DOI: 10.46793/41DAS2025.115B

EXPERIMENTAL VALIDATION OF FRICTION STIR WELDING PARAMETERS FOR EN AW 6060 T6 ALUMINUM ALLOY

Aleksandar BODIĆ[1], Vladimir MILOVANOVIĆ[2], Miroslav ŽIVKOVIĆ[3], Miloš PEŠIĆ[4], Dušan Milojević[5], Marko TOPALOVIĆ[6]

[1] 0000-0002-1713-6540, Faculty of Engineering University of Kragujevac, Sestre Janjić 6, Kragujevac, Serbia, E-mail: abodic@uni.kg.ac.rs;

[2] 0000-0003-3071-4728, Faculty of Engineering University of Kragujevac, Sestre Janjić 6, Kragujevac, Serbia, E-mail: vladicka@kg.ac.rs;

[3] 0000-0002-0752-6289, Faculty of Engineering University of Kragujevac, Sestre Janjić 6, Kragujevac, Serbia, E-mail: zile@kg.ac.rs;

[4] 0000-0002-3405-5216, Institute for Information Technologies, University of Kragujevac, Jovana Cvijića bb, Kragujevac, Serbia, E-mail: milospesic@uni.kg.ac.rs;

[5] Wacker Neuson Kragujevac DOO Kragujevac, Braće Nikolića 20A, Kragujevac, Serbia, E-mail: dusanmilojevic.kg@gmail.com

[6] 0000-0001-6101-755X, Institute for Information Technologies, University of Kragujevac, Jovana Cvijića bb, Kragujevac, Serbia, E-mail: topalovic@kg.ac.rs

Abstract

This paper presents an experimental validation of chosen process parameters for friction stir welding (FSW). The study was conducted on specimens made of aluminum alloy EN AW 6060 T6. Emphasis was placed on evaluating the effects of tool rotation speed, welding speed, and vertical force on weld quality and mechanical performance. Welding was performed using a cylindrical FSW tool with specified welding parameters. The welded joints were subjected to tensile and bending tests according to international standards. The strength and ductility of specimens machined from welded joints were analyzed. For this study, a set of welding parameters is carefully chosen based on experience and standards. These parameters should produce joints with the best mechanical properties that are comparable to the base material. The results provide valuable experimental data that validate the chosen process parameters, and can facilitate practical application of FSW for EN AW 6060 T6 aluminum alloy. This paper contributes to improvement and process optimization in industrial settings.

1. Introduction

Friction Stir Welding (FSW) is an innovative solid-state joining technique used extensively for aluminum alloys, which enables welding without melting the material [1]. The process utilizes a specially designed cylindrical tool that generates frictional heat through rotation and pressure, resulting in localized plastic deformation and material mixing to form a high-quality weld [1]. FSW is particularly important for aluminum because it overcomes common fusion welding issues such as solidification cracking and porosity, resulting in joints with superior mechanical properties, close to the base metal itself [2]. This makes it highly suitable for industries like aerospace, automotive, and marine, where lightweight, strong, and defect-free aluminum joints are critical. EN AW 6060 T6 alloy presents several challenges to the FSW technique due to its high strain-hardened state and sensitivity to thermal input. Excessive heat can lead to softening and loss of mechanical properties in the heat-affected zone, while insufficient heat results in poor material flow and defects like tunnel voids. Additionally, the alloy's strong tendency to form surface oxide layers complicates tool-material interaction. The aluminum oxide (Al_2O_3) layer acts as a mechanical and chemical barrier between materials. Therefore, proper choice of tool design, rotation speed, vertical force, and traverse speed is required in order to achieve defect-free welds with consistent strength and integrity, enabling further industrial adoption.

This paper aims to experimentally test chosen FSW parameters, such as tool rotation speed and welding speed, for EN AW 6060 T6 aluminum alloy. It further seeks to validate weld quality through mechanical testing, ensuring that the joints meet required strength and ductility standards for reliable industrial applications.

2. Materials and Methodology

2.1 Friction Stir Welding (FSW) technique

Friction stir welding (FSW) is a solid-state joining technique in which the base material does not melt [1]. Instead, heat generated by friction between the rotating tool and the workpieces softens the material, bringing it into a plasticized state. A specially designed cylindrical tool with a probe stirs and forges the materials together, resulting in joint formation. The process is highly nonlinear, involving large plastic deformations, elevated temperatures, and material flow in the weld zone. According to the international standard EN ISO 25239-1:2020 [2], FSW is divided into five stages. The first involves tool rotation and its downward movement toward the workpieces. The second, known as the plunging stage, includes penetration of the probe until the tool shoulder contacts the surface, generating increasing heat and accumulating displaced material. In the third stage, translational motion along the joint line begins, creating the weld. Here, the probe encounters less-heated material, which is softened by friction and transported to the rear of the tool, while new material is engaged at the front. The fourth stage marks the end of translational motion, and the fifth concludes with tool withdrawal from the solidified weld zone. A schematic of the FSW process is shown in Fig. 1.

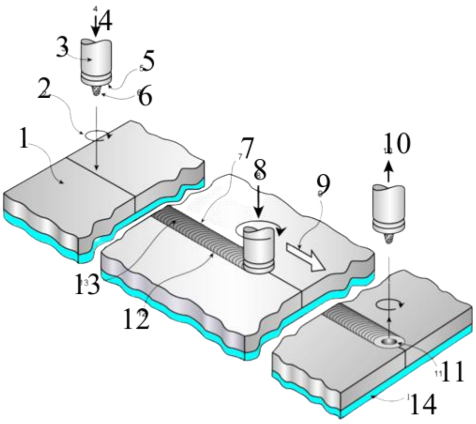

Fig. 1. Schematics of the FSW process

This figure first appeared in EN ISO 25239 standard [2], then Milčić et. al. [3] made it more accurate with the inclusion of the support plate, and we further enhanced this image from [3], which is available via CC BY 3.0 license, by adding a bigger font more suitable for double column paper. Schematic of the FSW process [2] shown in Fig. 1. depicts: 1) base material, 2) tool rotation direction, 3) welding tool, 4) downward tool movement, 5) tool shoulder, 6) tool probe, 7) advancing side of the weld, 8) axial (vertical) force, 9) welding direction, 10) upward tool movement, 11) exit hole, 12) retreating side of the weld, 13) weld face, and 14) support plate. The particular tool that was used for the welding of the studied plate is shown in Fig. 2.

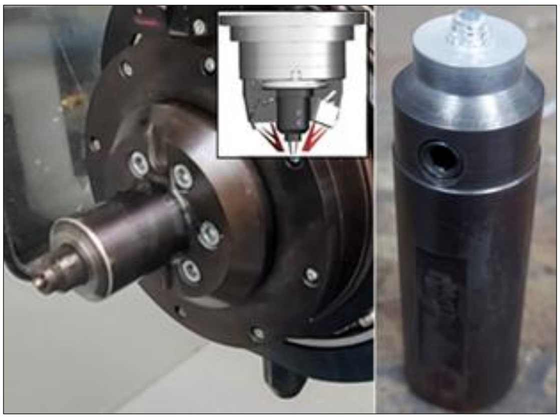

Fig. 2. FSW tool

The welding parameters are given in Table 1.

Table 1. FSW parameters

Probe length [mm]	**Welding speed** [mm/min]	**Axial force** [kN]	**Tool rotation speed** [rpm]	**Dwell time** [s]
3.7	1300	9	1650	0.2

The zoomed-in picture of the upper side of the weld is shown in Fig. 3.

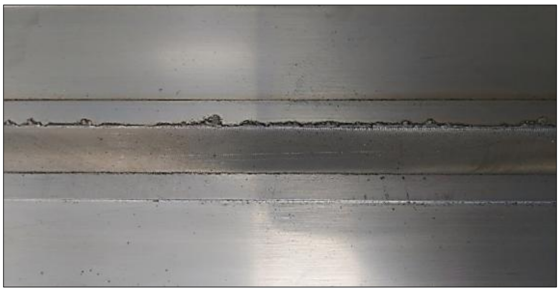

Fig. 3. The upper side of the weld

The zoomed-in picture of the exit hole is shown in Fig. 4.

Fig. 4. The FSW exit hole

The welded plates have reinforcement ribs on their back side, which can be seen in Fig. 5.

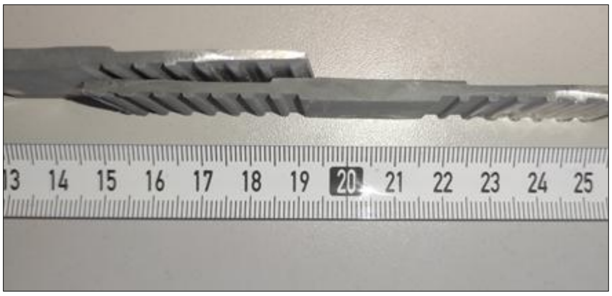

Fig. 5. The side view of EN AW 6060 T6 plates

A water jet machine is used to cut out specimens for bending and tension testing, as can be seen in Fig. 6. The figure also shows the welding direction.

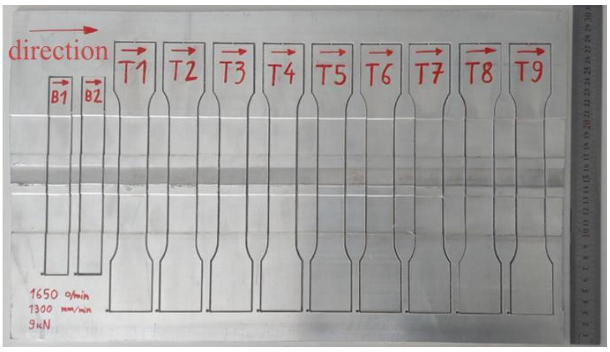

Fig. 6. Aluminum alloy welded plate with cut-out specimens

The specimens B1 and B2 are used for penetration and bending testing, which will not be discussed in this paper; instead, we will be focusing on the tension test performed using flat dog-bone specimens shown in Fig. 7.

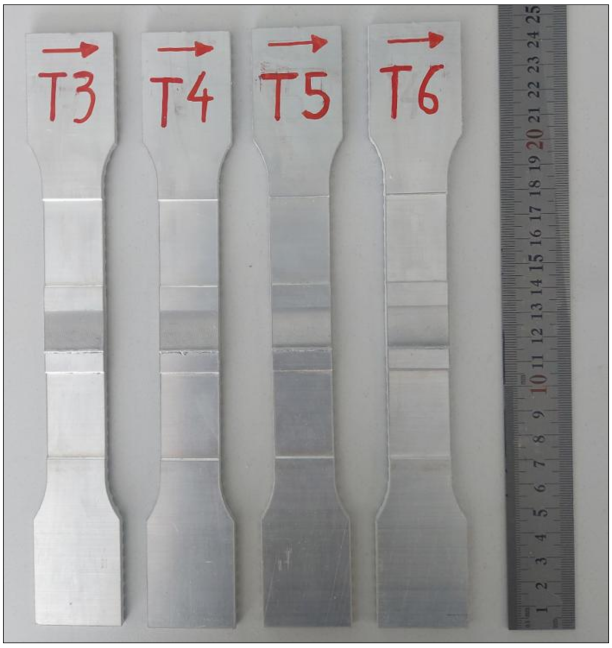

Fig. 7. Actual tension specimens before testing

2.2 *Static tension testing for mechanical characteristics assessment*

Uniaxial tensile tests were carried out on the specimens using a Shimadzu servo-hydraulic machine (EHF EV101K3-070-0A) with a capacity of ±100 kN and a stroke of ±100 mm. The purpose of the tests is to determine FSW weld mechanical properties, i.e., static strength parameters [4]. The testing machine is shown in Fig. 8.

Fig. 8. Shimadzu EHF EV101K3-070-0A

3. Results

The base material thickness in the weld region is 4 mm. Although tensile failure in welded joints typically initiates in the heat-affected zone [5], in this case, fracture is anticipated in the base material outside the weld due to profile geometry, where ribs reduce the cross-sectional thickness locally to 2 mm. Testing on specimens T3 and T4 confirmed this hypothesis, with the crack occurring precisely in the 2 mm-thick section between the ribs, as can be seen in Fig. 9.

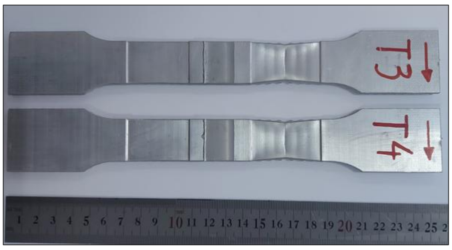

Fig. 9. T3 and T4 specimens after testing

According to EN 755-2 standard, the yield strength of EN AW 6060 T6 (Rp0.2) is 150 MPa, while the tensile strength (Rm) is 190 MPa. The EN ISO 25239 standard for friction stir welding requires that the welded joint achieve a minimum tensile strength of 0.7 Rm, i.e., 133 MPa. In specimens T3 and T4, material failure was observed at loads of 225.83 MPa and 225.56 MPa, respectively, indicating that the welded joints met the quality requirements. Stress-strain curves for T3 and T4 specimens are shown in Fig. 10.

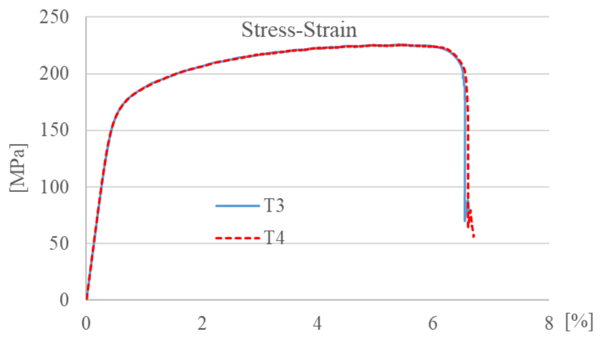

Fig. 10. Stress-Strain curves for T3 and T4

In order to remove the influence of ribs, they were removed by manual machining (fine grinding) of T5 and T6 specimens, reducing the thickness of the samples to 2 mm along their entire length. However, this led to the significant reduction of mechanical properties, with material failure occurring at 145.25 MPa and 114.85 MPa for T5 and T6 specimens, respectively. Stress-strain curves for T5 and T6 specimens are shown in Fig. 11.

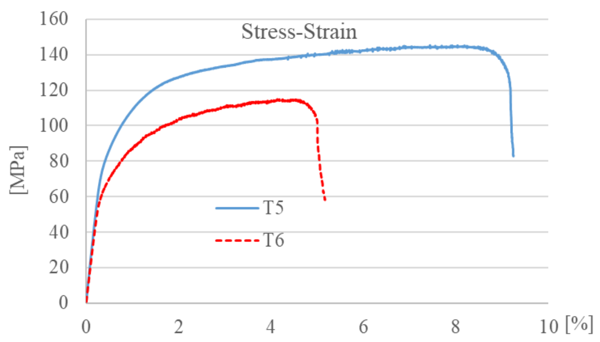

Fig. 11. Stress-Strain curves for T5 and T6

This significant reduction means the T6 specimen does not satisfy the safety criteria for a welded joint that prescribes a minimum tensile strength of 0.7 Rm, i.e., 133 MPa.

4. Conclusions

While the initial welded joints satisfied EN ISO 25239 requirements, manual machining that reduced the thickness to 2 mm caused a significant drop in tensile strength, so much so that specimen T6 failed to meet the minimum standard, highlighting the detrimental effect of post-weld modification.

Acknowledgments

This research was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, contract No. 451-03-66/2024-03/200378, and by the Science Fund of the Republic of Serbia, #GRANT No. 7475, Prediction of damage evolution in engineering structures – PROMINENT.

References

[1] Thomas, W. M., Nicholas, E. D., Needham, J. C., Murch, M. G., Templesmith, P., Dawes, C. J. Friction stir welding. International Patent Application No. PCT/GB92/02203; U.S. Patent No. 5,460,317, 1991

[2] EN ISO 25239:2020, Friction stir welding — Aluminium (Parts 1-5). International Organization for Standardization: Geneva.

[3] Milčić, D., Laban, M., Arsić, D., Nikolić, R., Hadzima, B., Konjatić, P. Improvement of welded joint quality obtained by friction stir welding. IOP Conf. Ser.: *Mater. Sci. Eng*., 2018, 393, 012107.

[4] Dunić, V., Živković, J., Milovanović, V., Pavlović, A., Radovanović, A., Živković, M. Two-Intervals Hardening Function in a Phase-Field Damage Model for the Simulation of Aluminum Alloy Ductile Behavior. *Metals*, 2021, 11(11), 1685.

[5] Lee, S., Kim, B.C., Kwon, D. Fracture Toughness Analysis of Heat-Affected Zones in High-Strength Low-Alloy Steel Welds. *Metallurgical Transactions A*, 1993, 24A, 1133–1145.