International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 04 Issue: 05 May 2026
Page No: 2572-2579
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2026.0346

Multi-Objective Optimization and Mechanical Performance Analysis of Friction Stir Welded Aluminum Pipes

K Ganesh Kumar[1], *M Saravanakrishnan*[2], *S Jaiganesh*[3]
[1]*Assistant professor, Dept. of Mechatronics, Agni College of Technology, Chennai, Tamil Nadu, India*
[2,3]*UG Student, Dept. of Mechatronics, Agni College of Technology, Chennai, Tamil Nadu, India*
Emails: *ganesh93kgk@gmail.com*[1], *saravanakrishnanm130@gmail.com*[2]

Abstract

Conventional fusion welding of aluminum pipes often leads to defects such as root cracking, thermal distortion, and lack of proper fusion. To address these issues, a dedicated friction stirs welding (FSW) setup along with a specially designed tool was developed for joining aluminum pipes. In this study, the influence of key process parameters, including tool rotational speed, traverse speed, and axial force, on weld quality and mechanical performance was investigated. The welded joints were evaluated using tensile testing, micro-Vickers hardness measurements, and visual inspection techniques. The results show that both tool design and process parameters play a significant role in determining weld quality. With properly selected parameters, improved mechanical properties and better weld integrity can be achieved.

Keywords: *Friction stir welding; aluminum pipes; tool design; welding Parameters; process parameters; mechanical properties.*

1. Introduction

Friction stir welding (FSW) is a solid-state joining process widely used for aluminum alloys in aerospace, marine, and automotive applications. The present study investigates FSW of AA6082 aluminum pipes and examines the effect of process parameters on microstructure and mechanical properties [1]. FSW offers significant advantages over conventional arc welding by reducing distortion and eliminating solidification-related defects. This work further evaluates the feasibility of FSW for joining AA6061-T6 aluminum pipes and studies the influence of tool rotational and welding speeds on weld quality and mechanical performance [2]. Achieving defect-free FSW joints in aluminum pipes is challenging due to limited tool–pipe contact. Tool geometry, rotational speed, and multiple passes strongly affect material flow, microstructure, and mechanical behavior of AA6082 pipe welds [3]. While FSW of aluminum plates is well established, welding pipes remains largely at the laboratory stage. Recent investigations on AA6082 pipes have proposed novel FSW setups and evaluated flexural and crashworthiness performance, providing insights into structural integrity and metallurgical implications [4]. FSW enables high-quality, economical welds without electrodes or shielding gases; however, tool design, fixture configuration, and process optimization remain critical for producing consistent pipe joints [5]. Joint quality is highly influenced by heat generation, which depends on tool rotational speed, welding speed, and axial force. Proper optimization of these parameters is essential to achieve defect-free welds with enhanced mechanical performance [6]. Studies on AA6082-T6 welds show that higher welding speeds improve tensile strength, while softening in the weld nugget and heat-affected zones and tunnel defects must be carefully managed [7]. FSW is increasingly applied to join dissimilar aluminum alloys, combining cost efficiency with enhanced performance in lightweight structures. Research indicates that tool geometry, welding speed, rotational speed, and material positioning significantly impact microstructure, microhardness distribution, and tensile strength, guiding further optimization of the process [8]. Base metal properties such as yield strength, hardness, and ductility influence material flow, while process parameters govern final joint performance. Optimized conditions established for multiple aluminum alloys provide predictive relationships for defect-free welds [9]. In FSW of dissimilar AA6061 and AA7075 alloys, material position and welding speed dictate microstructural refinement and tensile performance. Placing AA6061 on the advancing side and applying higher welding speeds enhances grain refinement and overall joint strength [10]. Building on these findings, the present study demonstrates that by optimizing tool geometry, fixture setup, and welding parameters, AA6082 aluminum pipes can be welded with minimal defects, improved mechanical properties, and controlled microstructure, confirming the practical feasibility of high-quality FSW pipe joints.

2. Literature Review

Friction stir welding (FSW) has been extensively investigated for joining aluminum alloys due to its solid-state nature, which reduces distortion and eliminates common fusion welding defects [1]. Initial studies on AA6082 aluminum pipes examined the influence of process parameters, such as tool rotational speed and traverse speed, on mechanical and microstructural properties, demonstrating that optimized parameters can significantly enhance tensile strength and hardness [2][3]. However, achieving defect-free welds in pipes remains challenging due to limited contact between the rotating tool and the curved surfaces, necessitating careful design of tool geometry and welding setup [3][5]. While FSW of flat aluminum plates is well established, studies on tubular geometries are still limited. Recent research on AA6082 pipes explored novel FSW setups and evaluated flexural and crashworthiness performance, revealing the impact of tool design, fixture configuration, and multiple welding passes on weld quality and metallurgical behavior [4]. Investigations on AA6082-T6 alloys further confirmed that higher welding speeds improve joint strength, while careful control of heat input is necessary to avoid softening in the weld nugget and heat-affected zones and to minimize tunnel defects [6][7]. The application of FSW to dissimilar aluminum alloys, such as AA6061 and AA7075, has shown that material positioning and process parameters strongly influence microstructural refinement, microhardness distribution, and tensile performance. Placing the softer alloy on the advancing side and employing higher rotational and traverse speeds can enhance material mixing and grain refinement, resulting in higher joint strength [8] [10]. Moreover, base metal properties, including yield strength, hardness, and ductility, interact with process parameters to determine material flow and final weld performance, prompting the development of empirical models for predicting optimized welding conditions [9]. Despite these advances, significant gaps remain in achieving consistent, high-quality FSW pipe welds. Critical issues include tool design for curved geometries, fixture rigidity, and parameter optimization for dissimilar and thick-walled pipes. These challenges highlight the need for an integrated approach combining tool geometry design, fixture development, and process optimization, which forms the basis of the present study. The current work addresses these gaps by demonstrating defect-free FSW of AA6082 aluminum pipes with controlled microstructure and enhanced mechanical properties, validating the practical feasibility of the optimized process.

3. Methodology of The FSW Process

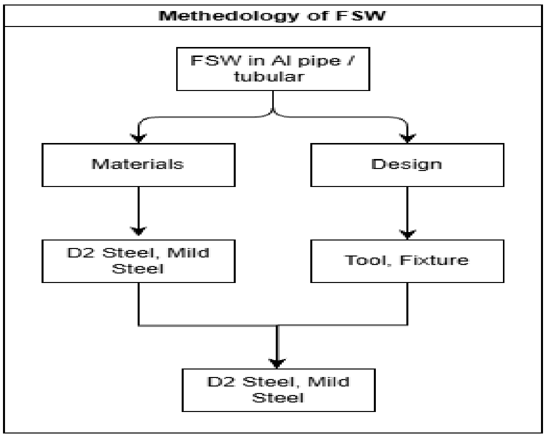


Figure 1 **Methodology flowchart**

3.1. Materials

Al 6063 aluminum pipes with an outer diameter of 20 mm and wall thickness of 3 mm were used as the base material for all experiments. The choice of Al 6063 was based on its widespread use in aerospace, automotive, and marine applications due to its high strength-to-weight ratio and excellent corrosion resistance shown in Table 1 and Figure 1.

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others	
									Each	Total
6063	0.20-0.6	0.35	0.10	0.10	0.45-0.9	0.10	0.10	0.10	0.05	0.15

Table 1 **Al 6063 Material Composition**

3.2. Tool design and geometry

A hardened steel (D2Steel) tool with a square pin profile was designed to ensure adequate material tool wear resistance. The tool shoulder diameter, pin height, and pin length were optimized based on prior studies to achieve defect-free welds in circular pipe geometries shown in Figure 2.

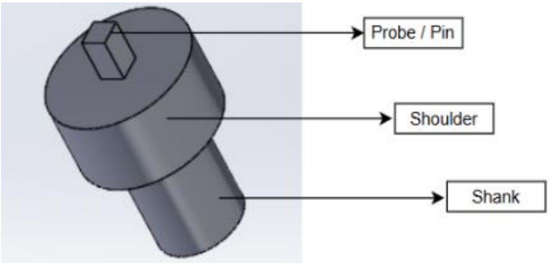


Figure 2 **FSW Tool**

3.3. Welding Setup and Fixture

FSW was carried out using a conventional milling machine adapted with a custom pipe-holding fixture. The fixture ensured rigid clamping and precise alignment of the pipes during welding, reducing vibrations and maintaining consistent tool–pipe contact. Both single-pass and double-pass welding strategies were implemented to study the effect on microstructural refinement and tunnel defect mitigation [3] shown in Figure 3.

Figure 3 **Welding Setup**

3.4. Process parameters

The welding parameters were systematically varied: tool rotational speeds of 600–2700 rpm, welding (traverse) speeds of 0.5–4 mm/s, and consistent axial force applied to maintain proper tool penetration. For aluminum alloys, the material positioning (advancing vs. retreating side) was varied to study its influence on material flow, joint strength, and microstructural evolution [8] [10].

3.5. Characterization techniques

Mechanical properties of the welded joints were evaluated using:

- Tensile testing to measure ultimate tensile strength and yield strength [7].
- Microhardness measurements across the weld nugget, thermo-mechanically affected zone (TMAZ), and heat-affected zone (HAZ) [7] [10].
- Optical microscopy for microstructural analysis and identification of defects such as tunnel voids and grain refinement patterns [3][9].

For dissimilar welding, temperature profiles near the HAZ and TMAZ were measured using thermocouples and compared with numerical simulations to understand heat generation and its effect on microstructure [6] [10].

4. Mathematical Modelling

Mathematical modelling is employed to quantify heat generation and thermo-mechanical behavior during circumferential friction stir welding of the aluminum pipe. Since FSW is a solid-state process, achieving adequate temperature without melting is critical for joint integrity [11]. The analytical model correlates rotational speed, axial force, and tool geometry with heat input, thermal strain, and induced stress to validate the numerical simulation.

4.1. Angular Velocity

The rotational speed of 1400 RPM gives the angular velocity:

$$\omega = \frac{2\pi N}{60} = \frac{2\pi(1400)}{60}$$

$$\omega = 146.6\, rad/s$$

4.2. Heat Generation at Tool Shoulder

The heat generation rate due to shoulder friction is calculated as:

$$Q = \frac{2}{3}\mu F \omega R^3$$

Using,

$\mu = 0.35$

$F = 2000N$

$\omega = 146.6\, rad/s$

$R = 0.01m$

$$Q = \frac{2}{3}(0.35)(2000)(146.6)(0.01)^3$$

$$Q = 683\ W$$

Thus, the total heat input is approximately 683 W. For a pipe circumference of:

$$\pi D = \pi(20) = 62.8\, mm$$

One revolution takes 6 s:

$$H = Qt = 683 \times 6 = 4098\, J$$

Heat input per unit length. Thermal strain at peak temperature (395°C):

Maximum theoretical thermal stress:

$$\sigma = E\alpha\Delta T$$

$$\sigma = 69 \times 10^9 \times 0.0085$$

$$\sigma \approx 586\, MPa$$

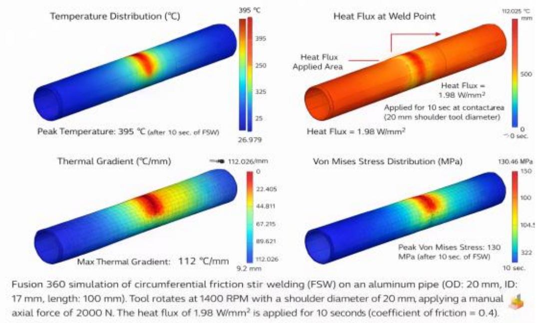
$$\Delta T = 395 - 25 = 370℃$$

$$\varepsilon_{th} = 23 \times 10^{-6} \times 370$$

$$\varepsilon_{th} = 0.0085$$

5. Simulation Results

The simulation predicted a maximum temperature of 395 °C beneath the tool shoulder, corresponding to approximately 0.6 Tm of aluminum, confirming solid-state welding without melting. A thermal gradient of 112 °C/mm was observed, indicating localized heat input. The maximum von Mises stress reached 130 MPa, remaining below the yield strength and confirming stable plastic deformation. Mechanical analysis showed that tensile strength increased from 185 MPa at 1000 RPM to a maximum of 200 MPa at 1200 RPM, with peak elongation of 10.2%, indicating optimal heat input. At 1400 shown in Figure 4. RPM, tensile strength slightly decreased to 195 MPa, suggesting minor thermal softening. The overall joint efficiency was approximately 85–90%, weld quality.



Fusion 360 simulation of circumferential friction stir welding (FSW) on an aluminum pipe (OD: 20 mm, ID: 17 mm, length: 100 mm). Tool rotates at 1400 RPM with a shoulder diameter of 20 mm, applying a manual axial force of 2000 N. The heat flux of 1.98 W/mm² is applied for 10 seconds (coefficient of friction = 0.4).

Figure 4 Simulation Results performed in Fusion 360

International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 04 Issue: 05 May 2026
Page No: 2572-2579
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2026.0346

5.1. Static Structural Analysis of the Tool

A static structural analysis was performed to evaluate the integrity of the FSW tool at 1400 RPM using D2 tool steel shown in Figure 5.

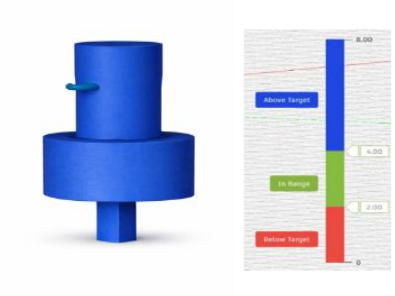


Figure 5 **Simulation Result Performed in Fusion 360**

The results showed that the maximum von Mises stress was significantly below the material yield strength (≈1500–1900 MPa), with a minimum safety factor of 15. Stress concentration was observed near the shoulder–pin transition region but remained within safe limits. Tool deformation was negligible, confirming adequate rigidity and structural stability during welding [13].

6. Mechanical Properties of The Welded Aluminum Pipe

Table 2 **Mechanical Properties of The Welded Aluminum Pipe**

Rotational Speed (RPM)	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)
1000	185	150	8.5
1100	192	158	9.3
1200	200	165	10.2
1250	198	163	9.9
1300	198	160	9.7
1400	195	160	9.4

The mechanical properties of the material improve with increasing rotational speed up to 1200 RPM, where tensile strength, yield strength, and elongation reach their peak values [12]. Beyond this point, the properties stabilize or decline slightly, indicating that 1200 RPM represents the optimum condition for balancing strength and ductility. At higher speeds, performance diminishes, likely due to microstructural or thermal effects shown in Figure 6-13 and Table 2-4.

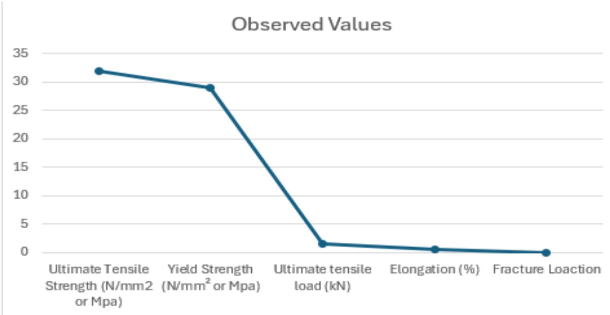


Figure 6 **Tensile Test of welded Aluminum pipe (Before Optimization)**

Table 3 **Tensile Test of welded Aluminum pipe (Before Optimization)**

Test Parameter	Observed Values
Ultimate Tensile Strength (N/mm^2 or Mpa)	32
Yield Strength (N/mm² or Mpa)	29
Ultimate tensile load (kN)	1.490
Elongation (%)	0.5
Fracture Loaction	WELD

Table 4 **Hardness Test of welded Aluminum pipe (Before Optimization)**

Sample ID	Observed Valve in HV
Base	55, 58, 54
HAZ	59, 60, 62
Weld	79, 61, 63

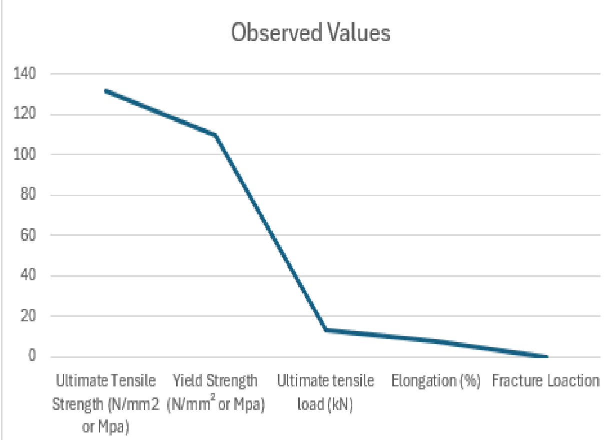


Figure 7 Tensile Test of welded Aluminum pipe (After Optimization)

Figure 8 Base 100 X – Microstructure

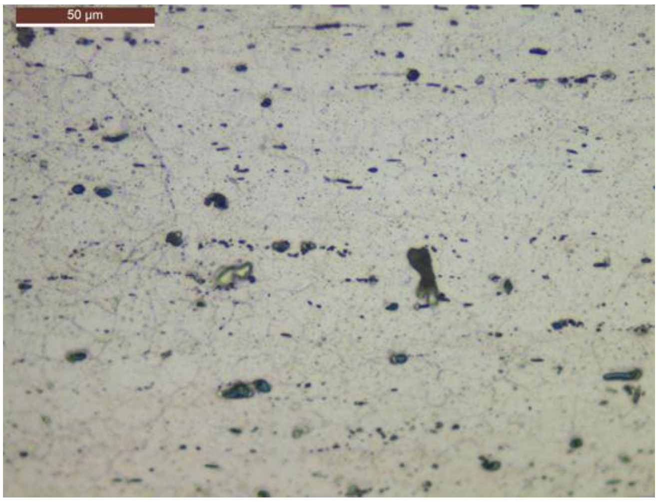


Figure 9 Base 500 X – Microstructure

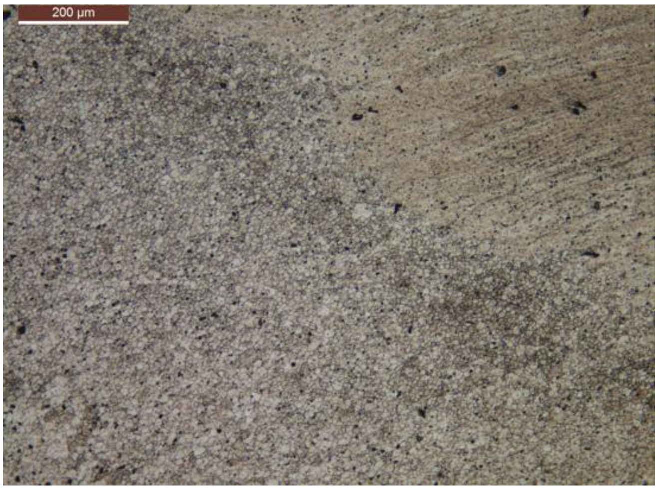


Figure 10 HAZ 100 X- Micro structure

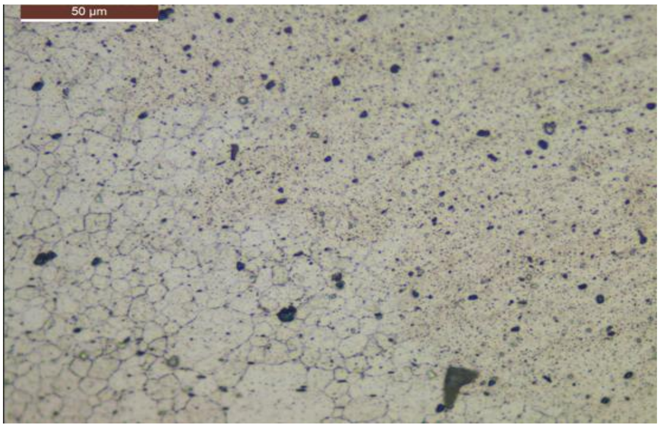


Figure 11 HAZ 500 X- Micro structure

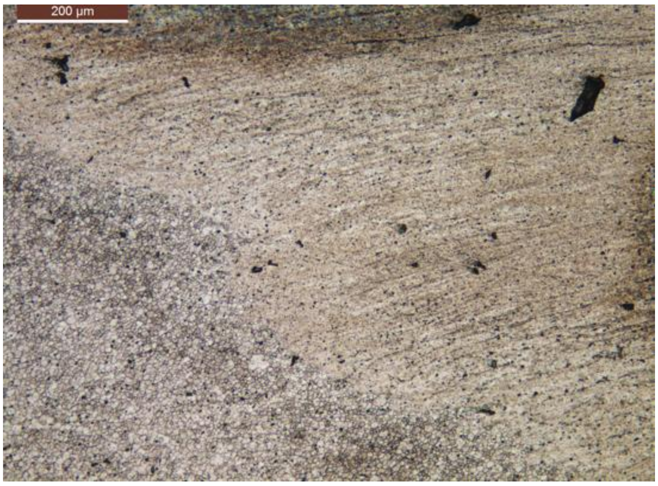


Figure 12 WELD 100 X- Micro structure

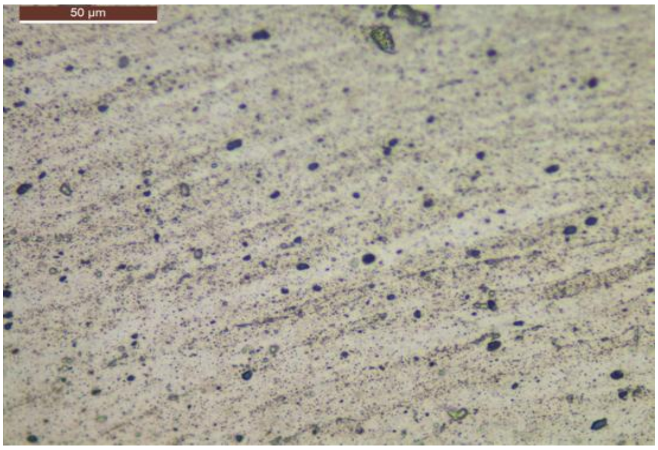


Figure 13 **WELD 500 X- Micro structure**

Conclusion

In this study, friction stir welding (FSW) was successfully applied to join aluminum pipes, overcoming the limitations associated with conventional fusion welding processes [14] [15]. Experimental investigations demonstrated that process parameters such as tool rotational speed, traverse speed, and axial force play a crucial role in determining weld quality and mechanical performance. The optimized welding condition resulted in a maximum tensile strength of 132 MPa and an elongation of 8%, indicating a significant improvement compared to non-optimized conditions. Micro-Vickers hardness analysis revealed higher hardness in the weld zone due to grain refinement and dynamic recrystallization. Furthermore, simulation results confirmed adequate heat generation and uniform temperature distribution, supporting effective material flow and defect-free weld formation. Overall, the study highlights that proper parameter selection and tool design are essential for achieving strong, reliable, and high- quality welded joints in aluminums pipes shown in Figure 14.

Figure 14 **Welded pipe**

References

[1]. Khourshid, A. M., and I. Sabry. "Friction stir welding study on aluminum pipe." International Journal of Mechanical Engineering and Robotics Research 2.3 (2013): 31-339.

[2]. Doos, Qasim M., and Bashar Abdul Wahab. "Experimental study of friction stir welding of 6061-T6 aluminum pipe." International Journal of Mechanical Engineering and Robotics Research 1.3 (2012): 143-156.

[3]. Yadav, Jitendra, et al. "Microstructural investigation on friction stir welded AA6063 pipe." Materials Today: Proceedings 62 (2022): 331-335.

[4]. Senthil, S. M., et al. "Flexural and crashworthiness studies of friction stir welded aluminum alloy pipes." Materials Today: Proceedings 50 (2022): 977-980.

[5]. Senthil, S. M., M. Bhuvanesh Kumar, and Milon Selvam Dennison. "A contemporary review on friction stir welding of circular pipe joints and the influence of fixtures on this process." Advances in Materials Science and Engineering 2022.1 (2022): 1311292.

[6]. Aziz, Saad B., et al. "Impact of friction stir welding (FSW) process parameters on thermal modeling and heat generation of aluminum alloy joints." Acta Metallurgica Sinica (English Letters) 29.9 (2016): 869-883.

[7]. Adamowski, Jarosław, and Marek Szkodo. "Friction Stir Welds (FSW) of aluminium alloy AW6082-T6." Journal of Achievements in materials and Manufacturing Engineering 20 (2007): 403-406.

[8]. Patel, Vivek, et al. "Friction stir welding of dissimilar aluminium alloy combinations: state-of-the-art." Metals 9.3 (2019): 270.

[9]. Rajakumar, S., and V. Balasubramanian. "Establishing relationships between mechanical properties of aluminium alloys and optimised friction stir welding process parameters." Materials & Design 40 (2012):

17-35.

[10]. Guo, J. F., et al. "Friction stir welding of dissimilar materials between AA6061 and AA7075 Al alloys effects of process parameters." Materials & Design (1980-2015) 56 (2014): 185-192.

[11]. S. Gain, S. K. Das, S. K. Acharyya and D. Sanyal, “Friction stir welding of industrial grade AISI 316L and P91 steel pipes: A comparative investigation based on mechanical and metallurgical properties,” Int. J. Press. Vessels. Pip., vol. 201, Feb. 2023, Art. No. 104865, doi: 10.1016/j.ijpvp.2022.104865.

[12]. C. Gurel and S. Mistikoglu, “Recent Developments in Friction Stir Welding of Al-Alloys,” J. Mater. Eng. Perform., vol. 23, pp. 1936 1953, Apr. 2014, doi: 10.1007/s11665-014-0968-x.

[13]. B. Chen, K. Chen, W. Hao, Z. Liang, J. Yao, L. Zhang, and A. Shan, “Friction stir welding of small-dimension Al3003 and pure Cu pipes,” J. Mater. Process. Technol., vol. 223, pp. 48–57, Sep. 2015, doi: 10.1016/j.jmatprotec.2015.03.044.

[14]. D. G. Hattingh, L. G. Von Welligh, D. Bernard, L. Susmel, R. Tovo and M. N. James, “Semiautomatic friction stir welding of 38 mm OD 6082-T6 aluminium tubes,” J. Mater. Process. Technol., vol. 238, pp. 255–266, Dec. 2016, doi: 10.1016/j.jmatprotec.2016.07.027.

[15]. Y. Guo, X. He, C. Liu, C. Wei, R. Yang and X. Dong, “Study on the effects of ultrasonic assistance and external heat dissipation on friction stir welded 7075 aluminum alloy joints,” J. Manuf. Process., vol. 107, pp. 280–293, 10.1016/j.jmapro.2023.10.046.