Effect of external heat assistance on the weld quality of AA2024 aluminium alloy during friction stir welding

Pilli Jaya Teja, Rahul Jain*

Indian Institute of Technology, Bhilai, Raipur, India

Presented in International Conference on Precision, Micro, Meso and Nano Engineering (COPEN - 12: 2022)
December 8th - 10th, 2022 IIT Kanpur, India

KEYWORDS

Friction Stir Welding,
TIG Preheating,
Heat Assisted Friction Stir Welding (HAFSW),
2024 Aluminium Alloy,
Defect Elimination.

ABSTRACT

Friction Stir Welding is one of the advanced and efficient methods to join aluminium alloys. The efforts to increase its productivity may sometimes lead to defective welds. Because, the increased welding speed may result in lesser heat input, inferior material flow and voids. To overcome this, external heat assistance can be provided to the FSW operation. This preheating of the material before it comes in contact with the FSW tool ensures better softening and material flow. In this work, external heat assistance was given with the help of a TIG during the FSW of 3mm thick AA2024. The FSW without TIG heat assistance resulted in defect formation, whereas the TIG-assisted FSW gave a defect-free weld; increase in the tensile strength, ductility and hardness at SZ by 25.8%, 47.57% and 24%, respectively. This external heat assistance boosts the productivity and might broaden the parameter window of this process.

1. Introduction

Application of lighter and stronger materials is a requirement in aerospace and automobile industries for its advantage of good strength-to-weight ratio. These materials are helpful in reducing the fuel consumption. One such aluminium alloy used in the aerospace industry for making fuselage, wings and other components of airplanes is AA2024 (Choudhary & Jain, 2021). It raises the requirement to weld AA2024 with good strength and without any defects. Traditional fusion welding methods may result in the formation of solidification defects. Solid-state welding could help to eliminate the solidification defects as the welding process takes place at a temperature below the melting point of the material. Friction Stir Welding is one such technique in which produces higher weld strength with lower defects (Chaurasia et al., 2018). The flexibility of the FSW process was confined as only high-capacity machines can withstand the large axial loads during the process (Able & Pfefferkorn, 2005). To increase productivity and industrial profitability, the welding speeds of the FSW process should be increased. But with the increase in welding speeds, there is a chance of reduced heat input into the welds which may result in improper material flow and defective welds. To overcome these confinements, FSW needs additional external heat assistance which would preheat the material. Thereby, the flow stress of the material reduces and helps in lowering the required welding force and productivity can also be accelerated by increasing the welding speeds. Various types of heat assistances (LASER, Ultrasonic, TIG, Plasma-arc, Induction, Electric resistance, Gas torch, etc.) were used in heat-assisted FSW (Able & Pfefferkorn, 2005; Gao et al., 2017; Liu et al., 2015). A concentrated energy source like TIG arc is used for preheating in this study, as it is economical and readily available in most of the workshops. A square pin profile was used for the advantageous pulsating effect it gives in material mixing due to its flat face, studies have shown that better mechanical properties were observed with the use of a square pin (Jain et al., 2019). Studies on a wide range of materials with heat assistance showed that better material flow and mechanical

*Corresponding author E-mail: rahul@iitbhilai.ac.in

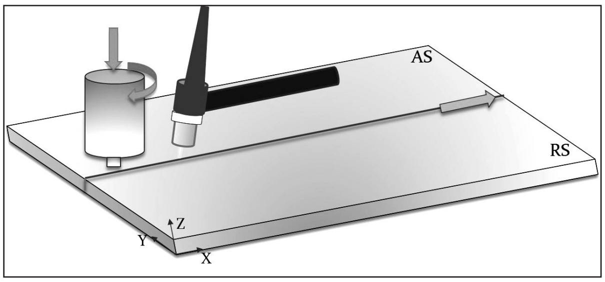

Fig. 1. Pictorial representation of TIG-assisted FSW.

https://doi.org/10.58368/MTT.22.1.2023.20-24

Table 1
Process parameters used in the experiments.

Process Parameters	
Rotational Speed	600 RPM
Welding Speed	150 mm/min
Tool tilt angle	2°
Plunge Depth	0.2 mm
Plunge Rate	3 mm/min
Dwell Time	10 Seconds
TIG welding Current (only for TIG-assisted FSW)	30 A

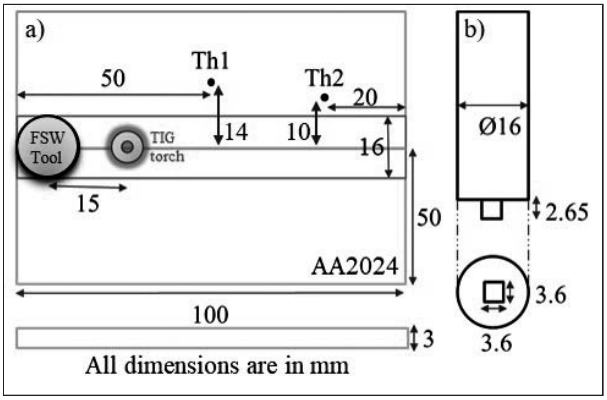

Fig. 2. Schematic illustration of FSW experimental details a) thermocouple placement, plate dimensions, TIG torch placement, and b) FSW tool dimensions.

properties were achieved (Yi et al., 2022). However, the effect of TIG preheating during the FSW of AA2024 on the defects, microstructure and mechanical properties is not clear and needs further research. In this study, we are going to observe the effect of TIG preheating on defect elimination, weld quality and improvement of mechanical properties like strength and hardness.

2. Experimental Details

3 mm thick AA2024 material was cut into 4 plates of dimensions 100 mm x 50mm x 3 mm and were butt welded using FSW without TIG and TIG-assisted FSW processes. A CNC-based FSW machine (ETA Bengaluru) of 50 kN capacity with a built-in load cell for force and torque measurement was used. The FSW process parameters taken were 600 RPM and 150 mm/min for both the welds, these parameters were selected in order study the effect of external heat assistance in extreme condition like high welding speed and low rotational speed. Other FSW parameters were mentioned in table 1. DC current of 30 A with straight polarity was used for TIG preheating during the TIG-assisted FSW, the other parameters followed were 15 lpm of Argon shielding gas flow, 2.4mm diameter thoriated tungsten electrode, 3 mm of stand-off distance and was fixed 15 mm in front of the FSW tool on the welding line. H13 steel tool was machined to make an FSW tool with dimensions 16mm shoulder diameter and a square pin profile of 3.6 mm side and 2.65 pin lengths. Two K-type thermocouples named as Th1 and Th2 were placed on the advancing side at different positions as shown in the figure to collect temperature variation during both welds. X-Ray defect visualization was carried out to visually identify the defect density on the samples. Wire cut-EDM was used to cut samples for microstructural analysis and tensile test of standard ASTM E8. Samples for microstructural analysis were mechanically polished from 1000 to 2000 grit papers followed by diamond polishing and colloidal silica polishing until we get a mirror finish. Etching was done using Keller's reagent (1.0 ml HF, 1.5 ml HCl, 2.5 ml HNO_3, 95.0 ml H_2O) for 10 seconds. An optical microscope was used to take the magnified images of the microstructure. A universal testing machine with a strain rate of 1mm/min was used to perform the tensile test. Vickers micro-hardness test was conducted with 100gf and 10 seconds of dwell time on the weld cross-section at 1.4 mm deep from the top surface.

3. Results and Discussion

From figure 3, it can be observed that the axial force while welding with TIG assistance was significantly reduced when compared to the axial force during FSW without TIG. Peak force during the plunging and axial force during the welding

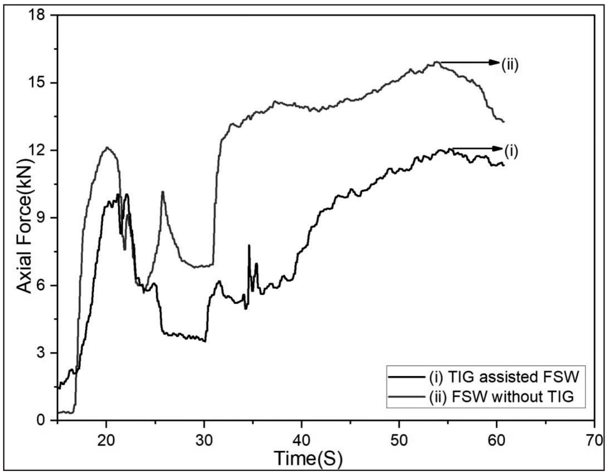

Fig. 3. Variation in axial force (Fz) during FSW and TIG-assisted FSW.

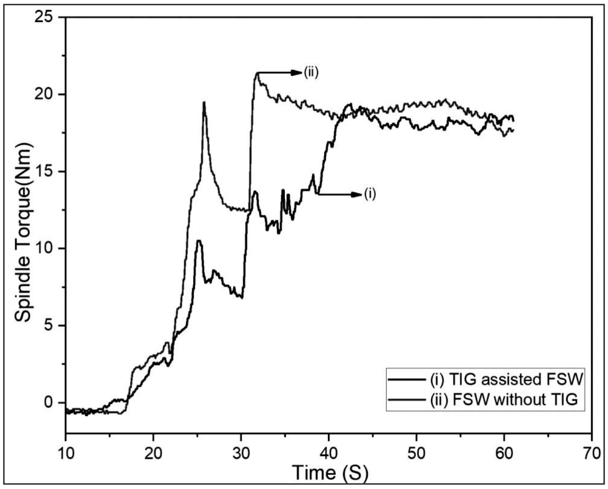

Fig. 4. Variation spindle torque during FSW and TIG-assisted FSW.

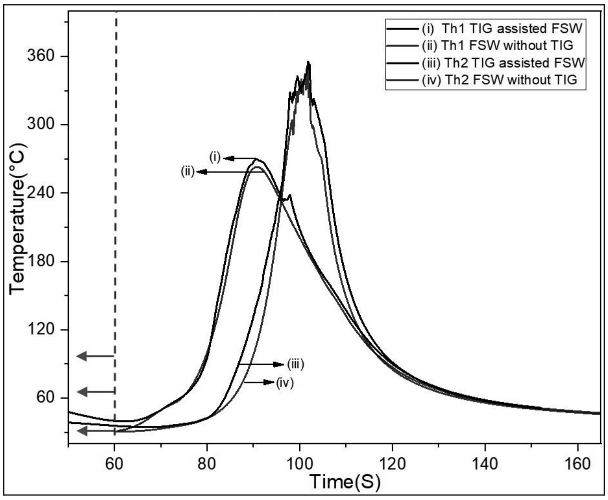

Fig. 5. Variation of temperature during FSW and TIG-assisted FSW shown by two thermocouples (arrows indicate the prior preheating period).

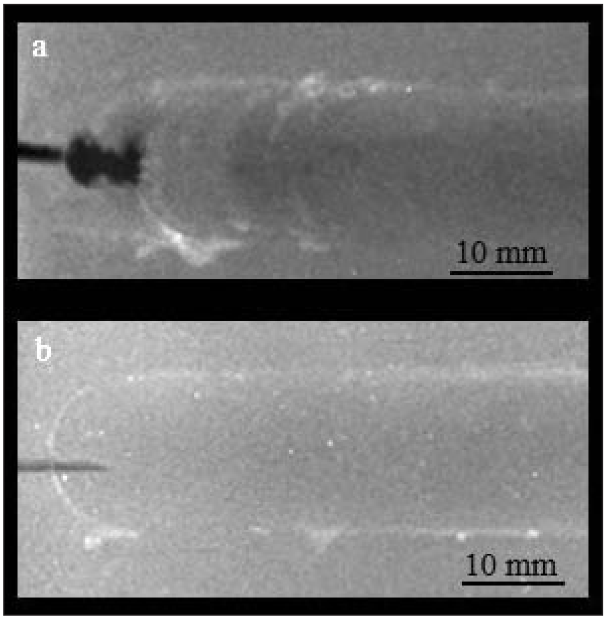

Fig. 6. X-Ray defect visualization a) FSW without TIG b) TIG-assisted FSW.

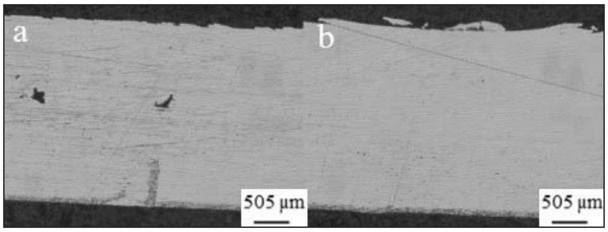

Fig. 7. Macrographs showing SZ in a) FSW without TIG b) TIG-assisted FSW.

phase got reduced by 17.21% and 24.20% respectively. The torque requirement by the spindle during the plunge phase was greatly reduced by 35.98% with the TIG heat assistance and the overall torque requirement for TIG-assisted FSW was lesser than the FSW without TIG. In FSW, the heat generation is largely dependent on the tool's shoulder rotation, as the incoming material is cold for the tool, the resistive flow stresses faced by the tool would be high. This TIG heat assistance helps in preheating the material before it comes in contact with the FSW tool, so the load on the tool decreases as the flow stresses of the incoming material were already lowered before coming into contact with the tool, now the primary duty of the tool would be is to stir the material. This reduced force during TIG-assisted FSW helps in reducing the need for high-capacity machines and rigid clamping systems (Able & Pfefferkorn, 2005). This technique allows the scope for miniaturization of the FSW process with the help of heat assistance and medium-capacity machines with moderate clamping systems could also perform highly demanding jobs.

The temperature data is received from two thermocouples Th1 and Th2 placed as shown in figure 2. From figure 5, we can observe that the TIG preheating increased the peak temperature of the process to facilitate softening of the material for better plastic flow. At the same time, it is to be taken care of, to avoid the demerits of overheating and grain coarsening (Yi et al., 2022). The arrows and the dashed line represents the preheating period prior to the start of the weld i.e. just before the start of plunge phase. We can observe a steep increase in the temperature peak of FSW without TIG and a more steadier and lesser steep peak was observed in TIG assisted FSW. This was clearly shown in the readings of Th2 thermocouple as it was near and only 10 mm away from the weld line. The slopes in Th1 readings does not give clear trend because it is 14 mm away from centre line and heat dissipation might have taken place. The time required for cooling in TIG-assisted FSW

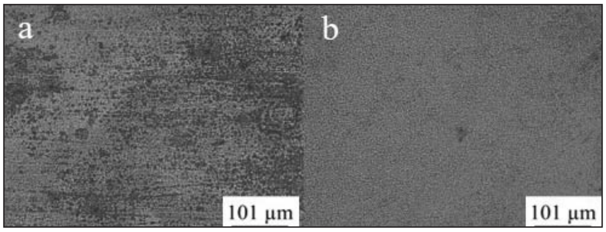

Fig. 8. Optical Microscope images showing centre of SZ in a) FSW without TIG b) TIG-assisted FSW.

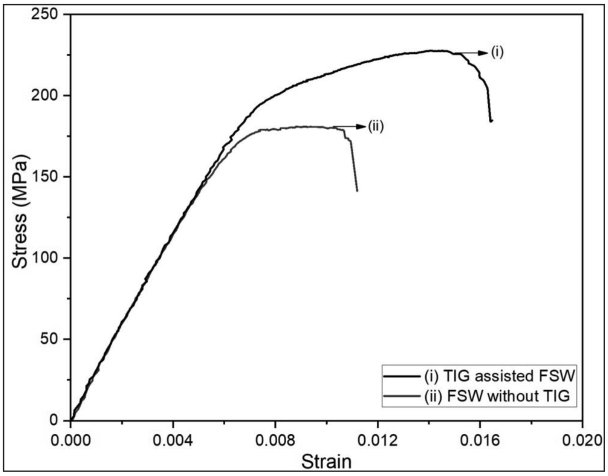

Fig. 9. Stress-strain curve for FSW without TIG and TIG-assisted FSW.

is slightly higher than the FSW without TIG. Time under heat was also high for the TIG Assisted FSW because the area under the temperature plot was higher than FSW without TIG. All these, may lead to grain coarsening in heat-affected zones of the TIG assisted weld.

Weld quality assessment could be done through several techniques and X-ray defect visualization is one such technique. It allows us to understand the potential defective welds without performing any other destructive tests. When there void or defect in the weld, the lack of material there allows the X-rays to pass through it and this can be seen as a dark shade in X-ray imaging. Figure 6 shows that the presence of defects in FSW without TIG weld and TIG assisted FSW was looking to be defect free. The samples for microscopic analysis were cut 55 mm away from the start of the weld, keeping the stir zone (SZ) at the centre. Macrographs obtained from the stir zones of both the welds shown in figure 7, confirm that defects like voids were present in the FSW without TIG sample. Whereas, the TIG-assisted FSW sample was found to be defect free. The heat assistance adequately softened the material and the stirring action of the tool further enhanced the material flow resulting in the filling of voids with material resulting in a

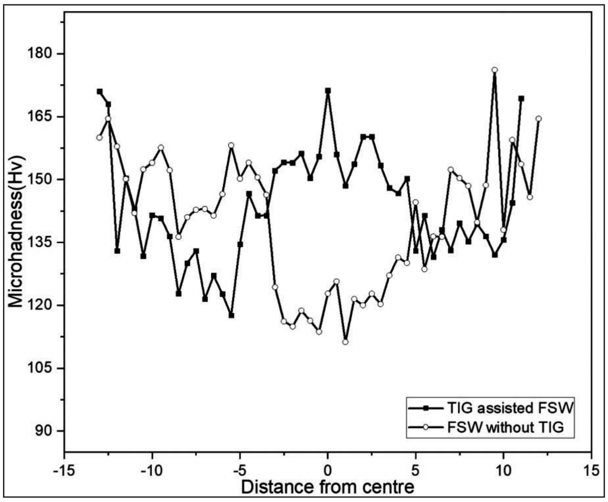

Fig. 10. Variation in micro-hardness for FSW without TIG and TIG-assisted FSW.

defect free weld (El-Morsy et al., 2018). It also increased the heat penetration in the weld, from figures 7a and 7b; we can observe that in FSW without TIG the generated heat couldn't reach the root of the weld due to higher welding speed. But this root defect can be reduced to an extent with the help of heat assistance as there is a penetration of heat, there will be proper mixing of material as well (Garg et al., 2019). Figure 8 gives the information of microstructure in the middle of the stir zone. If the heat input wasn't sufficient, there won't be enough plasticization that affects the material flow and recrystallization. If the material was properly plasticized and stirred, we can expect the recrystallization of new finer grains. These microscope images show that with the external heat assistance, material flow got better and recrystallization of grains to form new finer grains took place (Gao et al., 2017).

The stress-strain curve given in figure 9 shows that the tensile strength was increased by 25.8% and ductility was increased by 47.6%. As the FSW without TIG sample is having defects, it may lead to crack initiation and easier propagation, coarse grains can also be a reason for its lower strength (Yi et al., 2022). While TIG assisted FSW sample has better material flow and was observed to be defect-free, the grain coarsening effect in HAZ resulted in the weakening of the weld. The propagation of cracks could be easier in coarsened grains, this might have limited the improvement in strength with heat assistance. The hardness plot was given in figure 10, it can be observed that hardness in the stir zone was improved with TIG assistance because the extra heat resulted in the dissolution of residual coarse precipitates and the FSW action gave us the dispersed and distributed fine hardening precipitates in the stir zone. Whereas, the HAZ in the TIG-assisted FSW has a lower hardness than the FSW without TIG may be due to the combined effect of grain coarsening and precipitate dissolution (Liu et al., 2015).

4. Conclusion

In this work, it is found that TIG heat assistance to FSW improved the weld quality and its mechanical properties. This technique can be applied in the future for its advantages. The conclusions follow:

- Axial force got reduced by 17.21% during plunging and 24.20% during welding phase with the help of TIG heat assistance. Spindle torque also reduced by 35.98% during plunging with heat assistance.
- Softening of the material with heat assistance resulted in better material flow and defect elimination was observed.
- The preheating facilitated better material stirring that helped in the formation of fine grains and dispersion of fine hardening precipitates.
- Mechanical properties like tensile strength increased by 25.8%, ductility by 47.6% and hardness on average in the stir zone by 24% with the help of TIG heat assistance.
- The heat assistance might help in broadening the parameter window, this boosts the production speed.
- The force reduction observed during the heat assisted FSW helps in the miniaturization of the machine for flexible applications.

Acknowledgments

The authors would also like to thank the Indian Institute of Technology Bhilai for the provision of experimental facilities. The first author would like to thank MHRD for supporting with fellowship.

References

Able, N., & Pfefferkorn, F. (2005). Laser-assisted friction stir lap welding of aluminum. *Proceedings of the ASME Summer Heat Transfer Conference*, *3*, 425-429.

Chaurasia, P. K., Pandey, C., Giri, A., Saini, N., & Mahapatra, M. M. (2018). A comparative study of residual stress and mechanical properties for fsw and tig weld on structural steel. *Archives of Metallurgy and Materials*, *63*(2), 1019-1029.

Choudhary, A. K., & Jain, R. (2021). Fundamentals of Friction Stir Welding, Its Application, and Advancements. *Welding Technology*, 41-90.

El-Morsy, A. W., Ghanem, M., & Bahaitham, H. (2018). Effect of Friction Stir Welding Parameters on the Microstructure and Mechanical Properties of AA2024-T4 Aluminum Alloy. *Engineering, Technology & Applied Science Research*, *8*(1), 2493-2498.

Gao, S., Wu, C. S., & Padhy, G. K. (2017). Material flow, microstructure and mechanical properties of friction stir welded AA 2024-T3 enhanced by ultrasonic vibrations. *Journal of Manufacturing Processes*, *30*, 385-395.

Garg, A., Raturi, M., & Bhattacharya, A. (2019). Influence of additional heating in friction stir welding of dissimilar aluminum alloys with different tool pin profiles. In *International Journal of Advanced Manufacturing Technology, 105*(1-4), 155-175.

Jain, R., Pal, S. K., & Singh, S. B. (2019). Investigation on effect of pin shapes on temperature, material flow and forces during friction stir welding: A simulation study. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *233*(9), 1980-1992.

Liu, X. C., Wu, C. S., & Padhy, G. K. (2015). Improved weld macrosection, microstructure and mechanical properties of 2024Al-T4 butt joints in ultrasonic vibration enhanced friction stir welding. *Science and Technology of Welding and Joining*, *20*(4), 345-352.

Yi, T., Liu, S., Fang, C., & Jiang, G. (2022). Eliminating hole defects and improving microstructure and mechanical properties of friction stir welded joint of 2519 aluminum alloy via TIG arc. *Journal of Materials Processing Technology*, *310* (September), 117773.

Pilli Jaya Teja is a Doctoral Student at IIT Bhilai. He did his Master of Technology (MTech) in Manufacturing from the National Institute of Technology, Rourkela. His area of interest is welding and additive manufacturing.
(E-mail: pillij@iitbhilai.ac.in)

Dr. Rahul Jain is an Assistant Professor in the Department of Mechanical Engineering, IIT Bhilai. He completed his doctoral work at IIT Kharagpur. He has published 13 papers in the journals of international repute, and 4 book chapters, and has given a talk at various reputed conferences. His research area is numerical modeling, welding, and additive manufacturing process.