Silicon
https://doi.org/10.1007/s12633-023-02684-0

RESEARCH

Influences of Rotational Speed on Friction Stir Welding Quality, Mechanical and Fatigue Behaviour of AA6061/SiC Composite

J. Balaji[1] · A. H. Seikh[2] · M. A. Kalam[3] · R. Venkatesh[4]

Received: 27 June 2023 / Accepted: 15 September 2023

Abstract
The utilization of aluminium alloy composite materials is increased progressively in automotive, aerospace, and sports allocations due to their distinct physical and mechanical properties. The conventional metal joining process is not suitable for joining the composite material. The present work of silicon carbide (SiC) compacted aluminium alloy (AA6061) composite surface is joined by friction stir welding (FSW) process under the rotational speed of 800, 1200, and 1600 rpm. Influences of tool rotational speed on welding interface quality mechanical and fatigue properties of AA6061/SiC composite surface are evaluated. The internal defect area of the weld joint is detected by radiograph inspection, and its surface morphology is analyzed through the Scanning Electron Microscope (SEM) apparatus. It revealed that the coarse aggregated inter-metallic structure with an effective interface of weldment was observed. The 1200 rpm (rotational speed) performed AA6061 composite found enhanced yield and tensile strength of 23.7% and 25.66% improvement compared to the yield and tensile strength of weldment operated under 800 rpm rotational speed. The hardness of composite weldment is increased significantly with increased tool rotational speed. The maximum hardness of 88HV is by 1200 rpm performed weld joint. Sample 3 performed higher fatigue life (1.8×10^6 cycles) without failure.

Keywords AA6061 · SiC · Friction stir welding · Surface composite · Rotational speed · SEM and mechanical properties

1 Introduction

The development of advanced materials such as aluminium and magnesium matrix composites gained significance in various engineering sectors such as automotive, aviation, defence, and marine applications due to their excellent characteristics like lightweight, high specific strength, and better wear resistance than conventional materials [1–3]. The SiC-reinforced aluminium matrix composite has superior tensile strength, good thermal behaviour, and excellent resistance against corrosion [4, 5]. However, the utilization of aluminium matrix composites is limited due to the difficulties of joining these metals by traditional welding techniques [6]. Due to the difficulties of varied thermal expansion coefficient and melting temperature, the fusion weld was unsuitable for aluminium composite [7]. The solid-state friction stir welding of aluminium alloy composite decreased cracking, porosity, dissolution, and distortion [8]. The impact of FSW parameters on the welding characteristics of the composite was reviewed [9, 10]. The effective weld joints offered good mechanical characteristics [11].

✉ R. Venkatesh
venkisimats@gmail.com

J. Balaji
jbalajifsw@gmail.com

A. H. Seikh
asifulhs.dr@hotmail.com

M. A. Kalam
makalam.phd@outlook.com

1 Department of Mechanical Engineering, Erode Sengunthar Engineering College, Erode 638057, Tamil Nadu, India

2 Mechanical Engineering Department, College of Engineering, King Saud University, 11421 Riyadh, Saudi Arabia

3 School of Civil and Environmental Engineering, FEIT, University of Technology Sydney, Ultimo, NSW 2007, Australia

4 Department of Mechanical Engineering, Saveetha School of Engineering, SIMATS, Chennai 602105, Tamil Nadu, India

Published online: 22 September 2023

The SiC-reinforced aluminium alloy composite butt joint was made by friction stir welding and had good mechanical characteristics. The SEM image revealed the heat-affected zone (HAZ), parent material, thermo-mechanical affected zone (TMAZ), and weld nugget [12]. The corrosion performance of friction stir welded aluminium alloy (AA2024) was evaluated by chloride ion and alkaline solution, and its optimum FSW parameters were noted using response surface methodology. The corrosion rate of friction welded AA2024 was gradually increased with increased chloride concentration [13]. Moreover, several studies related to FSW feasibility on aluminium alloy composite and benefit to zero defects, improved interface quality, and homogenous distribution of particles [14–16]. Researchers et al. [15] investigated the micro-structural and mechanical behaviour of FSW aluminium alloy (Al2009)/SiC composite developed by powder metallurgy route. The SEM results revealed good grain refinement, uniform distribution of SiC particles in the Al2009 matrix and good interface quality. The mechanical strength of the composite was increased by high rotational speed friction weld Al2009 alloy composites. Friction stir welding input process parameters were optimized via ANOVA, and its frictional power was the dominating factor for increased tensile and fatigue characteristics [16]. The microstructure and mechanical behaviour of the FSW AA7075/alumina composite joint were evaluated, and its stir zone found significant refinement microstructure, resulting in increased mechanical strength and reduced fatigue properties [17].

The effect of welding rotational speed on the mechanical and microstructural performance of aluminium alloy (Al5083) composite with pure copper plated lap joint was evaluated, and results showed superior tensile strength and reduced defects of 74% and 78% improvement in tensile strength of aluminium alloy parent and copper material [18]. The mechanical and micro-structural behaviour of the FSW butt aluminium alloy/TiO_2 composite joint was evaluated, and its SEM revealed uniform particle dispersion, which resulted in superior mechanical strength. The hardness of the joint increased by 22% compared to the parent material [19]. The process parameters were also optimized via the ANOVA route [20–22].

The present research aims to develop the aluminium alloy composite FSW joint with different rotational speeds. Influences of rotational speed on surface morphology and mechanical behaviour were analyzed. The optimum weld joint input rotational speed properties are identified for mass production.

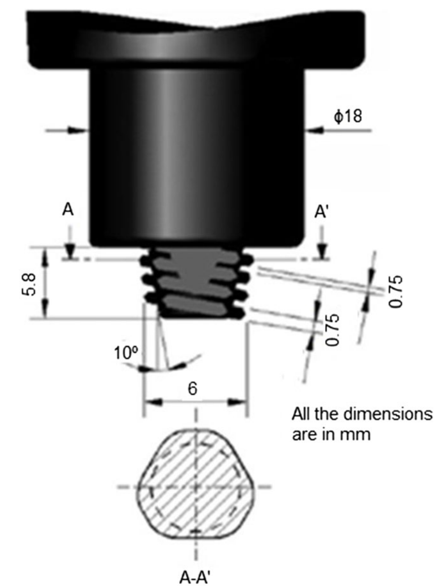

Fig. 1 Tool pin profile

2 Materials and Methods

2.1 Selection of Materials

Aluminium alloy (Al6061) with 150mmX100mmX5mm size was chosen as the base matrix, and phase silicon carbide microparticles (SiC-10 µm)were fixed as secondary compact material and kept in the groove. The chemical composition of AA6061 is shown in Table 1.

2.2 Selection of Friction Stir Tool

Based on the friction stir tool pin profile, it is classified as cylindrical, triangular, square, and conical. Among the various tool pins, the 18 mm concave H-13 steel tool with a cylindrical threaded pin was selected for this study and is shown in Fig. 1.

2.3 Experimental Details

Figure 2 shows the actual friction stir welding setup of aluminium alloy composite joint fabrication configured with computer numerical control (CNC). The 22 kW capacity with 4000 rpm maximum spindle speed and 50KN capacity FSW machine is utilized for this study. Initially, acetone solution is used to clean the surfaces and SiC is

Table 1 Chemical composition of AA6061

Elements	Mg	Cu	Cr	Fe	Si	Ti	Zn	Al
%	0.9	0.28	0.17	0.33	0.62	0.02	0.02	balance

Fig. 2 Actual setup of friction stir welding (FSW)

kept in the groove. The composite plates are held in the worktable and fixed via mechanical clamps. The composite joint was framed by a single pass via an H-13 steel tool with a thread pin profile, as shown in Fig. 2(a). The successful joint was prepared using different tool rotational speeds of 800, 1200, and 1600 rpm. The welded samples are polished by other emery sheets (500, 1200, and 1500 grid emery). Finally, it was cleaned using acetone solutions and dipped into distilled water. The welded samples are shown in Fig. 3. The developed wire-cut EDM prepared weld samples for SEM and tensile test evaluation.

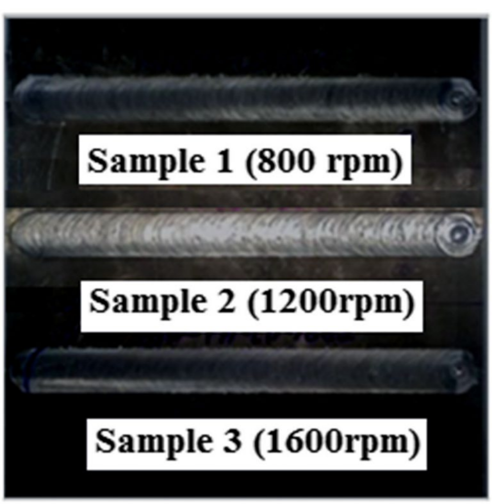

Fig. 3 Welded samples

Fig. 4 ROLI-2 60 curie—actual setup of radiographic equipment

2.4 Characteristics Details

2.4.1 Radiographic Test

Figure 4 illustrates the image of the radiographic camera (ROLI-2 60 curie) equipment used to detect welding defects. It was the one type's non-destructive test and was reliable & most reliable compared to other techniques. The Kodak film with 0.1 mm thickness was used to capture the surface image. The 600 mm distance was followed from the position of the surface to the film and the image captured.

Scanning Electron Microscope (SEM) The developed composite samples are sized by 10mmX10mmX10mm and polished using different grade emery sheets. Figure 5 shows the actual setup of the ZEISS model scanning electron microscope utilized to examine the surface morphology of the weld zone.

Tensile Strength The tensile strength of the weld joint is evaluated by ASTM E8 standard via Instron model tensile testing machine with 5 mm/min cross slide speed.

Fig. 5 Scanning electron microscope analyzer

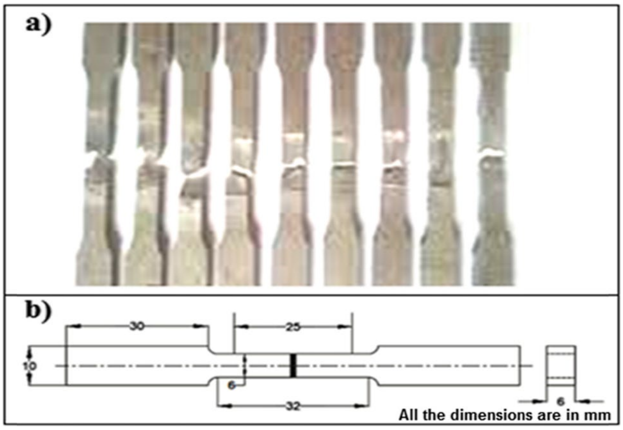

Fig. 6 (**a**) Tensile tested specimen (**b**) ASTM E8 dimension

Figure 6(a) shows the tensile tested specimen, and b) shows the ASTM standard dimension.

Vickers Hardness Number The Vickers hardness number of weld joints is evaluated by hardness tester equipment. The 100-g load is applied for 15 s to measure the hardness value. For each sample, three trials are made and their average value is considered.

Fatigue Test Instron evaluates the fatigue life of friction stir weld joints, making fatigue tester. The specimen is machined by ASTM E466 standard, and Fig. 7(a-c) shows the fatigue test setup, specimen, and ASTM E466 dimension. The SN life curve is plotted by using a MatrixTM electronic curve.

3 Results and Discussions

3.1 Radio Graphic Test

Figure 8 illustrates the radiographic tested images of aluminium alloy composite friction stir welding samples with

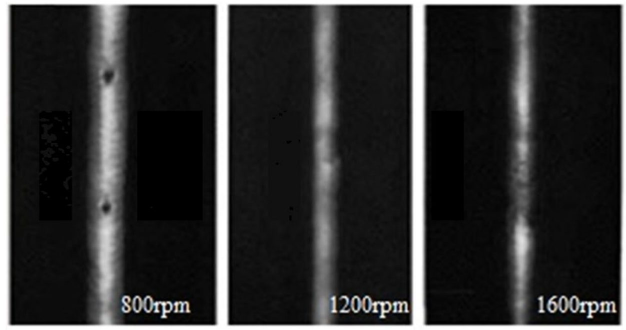

Fig. 8 Captured Film Image

different rotational speeds. It clearly shows that the dark field indicates the aluminium alloy metal surfaces, and the white field represents the weldment area. The dark black dotted field highlights the defect area. The internal defect is found on the 800-rpm rotational speed. It was due to low frictional speed, leading to insufficient heat transfer. It may cause poor bonding between the materials.

3.2 SEM Evaluation

Figure 9 illustrates the SEM images of aluminium alloy composite by 800 rpm rotational speed. It showed a large grain with a coarse grain structure. The dendritic close large grains aggregated with increased SiC particles. The adequate bonding of weldment showed a high interfacial bond with identical porous. It may lead to a decrease in the mechanical properties of the weld.

Figure 10 represents the SEM micrograph of friction stir welded aluminium alloy composite by 1200 rpm rotational speed. It was proof of good interfacial bonding between the two metals. It was due to the applied rotational speed of 1200 rpm and the applied 10kN axial force. Compared to Fig. 9 SEM image, fine grain structure with reduced weld defects was found. The increased particle distribution with efficient bonds was found to increase mechanical strength.

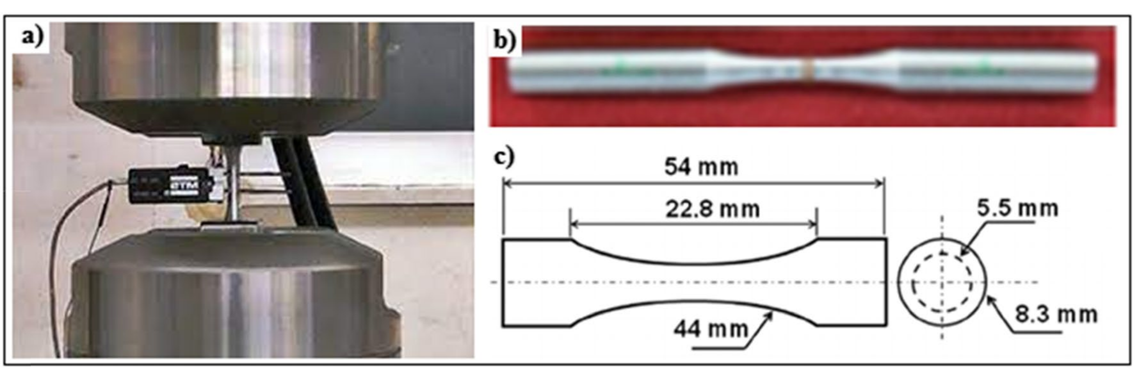

Fig. 7 (**a**) Fatigue setup with test specimen, (**b**) machined test specimen, (**c**) ASTM E466 Dimension

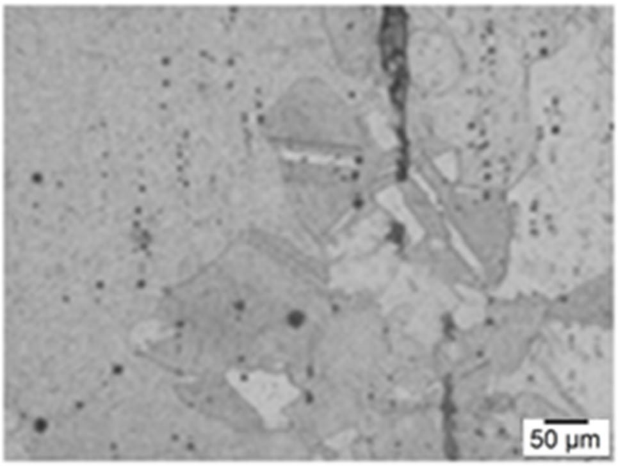

Fig. 9 SEM Micrograph of Al6061 Composite Joint –Sample 1 (800 rpm Rotational Speed)

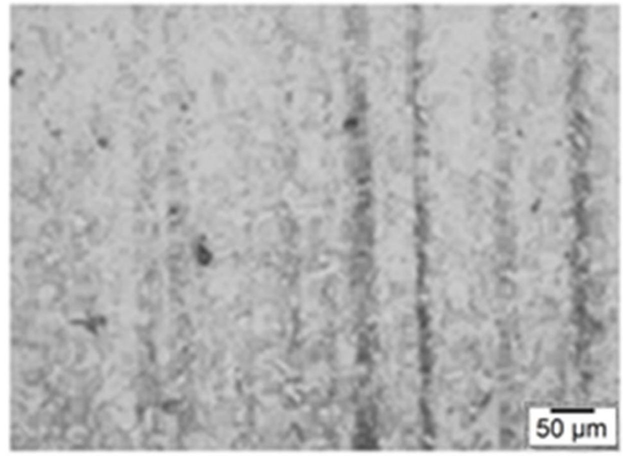

Fig. 11 SEM Micrograph of Al6061 Composite Joint –Sample 2 (1200 rpm Rotational Speed)

However, the high rotational speed increases the friction temperature above the parent metal solidifications. So, both of the aluminium alloy composites are welded successfully.

The SEM micrograph noted the fine grain with increased interfacial quality of the composite weld joint, as shown in Fig. 11. It was due to the high rotational speed that increased the frictional temperature on the applied force of 10kN at 1600 rpm speed. The temperature of the parent metal was increased as soluble condition and diffused parallel to the adjusting metal with their interface quality increased. However, the higher temperature on increased frictional pressure on SEM may affect the structure, resulting in reduced mechanical properties.

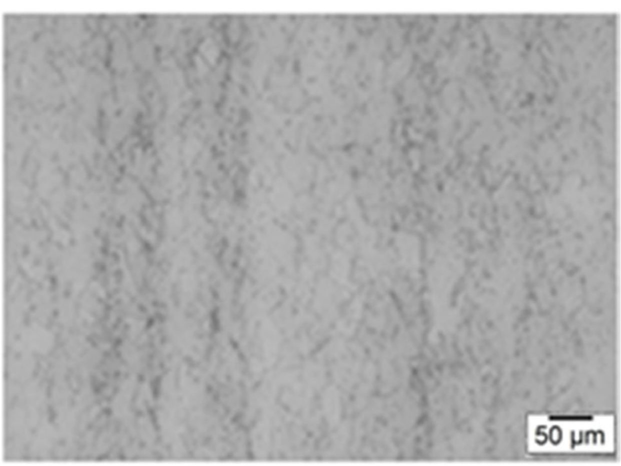

Fig. 10 SEM Micrograph of Al6061 Composite Joint –Sample 2 (1200 rpm Rotational Speed)

3.3 Weld Strength of Welded Samples

Figure 12 indicates the welding strength of the aluminium alloy composite welded sample followed by 800, 1200, and 1600 rpm respectively. The yield and tensile strength of sample 1 weld joint was found to be 135 ± 1.5 MPa and 187 ± 2 MPa. It was improved by 1.44 and 0.5 times yield and tensile strength by AA6061 alloy.

The improvement in tensile strength was due to the presence of SiC and effective interface quality. The SiC exhibited good tensile strength and particle stability [23, 24]. While the weld rotational speed was increased by 1200 rpm, results improved yield and tensile strength of 167 ± 1.8 MPa and 235 ± 2 MPa. It was increased by 23.7% and 25.66% of sample 1 (800 rpm) treated weld sample. The improvement in weld strength of the composite was due to the quality interface between the weld joint with fine grain structure

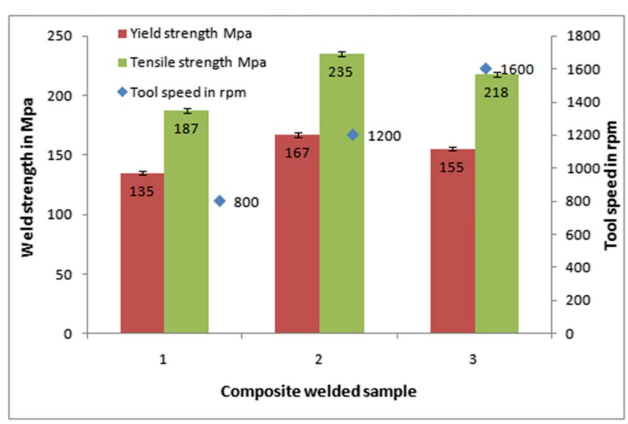

Fig. 12 Strength of Welded Samples

able to resist the break with an increased elongation rate of 2.3 mm. The effective interface quality is reported in Fig. 10.

The weld strength of aluminium alloy composite treated by 1600 rpm rotational speed slightly decreased yield and tensile strength of 155 ± 1.2 MPa and 218 ± 1.7 MPa. The gradual decrement in weld strength was due to the fine grain with aggregated structure, as evidenced in Fig. 11. However, the 1200 rpm operated rotational speed enhanced mechanical weld strength compared to others.

3.4 Vickers Hardness of Welded Samples

Figure 13 shows the Vickers hardness of FSW welded aluminium alloy composite with various rotational speeds of 800, 1200, and 1600 rpm. The weld zone took the hardness and showed a progressive improvement in hardness. The sample 1 composite with 800 rpm speed found a hardness of 82 ± 1.6Hv, and an increased hardness value of 88 ± 1.2Hv was found by 1200 rpm. The hardness value increased due to the hard SiC particle in AA6061 alloy. However, the hardness of weldment was increased by the resistance of SiC on high indentation force.

The sample 3, 1600 rpm performed welded aluminium alloy composite decreased in hardness due to the elongated structure may permit the load. The effective joint can resist indentation against high force.

3.5 Fatigue Test of a Welded Sample

Figure 14 shows the fatigue strength with cycles to failure of aluminium alloy composite tested by 100N to 100kN load. The proof stress of the composite joint increased gradually with an increase in rotational speed. Sample 3 was found to have a maximum proof stress of 62 ± 1.2 MPa and increased by 12.7% compared to sample 1. The increase in fatigue-proof stress is due to good interface weld quality, evidenced by Fig. 11. However, the cycles to failure are increased progressively. Sample 1 was 0.8X10^{6} cycles, and sample 2 increased the 50% of life compared to sample 1. However, the maximum fatigue cycle is shown in sample 3 and increased by 63% compared to sample 1. Sample 3 found maximum cycles without failure.

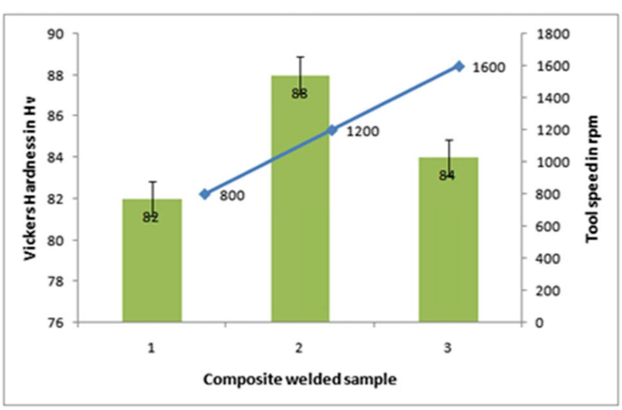

Fig. 13 Vickers Hardness of Welded Samples

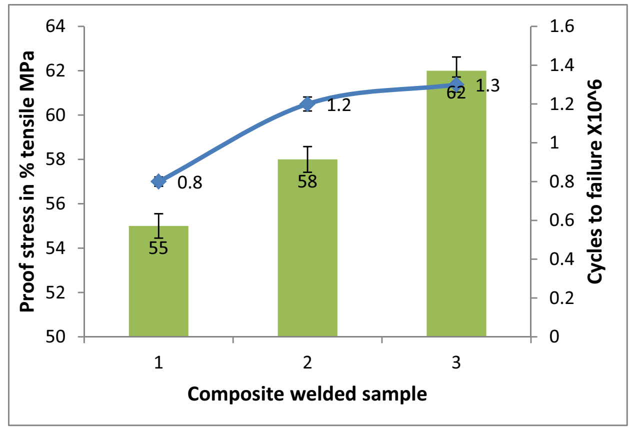

Fig. 14 Fatigue Strength of Welded Samples

4 Conclusions

The aluminium alloy (AA6061) with SiC compacted surface composite was successfully joined by friction stir welding on different rotational speeds like 800 rpm, 1200 rpm, and 1600 rpm. The radiography test found a few porous on 800 rpm rotational speed performed sample 1 weld. The SEM image discussed microstructure with their different grain and interface quality. Samples 2 and 3 found good interface quality, which results in increased yield and tensile strength of the composite. While compared to sample 1 weld joint, it was improved by 23.7% of yield and 25.66% of ultimate tensile strength. The hardness of composite weld joint with 1200 rpm made sample offered good hardness value, and sample 2 (1200 rpm) observed a maximum hardness value of 88 ± 1.2Hv. Sample 3 (1600 rpm) joint completed its entire fatigue life without failure. It is improved by 63% compared to sample 1 fatigue cycle.

Acknowledgements The authors would like to acknowledge the Researchers Supporting Project number (RSP2023R373), King Saud University, Riyadh, Saudi Arabia.

Author Contributions All authors contributed to the study's conception and design. Material preparation, data collection and analysis were performed by J. Balaji, A.H. Seikh, M.A. Kalam and R. Venkatesh. The first draft of the manuscript was written by [R. Venkatesh] and all authors provided language help, writing assistance and proofreading of the manuscript. All authors read and approved the final manuscript.

Funding
• The authors did not receive support from any organization for the submitted work.
• No funding was received to assist with the preparation of this manuscript.
• No funding was received for conducting this study.
• No funds, grants, or other support were received.

Data Availability All the data required are available within the manuscript.

Declarations

Competing interests The authors declare no competing interests.

Ethics Approval This is an observational study. Influences of rotational speed on friction stir welding quality, mechanical and fatigue behaviour of AA6061/SiC composite, Research Ethics Committee has confirmed that no ethical approval is required.

Consent to Participate Informed consent was obtained from all individual authors included in the study.

Consent for Publication We give our consent for the publication of Influences of rotational speed on friction stir welding quality, mechanical and fatigue behaviour of AA6061/SiC composite to be published in the Silicon Journal.

References

1. Çam G, Koçak M (1998) Progress in joining of advanced materials. Int Mater Rev 43(1):1–44
2. Venkatesh R (2023) Mechanical and thermal properties of a waste fly ash-bonded Al-10 Mg alloy composite improved by bioceramic silicon nanoparticles. Biomass Convers Biorefin. https://doi.org/10.1007/s13399-023-04588-w
3. Padmavathi KR et al (2023) Synthesis of Al/Mg hybrid nanocomposite by electromagnetic stir cast: characteristics study. SILICON. https://doi.org/10.1007/s12633-023-02595-0
4. Rathee S et al (2019) Investigating the effects of SiC particle sizes on microstructural and mechanical properties of AA5059/SiC surface composites during multi-pass FSP. SILICON 11(2):797–805
5. Baraniraj A et al (2023) Silicon carbide particle enriched magnesium alloy (az91) composite: physical, microstructural and mechanical studies. SILICON. https://doi.org/10.1007/s12633-023-02516-1
6. Ellis MBD (1996) Joining of aluminium based metal matrix composites. Int Mater Rev 41(2):41–58
7. Huang RY et al (2001) Electron and laser beam welding of high strain rate superplastic Al-6061/SiC composites. Metall Mater Trans A Phys Metall Mater Sci 32(10):2575–2584
8. Rai R (2011) Review: friction stir welding tools. Sci Technol Weld Join 16(4):325–342
9. Zhang YN et al (2012) Review of tools for friction stir welding and processing. Can Metall Q 51(3):250–261
10. Daniel Das A et al (2023) Effect of Tensile Strength on Friction Welding of Tube-to-Tube Plate Processed Samples: A Mechanical and Metallurgical Approach. J Mater Eng. https://doi.org/10.1007/s11665-023-08626-6
11. Threadgill L et al (2009) Friction stir welding of aluminium alloys. Int Mater Rev 54(2):49–93
12. Uzun (2007) Friction stir welding of SiC particulate reinforced AA2124 aluminium alloy matrix composite. Mate Des 28:1440–1446
13. Seetharaman R et al (2019) A statistical evaluation of the corrosion behaviour of friction stir welded AA2024 aluminium alloy. Mat Today Proc. https://doi.org/10.1016/j.matpr.2019.09.066
14. Saeidi M, Barmouz M, Givi MKB (2015) Investigation on AA5083/AA7075+Al2O3 joint fabricated by friction stir welding: characterizing microstructure, corrosion and toughness behavior. Mater Res 18(6). https://doi.org/10.1590/1516-1439.357714
15. Feng H, Xiao BL, Ma ZY (2008) Effect of micro structural evolution on mechanical properties of friction stir welded AA2009/SiCp composite. Compos Sci Technol 68(9):2141–2148. https://doi.org/10.1016/j.compscitech.2008.03.010
16. Lombard H, Hattingh DG, Steuwer A, James MN (2008) Optimising FSW process parameters to minimise defects and maximise fatigue life in 5083-H321 aluminium alloy. Eng Fract Mech 75(3–4):341–354. https://doi.org/10.1016/j.engfracmech.2007.01.026
17. Ceschini L, Boromei I, Minak G, Morri A, Tarterini F (2007) Compos Sci Technol 67:605e615
18. Bisadi H, Tavakoli A, Tour Sangsaraki M, Tour Sangsaraki K (2013) The infuences of rotational and welding speeds on microstructures and mechanical properties of friction stir welded Al5083 and commercially pure copper sheets lap joints. Mater Des 43:80–88. https://doi.org/10.1016/j.matdes.2012.06.029
19. Seyed et al (2017) Influence of TiO_2 nanoparticles incorporation to friction stir welded 5083 aluminum alloy on the microstructure, mechanical properties and wear resistance. J Alloys Comp 712:795–803. https://doi.org/10.1016/j.jallcom.2017.04.114
20. Krishnan MA et al (2023) Optimization and prediction of CBN tool life sustainability during AA1100 CNC turning by response surface methodology. Heliyon 9:e18807
21. Mohana Krishnan A, Laxmanan P (2022) Salt spray corrosion study on aluminium metal matrix composites (AMMCs) prepared by powder metallurgy route. Mater Today: Proc 62(4):1954–1957
22. Rajkumar S, Loganathan S, Venkatesh R, MadhanPrabhu Deva BS (2022) Investigate of Wear Behaviour and Mechanical Properties of Titanium Diboride Reinforced AMMC Composites. J New Mater Electrochem 24(4):254–260
23. Sekaran PR, Ramakrishnan H (2023) Mechanical and physical characterization studies of nano ceramic reinforced Al–Mg hybrid nanocomposites. SILICON 15(10):1–13
24. Venkatesh R, Manivannan S (2022) Studies on Corrosion Behavior of Mg-Al- Zn- RE Cast alloy with a powder coated Al and CED Mg by salt spray Test, Immersion Test and Electrochemical Test. Int J Chem Eng 2022, Article ID 1891419, pp. 11