Through Thickness Tensile Properties of Thick AA6061-T6 Plates Produced by Simultaneous Double-Sided Friction Stir Welding

Filbert Manggala Sulianto [1], Sulardjaka Sulardjaka [2], Budi Setiyana [2]

[1]P.G, Student, Department of Mechanical Engineering, Diponegoro University, Semarang, Central Java, Indonesia
[2]Professor, Department of Mechanical Engineering, Diponegoro University, Semarang, Central Java, Indonesia

***

Abstract - *Simultaneous double-sided friction stir welding (SDFSW) offers advantages in producing more symmetric heat input and material flow compared with conventional friction stir welding, which can lead to improved joint performance. Although SDFSW has been successfully applied to butt joint configurations, limited studies have investigated the through-thickness mechanical behavior of thick aluminum joints produced by this process. In this study, AA6061-T6 butt-welded plates with a thickness of 8 mm were investigated to evaluate the variation of mechanical properties along the plate thickness. Welding was performed using identical upper and lower tool rotational speeds of 1500 rpm, a tool traverse speed of 30 mm/min, and a tool tilt angle of 2°. Three standardized ASTM E8 sub-sized tensile specimens were extracted from the welded plates. Each specimen was subsequently divided into three regions along the thickness direction, namely the upper, middle, and lower regions. The mechanical performance was evaluated through ultimate tensile strength (UTS) and microhardness distribution across the weld joint. The results show that the UTS values among the three regions are relatively comparable, although a slight increasing trend from the upper to the lower region was observed. The average UTS values were 155.320 MPa in the upper region, 157.573 MPa in the middle region, and 160.039 MPa in the lower region. The minimum hardness of approximately 40-50 HV was observed in the HAZ, which also corresponded to the fracture location of all tensile specimens. These findings indicate that SDFSW can produce relatively uniform mechanical properties through the thickness of AA6061-T6 butt joints.*

***Key Words*: SDFSW, AA6061-T6, Through-thickness properties, Tensile strength, Microhardness.**

1. INTRODUCTION

Aluminum alloys are extensively used in a wide range of structural applications, including aerospace, automotive, and marine industries, primarily due to their low density, high strength-to-weight ratio, and excellent corrosion resistance [1]. Among the available aluminum alloys, AA6061-T6 is widely used in engineering structures because of its good mechanical performance and favorable weldability characteristics [2]. However, traditional fusion welding techniques frequently introduce metallurgical problems such as residual stresses, porosity, solidification cracking, and distortion, which can negatively affect the mechanical integrity of welded joints [1,3]. These limitations have encouraged the development of alternative welding methods capable of producing higher-quality joints with improved mechanical reliability. Friction stir welding (FSW) has been recognized as an effective solid-state joining process that can mitigate many of the issues associated with conventional fusion welding techniques [4]. During the FSW process, a rotating non-consumable tool generates frictional heat and severe plastic deformation, enabling material mixing and bonding without melting the base material. Owing to its relatively low heat input, minimal distortion, and reduced residual stresses, FSW has become a widely adopted joining technique for aluminum alloys, particularly in butt joint configurations used in structural applications that require high joint reliability [3].

Despite these advantages, conventional FSW presents certain limitations when applied to thick plates. The process requires a relatively long stirring pin to ensure sufficient material mixing through the plate thickness, which increases the possibility of tool failure during welding [5]. Furthermore, the heat input generated by a single tool acting on only one side of the workpiece may produce an asymmetric thermal distribution. This condition can lead to non-uniform material flow and temperature gradients along the thickness direction of the welded joint [6]. Consequently, variations in microstructure and mechanical properties may occur across the thickness of the weld, potentially affecting the overall performance of the joint.

To overcome these challenges, several modified friction stir welding configurations have been proposed, including conventional double-sided friction stir welding (CDFSW) and simultaneous double-sided friction stir welding (SDFSW). In the CDFSW approach, a single welding tool is used sequentially on both sides of the plate by flipping the workpiece after completing the first welding pass. However, this method increases fixture complexity and exposes the joint to two separate thermal cycles, which may influence the resulting microstructure and mechanical properties. In contrast, SDFSW employs two welding tools operating simultaneously from the upper and lower surfaces of the plates. This configuration can generate more balanced heat input and facilitate more symmetric material flow through the weld thickness during the welding process [3,6]. Previous studies have reported that SDFSW can enhance weld quality by reducing defects, improving material mixing, and producing better mechanical performance compared with conventional FSW and CDFSW processes [5–8]. However, most of these studies mainly focus on overall joint strength, microstructural characteristics, and welding parameter optimization. Limited attention has been given to the variation of mechanical properties along the thickness direction of SDFSW joints, particularly for thick aluminum plates.

In thick welded structures, differences in thermal history, material flow behavior, and cooling conditions may lead to variations in mechanical properties along the thickness of the joint. Such variations can influence the structural reliability and service performance of welded components [9]. Therefore, investigating the through-thickness mechanical behavior of SDFSW joints is important for evaluating the uniformity and structural integrity of the weld. The findings of this study provide insight into the variation of mechanical properties along the thickness direction and contribute to a better understanding of the mechanical performance of SDFSW joints in thick aluminum plates.

2. METHOD

This experiment employed a heat-treatable aluminum alloy AA6061-T6 with dimensions of 200 × 125 × 8 mm. Two plates were joined in a butt joint configuration. Simultaneously double-sided friction stir welding SDFSW was performed using two pin tools operating from the upper and lower surfaces as shown in Fig 1.

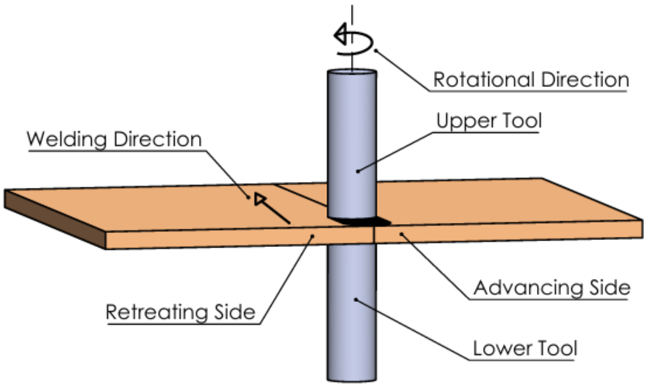

Fig -1: Schematic illustration of the SDFSW process.

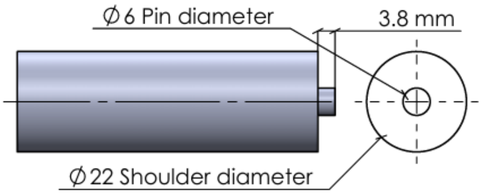

Fig -2: Geometry and dimensions of the welding tool.

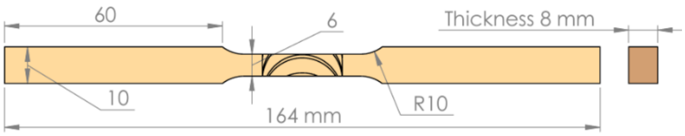

Fig -3: Dimensions of the tensile specimen.

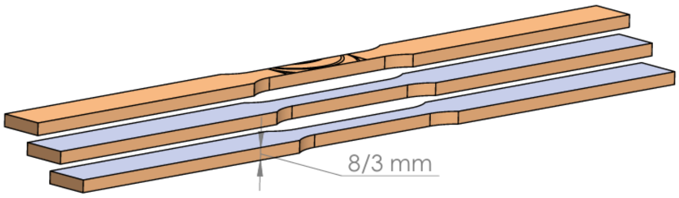

Fig -4: Illustration of the sliced tensile specimen.

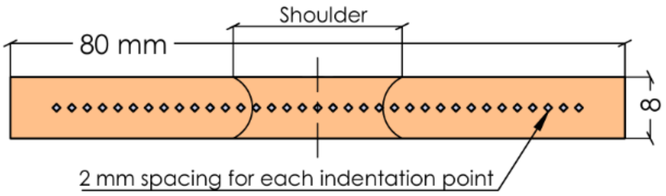

Fig -5: Microhardness indentation layout.

The pin tools had a cylindrical geometry with a pin height of 3.8 mm and a pin diameter of 6 mm. The detailed tool geometry and dimensions are presented in Fig 2. A total of three tensile test specimens were extracted from the welded plates in accordance with the ASTM E8 sub-sized tensile specimen standard. The geometry and dimensions of the tensile specimens are illustrated in Fig 3. Specimen cutting was carried out using a five-axis water jet cutting machine manufactured by Foshan Ruichi Technology to minimize thermal and mechanical effects. Each standardized tensile specimen was subsequently divided into three equal parts along the plate thickness direction, referred to as the upper, middle, and lower regions. As the plate thickness was 8 mm, each region corresponded to approximately one third of the total thickness. The slicing process was performed using a wire electrical discharge machining system MV1200-S manufactured by Mitsubishi Electric to ensure cutting precision. The illustration of sliced specimen are presented in Fig 4. Tensile tests were conducted at room temperature using a 100 kN universal testing machine to evaluate the through-thickness tensile strength. Vickers microhardness measurements were performed to assess the hardness distribution across the weld joint. Hardness measurements were taken at the middle section of the weld, and the indentation layout is shown in Fig 5. A Shimadzu HMV 2000 micro Vickers hardness tester was used for all hardness measurements.

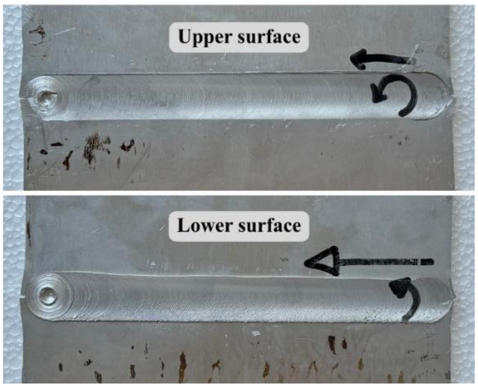

Fig -6: Surface appearance of the SDFSW.

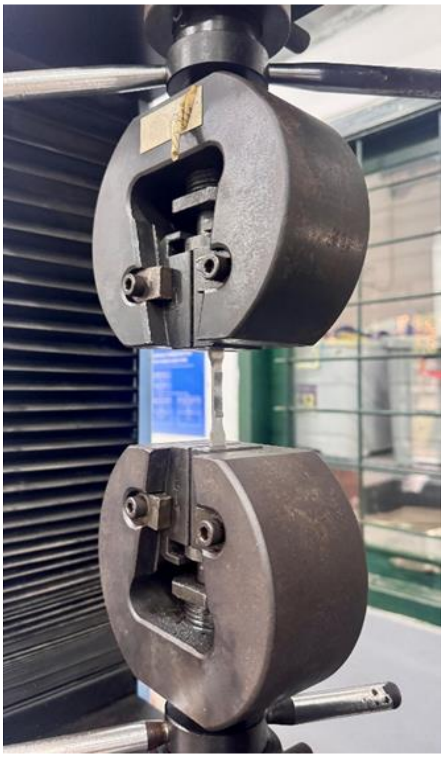

Fig -7: Tensile testing setup.

3. RESULT AND DISCUSSION

3.1 Tensile strength result

The surface appearance of the weld produced by the simultaneous double-sided friction stir welding process is shown in Fig. 6. The figure presents the weld bead observed from the upper and lower surfaces of the welded plates. A continuous and uniform weld surface can be observed along the entire welding direction without visible defects such as surface cracks, voids, or excessive flash.

Table -1: Ultimate tensile strength values of the tensile specimens

Specimens	Region	Ultimate tensile strength (Mpa)
1	Upper	153.408
	Middle	158.513
	Lower	157.996
2	Upper	155.559
	Middle	157.808
	Lower	159.358
3	Upper	156.992
	Middle	156.399
	Lower	162.763

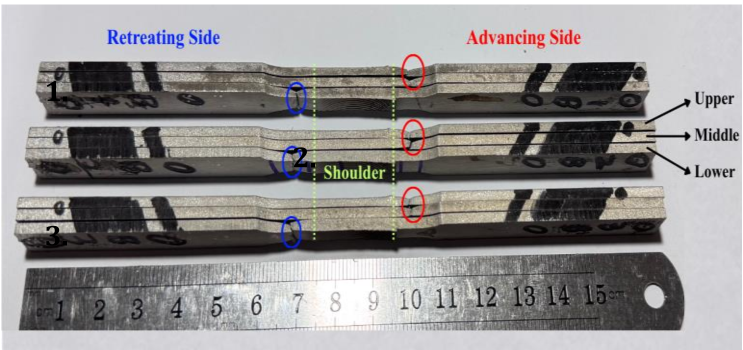

Fig -8: Fracture locations of tensile specimens after testing.

The tensile test results obtained from the upper, middle, and lower regions of the welded joint are summarized in Table 1. The table presents the ultimate tensile strength values of three standardized ASTM E8 sub-sized tensile specimens extracted from the SDFSW welded plate. Each specimen was divided into three regions along the thickness direction and subjected to tensile testing to examine the variation of tensile properties through the plate thickness. The tensile testing process and specimen during testing are shown in Fig. 7.

The average ultimate tensile strength values for each region are illustrated in Fig. 8. The upper region exhibited an average tensile strength of 155.32 MPa, while the middle region showed a slightly higher value of 157.57 MPa. The lower region presented the highest average tensile strength of 160.04 MPa. Although the differences are relatively small, a gradual increase in tensile strength from the upper region toward the lower region can be observed. To further evaluate the variation of tensile strength among the three regions, a statistical analysis was conducted. The results indicate that the differences in ultimate tensile strength between the upper, middle, and lower regions are statistically insignificant ($p > 0.05$). This finding suggests that the tensile properties across the thickness of the welded plate are relatively consistent.

The relatively uniform tensile behavior can be associated with the characteristics of the SDFSW process. In this welding configuration, two tools operate simultaneously from the upper and lower surfaces of the plates, which promotes a more balanced heat input and material flow along the thickness direction [5,8,10]. This condition may contribute to a more homogeneous plastic deformation and thermal distribution compared with conventional single-sided friction stir welding, where asymmetric heat input often results in greater variation of mechanical properties through the thickness [11].

The fracture locations of the tensile specimens are presented in Fig. 9. All specimens fractured in the heat-affected zone (HAZ) about 16–18 mm away from the weld centreline. The occurrence of fracture in the HAZ indicates that this region represents the weakest zone within the welded joint. The reduced strength in the HAZ is associated with the thermal cycle experienced during the welding process. In precipitation-hardened aluminum alloys such as AA6061-T6, exposure to elevated temperatures during welding can cause dissolution or coarsening of strengthening precipitates [11,12]. This phenomenon leads to local softening of the material, which makes the HAZ more susceptible to tensile failure compared with other regions of the weld [13].

Among the nine tested specimens, six fractures occurred in the HAZ on the advancing side, while three fractures were observed in the HAZ on the retreating side. The higher fracture frequency on the advancing side can be attributed to the asymmetric temperature distribution during the welding process, where the advancing side generally experiences higher temperatures than the retreating side. This condition may promote greater overaging of strengthening precipitates, resulting in a higher tendency for fracture in this region [14].

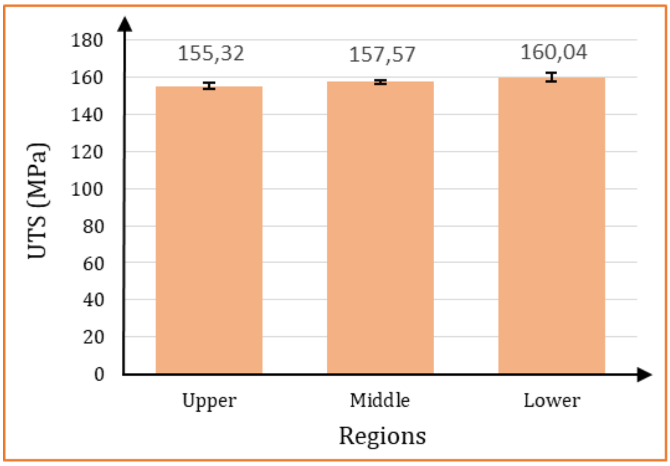

Fig -9: Average ultimate tensile strength (UTS) of the upper, middle, and lower regions.

3.2 Hardness distribution result

The microhardness distribution across the weld joint at the mid-thickness region is presented in Fig. 10. The hardness profile shows a typical variation across the welded joint consisting of the base metal (BM), heat-affected zone (HAZ), thermo-mechanically affected zone (TMAZ), and stir zone (SZ).

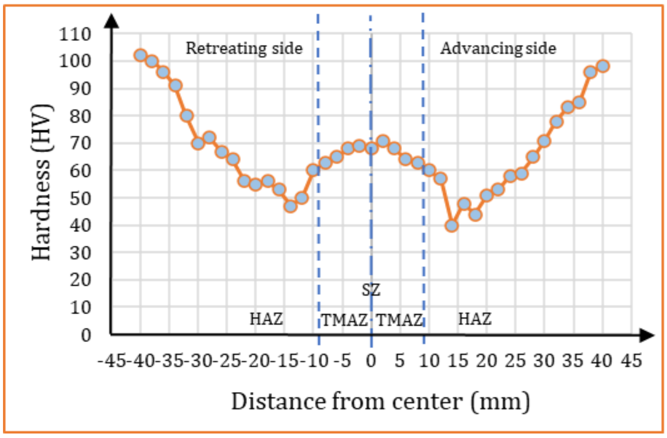

Fig -10: Micro hardness distribution across the weld joint

A noticeable decrease in hardness is observed in the heat-affected zone (HAZ). The lowest hardness values, approximately 40–50 HV, were measured in this region. This reduction in hardness is associated with the thermal cycle experienced during the welding process, which can lead to dissolution or coarsening of strengthening precipitates in precipitation-hardened aluminum alloys such as AA6061-T6. As a result, the material in the HAZ undergoes significant softening compared with the base metal. [11,15,16].

Within the thermo-mechanically affected zone (TMAZ) and stir zone (SZ), the hardness values increase slightly compared with the HAZ, reaching approximately 60–70 HV near the weld center. This is related to the plastic deformation high density of dislocations and dynamic recrystallization that occur during the friction stir welding process, which can refine the grain structure and resulted in an enhanced hardness value of the material. [16,17].

The hardness profile across the weld joint exhibits a characteristic W-shaped distribution, which is commonly reported in friction stir welded aluminum alloys. This hardness distribution is consistent with the tensile test results discussed in the previous section, where all tensile specimens fractured in the HAZ region. The coincidence between the lowest hardness values and the fracture location indicates that the softening occurring in the HAZ significantly reduces the local strength, making this region the most susceptible to tensile failure in the SDFSW joint.

3. CONCLUSIONS

The SDFSW process successfully produced a continuous and defect-free weld surface on both the upper and lower sides of the plate. Based on the experimental results, the following conclusions can be drawn:

- The average ultimate tensile strength values for the upper, middle, and lower regions were 155.320 MPa, 157.573 MPa, and 160.039 MPa, respectively, showing only slight variation along the thickness. and statistical analysis indicates that the differences are not statistically significant ($p > 0.05$).

- All tensile specimens fractured in the heat-affected zone (HAZ), with six fractures on the advancing side and three on the retreating side, indicating that the HAZ is the weakest region of the joint.

- The hardness profile showed a W-shaped distribution, with the lowest hardness of about 40–50 HV located in the HAZ.

- The coincidence between the lowest hardness values and the tensile test fracture location in the HAZ confirms that the softening in this region significantly reduces the local strength and governs the tensile failure behavior of the SDFSW joint.

- Overall, the results demonstrate that the simultaneous double-sided friction stir welding process can produce relatively uniform mechanical properties through the thickness of AA6061-T6 butt joints.

ACKNOWLEDGEMENT

REFERENCES

[1] Patil S, Nagamadhu M, Malyadri T. A critical review on microstructure and hardness of aluminum alloy 6061 joints obtained by friction stir welding-past , present , and its prospects. Mater Today Proc 2023;82:75–8. https://doi.org/10.1016/j.matpr.2022.11.362.

[2] Guzm I, Granda E, Acevedo J, Mart A. Comparative in Mechanical Behavior of 6061 Aluminum Alloy Welded by Pulsed GMAW with Di ff erent Filler Metals and Heat Treatments. Materials (Basel) 2019:1–14.

[3] Dharavathu R, Shetty K, Muvvala G. A study on mitigation of tunneling defects and investigation on the mechanical behavior of double-sided friction stir welded Al 2014 plates. J Manuf Process 2026;159:460–80.

[4] Thomas; WM, Nicholas ED, Needham JC, Murch ichael G, Peter Temple-Smith, Christopher J. Dawes. United States Patent, 1995.

[5] Eko Y, Uematsu Y, Istiyanto J. Comparative analysis of bobbin tool and one-step double-acting tool in friction stir welding of aluminum AA1100. Int J Light Mater Manuf 8 2025;8:577–94.

[6] Xu Q, Liu H, Meng S, Ding Y, Liu Y, Xiao J, et al. A method for predicting the strength of simultaneous double-sided friction stir welding joints in a small-sample data environment. Chinese J Mech Eng 2025:100113. https://doi.org/10.1016/j.cjme.2025.100113.

[7] Meng S, Zhao H, Dong J, Liu W, Liu H, Xiao J. Effect of Process Parameters on the Mechanical Properties of Simultaneous Double - Sided Friction Stir Welding Joints. Chinese J Mech Eng 2024:1–11. https://doi.org/10.1186/s10033-024-01126-1.

[8] Budiana EP, Gading S, Hapsari H, Mahmoud ERI. Mechanical Engineering for Society and Industry Temperature and material flow in one-step double-acting friction stir welding process of aluminum alloy : Modeling and experimental. Mech Eng Soc Ind 2025;5.

[9] Su HAO, Chen JI, Wu C. Elucidation for the Correlation Between Material Flow and Intermixing Behavior and Joint Performances in Friction Stir Welding of Al / Cu Dissimilar Alloys. Metall Mater Trans B 2025;56:3282–308. https://doi.org/10.1007/s11663-025-03574-z.

[10] Nath RK, Jha V, Maji P, Barma JD. A novel double-side welding approach for friction stir welding of polypropylene plate. Int J Adv Manuf Technol 2021:691–703.

[11] Yang C, Zhang JF, Ma GN, Wu LH, Zhang XM, He GZ, et al. Journal of Materials Science & Technology Microstructure and mechanical properties of double-

side friction stir welded 6082Al ultra-thick plates. J MaterSciTechnol2020;41:105–16. https://doi.org/10.1016/j.jmst.2019.10.005.

[12] Ogunsemi BT, Abioye TE, Ogedengbe TI, Zuhailawati H. A review of various improvement strategies for joint quality of AA 6061-T6 friction stir weldments. J Mater Res Technol 2021;11:1061–89. https://doi.org/10.1016/j.jmrt.2021.01.070.

[13] Mehri A, Abdollah-zadeh A, Entesari S, Saeid T, Tao J. Results in Engineering The effects of friction stir welding on microstructure and formability of 7075-T6 sheet. Results Eng 2023;18:101041. https://doi.org/10.1016/j.rineng.2023.101041.

[14] Harachai K, Prasomthong S. Investigation of the optimal parameters for butt joints in a friction stir welding (FSW) process with dissimilar aluminium alloys Investigation of the optimal parameters for butt joints in a friction stir welding (FSW) process with dissimilar aluminiu. Mater Res Express Pap 2023;10.

[15] Won J, Ryutaro C, Kohsaku H, Hidetoshi U, Seung F, Lee J. Critical Review of Solid - State Welding for Al Alloys with High Joint Efficiency : Friction Stir Welding (FSW) vs . Linear Friction Welding (LFW). Met Mater Int 2026;32:139–63. https://doi.org/10.1007/s12540-025-02007-5.

[16] Ambriz RR, Jaramillo D. Mechanical Behavior of Precipitation Hardened Aluminum Alloys Welds. Light Met. Alloy. Appl., 2014. https://doi.org/http://dx.doi.org/10.5772/58418.

[17] Nguyen T, Singh C, Sub Y, Hyun J, Lee D, Lee K, et al. Mechanical properties of base metal and heat-affected zone in friction-stir-welded AA6061-T6 at ultra-low temperature of 20 K. J Mater Res Technol 2024;31:1547–56. https://doi.org/10.1016/j.jmrt.2024.06.165.