness in a friction stir welded aluminum alloy, Materials and Design 47 (2013) 599-606. DOI: https://doi.org/10.1016/j.matdes.2012.12.065

[16] R. Hariharan, R.J. Golden Renjith Nimal, Friction stir welding of dissimilar aluminium alloys (6061&7075) by using computerized numerical control machine, Middle-East Journal of Scientific Research 20/5 (2014) 601-605. DOI: https://doi.org/10.5829/idosi.mejsr.2014.20.05.201

[17] R. Ranjith, B. Senthil Kumar, Joining of dissimilar aluminium alloys AA2014 T651 and AA6063 T651 by friction stir welding process, WSEAS Transactions on Applied and Theoretical Mechanics 9 (2014) 179-186.

[18] S. Ravikumar, V.S. Rao, R.V. Pranesh, Effect of process parameters on mechanical properties of friction stir welded dissimilar materials between AA6061-T651 and AA7075-T651 alloys, International Journal of Advanced Mechanical Engineering 4/1 (2014) 101-114.

[19] A.A. Shehab, S.A. Nawi, A.A.A.G. Al-Rubaiy, Z. Hammoudi, S.A. Hafedh, M.H. Abass, M.S. Alali, S.D. Ali, CO_2 laser spot welding of thin sheets AISI 321 austenitic stainless steel, Archives of Materials Science and Engineering 106/2 (2020) 68-77. DOI: https://doi.org/10.5604/01.3001.0014.6974

[20] S. Kumar, J.K. Katiyar, B.S. Roy, Influence of Tool Tilt Angle on Physical, Thermal, and Mechanical Properties of Friction Stir Welded Al-Cu-Li Alloys, Materials Today Communications 34 (2023) 105348. DOI: https://doi.org/10.1016/j.mtcomm.2023.105348

[21] S. Kumar, S.K. Chaubey, D. Sethi, S.C. Saha, B.S. Roy, Performance analysis of varying tool pin profile on friction stir welded 2050-T84Al-Cu-Li alloy plates, Journal of Materials Engineering and Performance 31 (2022) 2074-2085.
DOI: https://doi.org/10.1007/s11665-021-06315-w
[22] S. Kumar, J.K. Katiyar, U. Acharya, S.C. Saha, B.S. Roy, Influence of tool rotational speed on Microstructure and Mechanical Properties of Al-Li Alloy using Friction Stir Welding, Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering 236/5 (2022) 2106-2117.
DOI: https://doi.org/10.1177/09544089221080823
[23] S. Kumar, M.K. Triveni, J.K. Katiyar, T.N. Tiwari, B.S. Roy, Prediction of heat generation effect on force torque and mechanical properties at varying tool rotational speed in friction stir welding using Artificial Neural Network, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 237/19 (2023) 4495-4514. DOI: https://doi.org/10.1177/09544062231155737
[24] ASM Handbook Committee, Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, ASM Metals Handbook, vol. 2, ASM International, Almere, 1990. DOI: https://doi.org/10.31399/asm.hb.v02.9781627081627
[25] N. Rajamanickam, V. Balusamy, Effects of Process Parameters on Mechanical Properties of Friction Stir Welds Using Design of Experiments, Indian Journal of Engineering and Materials Sciences 15 (2008) 293-299.
[26] Q. Zhang, W. Gong, W. Liu, Microstructure and mechanical properties of dissimilar Al–Cu joints by friction stir welding, Transactions of Nonferrous Metals Society of China 25/6 (2015) 1779-1786. DOI: https://doi.org/10.1016/S1003-6326(15)63783-9