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The Effect of Friction Stir Welding Process Parameters on the Butt Joint Strength of 5083 and 6061 Aluminum Alloys

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***Abstract* - This journal discusses the process parameters of friction stir welding (FSW) for joining aluminum 5083 and aluminum 6061. The welding process was conducted to identify the optimal parameters for achieving high-quality joints. Based on the study's findings, the welding parameters of a tool rotational speed of 1400 rpm, a travel speed of 30 mm/s, and a tool tilt angle of 1° were identified as the best. Various tests, properties mechanical and microstructural evaluations, were conducted to assess the quality of the joints. The results indicated that the best tensile strength achieved was 180.45 MPa, corresponding to an efficiency of 78%, while the hardness value reached 65 Hv. Furthermore, the welding process under these parameters facilitated the refinement of grain size in the Weld Nugget (WN) zone, enhancing the bonding area between the two materials. This is attributed to the ability of FSW to break coarse grains into finer grains, leading to improved microstructural uniformity and consistent grain size due to the optimized process parameters.**

Keywords: Friction Stir Welding, Dissimilar Welding, Aluminum 5083-6061, Grain Size, Process Parameters.

I. INTRODUCTION

The joining of heat-treatable and non-heat-treatable materials presents a significant challenge in the field of welding due to differences in their chemical compositions and properties, making this process worthy of further investigation[1]. This type of welding falls under the category of solid-state welding, as it does not require the melting or fusion of materials during the joining process. Aluminum, with its low melting point, is highly sensitive to high temperatures. Consequently, processes such as fusion welding, which utilize fillers, are more susceptible to welding defects, including porosity and other imperfections [2].

Friction Stir Welding (FSW) was developed at The Welding Institute (TWI) in the United Kingdom in 1991 as a solid-state joining technique and was initially applied to aluminum alloys (Thomas *et al.*, 1991; Dawes and Thomas, 1995) [3]. The FSW tool rotates clockwise and moves laterally (or from left to right). The advancing side is on the right, where the tool's tangential rotational speed aligns with the tool's movement direction. Meanwhile, the retreating side is on the left, where the tangential rotational speed opposes the tool's movement.FSW is a metal joining method that employs a non-consumable rotating tool to perform welding. This technology is used to join high-strength metal alloys that are challenging to weld using traditional methods. As one of the key innovations in metal joining, FSW is an environmentally friendly technology that consumes less energy than conventional welding methods. Additionally, it does not require flux or shielding gases, making it a safer process for the environment [4].

In practical applications, aluminum series 5083 and 6061 are widely utilized in the automotive and aerospace industries. This study focuses on the joint between aluminum 5083 and 6061, specifically in the automotive sector. Aluminum 5083 is employed for car bodies due to its corrosion resistance and lightweight properties, while aluminum 6061 is used for vehicle chassis frames because of its superior strength and robustness compared to series 5083[5].

Several previous studies have explored the friction stir welding (FSW) of aluminum 5083 and 6061. Nishant and Jha [6] conducted experimental research on the effects of tool rotational speed on the mechanical properties of FSW joints between aluminum 6061-T6 and 5083-H12. This study utilized a vertical milling machine with four different tool rotational speeds (TRS) of 710, 900, 1120, and 1400 rpm, while maintaining a constant welding speed of 63 mm/s. Hardness measurements revealed predominantly brittle fracture modes at rotational speeds between 710 and 1200 rpm, whereas weld joints at 1400 rpm exhibited ductile fracture modes. Further investigations were conducted by Bella and Tizziana [7], who examined dissimilar aluminum welding (AA6082 and AA5083) for shipbuilding applications. The welding method used was friction stir welding with a tapered threaded pin profile. The objective of their study was to assess the influence of tool tilt angles on the rotational speed and tool travel speed. Several combinations were tested,

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including 1000 rpm/100 mm/s, 1300 rpm/75 mm/s, and 1600 rpm/50 mm/s. The results indicated that a smaller spindle tilt angle significantly improved joint strength.

Subsequently, Balamurugan and Jayakumar [8] conducted a study on the mechanical and microstructural properties of weld joints using Friction Stir Welding (FSW) for aluminum alloys 5052-H32 and 6061-T6 (AA). Utilizing two different tool designsa tapered cylindrical pin and a threaded cylindrical pinthey evaluated the microstructural changes influencing the mechanical properties of FSW joints under constant welding conditions, with a welding speed (WS) of 60 mm/min and a tool rotational speed (TRS) of 900 rpm. The findings revealed that tools with tapered and threaded pin profiles produced joints with higher tensile strength, larger nugget areas, and smoother surface finishes. Furthermore, the fine grain microstructure formed by the tapered pin profile contributed to superior joint strength compared to conventional pin profiles.

Research on FSW welding has also been conducted by Devaiah and Kishore [9]. This study discusses the influence of FSW parameters such as tool rotational speed, travel speed, and tilt angle on the mechanical properties and microstructure of the FSW weld. The research was carried out using Taguchi's concept, employing an L9 array to optimize various parameter combinations. The most optimal parameters in this study were a tool rotational speed (TRS) of 1200 RPM, a welding speed (WS) of 70 mm/s, and a tilt angle of 2° to achieve the best results.

Research on FSW welding has also been conducted by Devaiah and Laxminrayana [1], The solid-state welding process of Friction Stir Welding (FSW) is more commonly used to join different alloys. Who discussed an experiment on FSW welding of AA 5083 and 6061. The results showed that defect-free and high-quality welds were achieved using a rotational speed parameter of 900 rpm, which exhibited higher mechanical properties compared to those made at 560 rpm and 1800 rpm, with AA5083 located at the advancing side (AS).

The welding of aluminum 5083 and 6061 aims to combine two types of joints with distinct properties, namely the hardness and weldability of aluminum 6061, and the corrosion resistance and lightweight characteristics of aluminum 5083. Based on the aforementioned studies, this research focuses on the effects of variations in tool rotational speed on the mechanical strength and microstructural properties of the welds. The study employs tool rotational speed variations of 1100 rpm, 1400 rpm, and 1800 rpm, while maintaining a constant travel speed of 30 mm/s, a tool tilt angle of 1°, and an aluminum plate thickness of 3 mm for the welding process.

II. RESEARCH METHODOLOGY

2.1 Size and Type of FSW Plate

The material plates used are sized 50 mm x 100 mm x 3 mm for both aluminum 5083 and 6061 plates. The joint type used is a butt joint, and the welding process is performed in the center of the plates. The welding process is carried out using a GUT DRO x 6325 vertical milling machine, with the welding direction following a clockwise motion. The advancing side is the 5083 plate, while the retreating side is the 6061 plate. Below is the schematic diagram of the FSW welding process for aluminum 5083 and 6061:

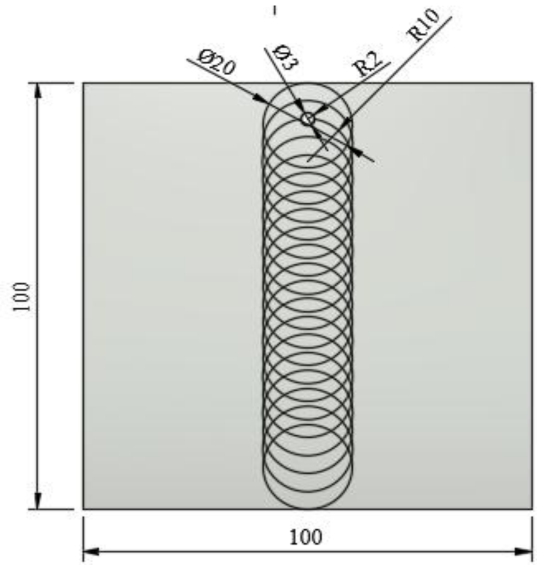

Figure 1: Schematic of FSW Welding Process for 5083-6061

2.2 Tool Geometry

The type of FSW tool used in this study is a cylindrical tapered tool pin, due to its efficient design for controlling material flow and optimizing energy transfer during the welding process. This shape also helps generate more controlled frictional forces, which assist in producing sufficient heat to transform the material's grain structure into a plastic form without melting it, while ensuring a uniform material flow along the joint [10]. According to Zhao and Lin [11], the geometry of the tool significantly influences the material mixing flow in FSW welding. When a tapered pin tool is used, voids appear during the mixing process; however, when a tapered screw pin tool is used, the material flow becomes more compact, and no significant voids are present. The tool has an overall height of 47.8 mm, with pin 1 diameter measuring 5 mm and pin 2 diameter measuring 3 mm. The shoulder diameter is 15 mm. The tool material used is H13 tool steel. H13 tool steel is particularly suitable for FSW applications due to its hardness of up to 45 HV. After hardening treatment, its hardness reaches 65 HV, giving it

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excellent wear resistance, as well as the strength and toughness to withstand high friction and pressure during welding [12]. The design of the cylindrical tapered thread tool is as follows:

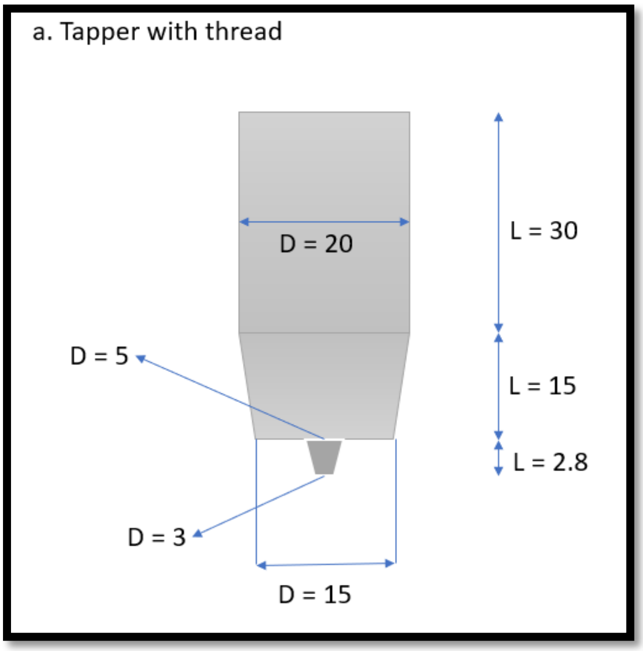

Figure 2: Desain cylindrical tapered tool pin

2.3 Chemical composition

The difference in material composition between aluminum 5083 and 6061 in FSW welding requires a thorough identification of their contents and compositions. This is due to the differences inThe chemical composition and mechanical properties can influence the quality of the resulting joint. In fact, material 5083 contains a high amount of magnesium, which provides excellent corrosion resistance, while aluminum 6061 contains silicon and magnesium, offering good weldability, superior strength, and heat treatable properties that enhance its welding performance [13]. These characteristics are particularly useful in the FSW process for joining 5083 and 6061 materials. The following table shows the chemical composition of materials 5083 and 6061.

Table 1: Element Composition (wt %)

Material	Si	Cu	Mn	Mg	Cr	Zn	Fe	Ti	Al
5083	0.08	0.011	0.019	2.56	0.20	0.01	0.28	0.01	96.8
6061	0.63	0.244	0.14	0.9	0.15	0.02	0.4	0.02	97.4

III. RESULTS AND DISCUSSIONS

3.1 Result of FSW Joining

The Friction Stir Welding (FSW) of dissimilar aluminum joints AA5083 and AA6061 revealed several interesting characteristics that influence the mechanical properties and microstructure of the welded joints. FSW, as a solid-state welding method, creates joints without melting; meaning the weld zone (stir zone) is formed through plastic deformation and frictional heating. During this joining process, the microstructure in the stir zone generally exhibits dynamic recrystallization with fine and homogeneous grains.

This study investigates the results of dissimilar aluminum 5083-6061 welding using a butt joint configuration, with variations in rotational tool speeds of 1100 rpm, 1400 rpm, and 1800 rpm, while maintaining a constant travel speed of 30 mm/s and a tilt angle of 1°. The following results were obtained:

Figure 3: Result of FSW 1100 rpm

The visual results show that the weld joint appears relatively clean, but there is still inconsistency in terms of material mixing. This occurs due to the rotation speed not being in accordance with the parameters or being too slow, which results in an incomplete material mixing process on the surface. However, the weld is free of major defects such as cracks or voids. Upon closer inspection, differences in color or smooth texture can be observed between the weld zone near AA5083 and AA6061. The grain surface distribution still appears rough, and there are remnants of inconsistent mixing in the weld.

Next, the image with a tool rotational speed of 1400 rpm shows results indicating a significant improvement in the weld surface compared to the previous parameters. The FSW weld joint surface appears smoother and more even, suggesting an improvement in the homogeneity of the material grain mixing process. The increase in rotational speed results in better heat distribution, which contributes to the enhancement of the stir zone (SZ) quality. This zone appears more consistent with a uniform text.

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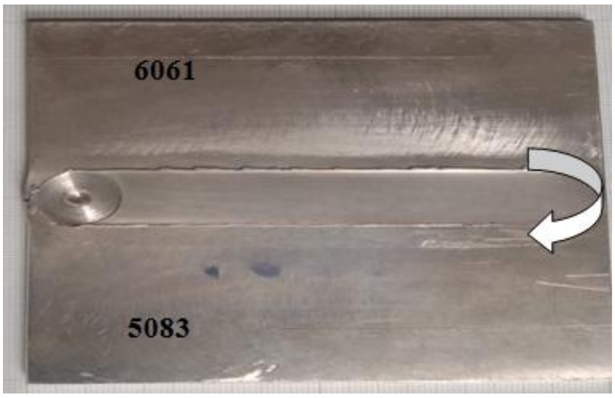

Figure 4: Result of FSW 1400 rpm

Next, at the parameter of 1800 rpm, the results of FSW welding show a rough weld surface and uneven grain distribution, as seen in the image below. This is accompanied by material spillover on the side, which occurs due to the increased rotational speed, leading to excessive flash at the weld edge. This flash formation is a result of the higher extrusion pressure of the material.

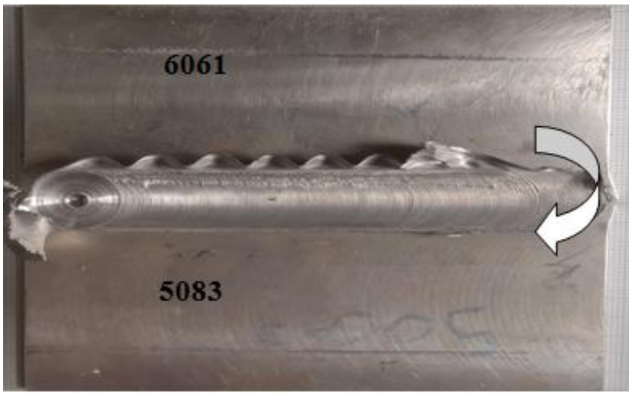

Figure 5: Result of FSW 1800 rpm

3.2 Results of Microstructure Observation

This study discusses the effects of the microstructure in the Weld Nugget (WN) area at rotational speeds of 1100 rpm, 1400 rpm, and 1800 rpm. This is done in order to identify the effect of tool rotation on the mixing of aluminum alloys 5083 and 6061, as well as the grain distribution and quality, which will influence the overall quality of the weld joint. Figure 4.1 shows a nearly uniform grain distribution with uniform grain size, although there is still a separation between the 5083 and 6061 joints. This occurs because the tool rotation was too fast, resulting in incomplete grain mixing due to the slow material stirring process, which prevented the material from mixing thoroughly, while the recrystallization temperature had already started to harden. In Figure 4.2, the microstructure shows fine and uniform grains, indicating that dynamic recrystallization (DRX) occurred effectively during the FSW process. Additionally, in Figure 4.2, there is no significant difference between the grain boundaries and the mixing quality, with the material mixing of 5083 and 6061 being uniform, exhibiting minimal defects, and a consistent grain size. This indicates that the joint quality at this parameter is sufficiently strong.Further, at the 1800 rpm parameter, the weld results in the WN area show random grain distribution, with visible gaps between the 5083 and 6061 sides, and uneven grain size. During the FSW process, uneven temperature distribution in the weld joint leads to slower diffusion and material flow, which changes the material flow pattern, causing the formation of irregular grain structures and more pronounced grain vortices. This occurs due to the weak rotational speed of the tool, which causes random movement of the grains during the mixing process, forming vortices that may result in reduced joint strength and the presence of some defects such as holes or voids in the WN area. This is because the material does not reach sufficient temperature due to the non-optimal tool rotation, resulting in uneven material mixing and the presence of gaps or cavities during the process. Therefore, the optimal process parameter for achieving the best FSW weld results is 1400 rpm, with a travel speed of 30 mm/s and a tilt angle of 1°. Below are the micrograph images of the WN zone at welding parameters of 1100 rpm, 1400 rpm, and 1800 rpm:

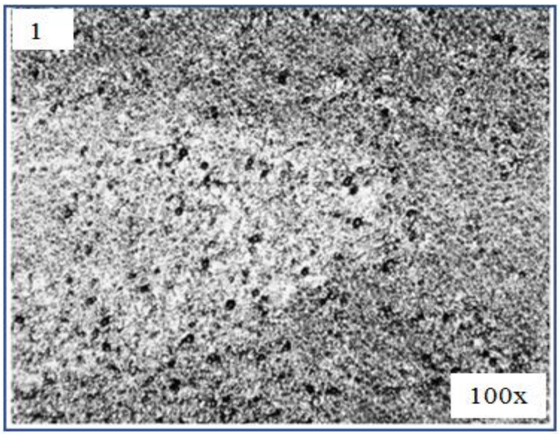

Figure 6.1: Microstructure Observation FSW 1100 rpm

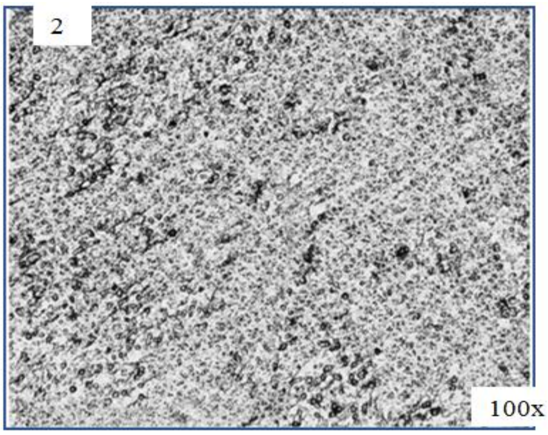

Figure 6.2: Microstructure Observation FSW 1400 rpm

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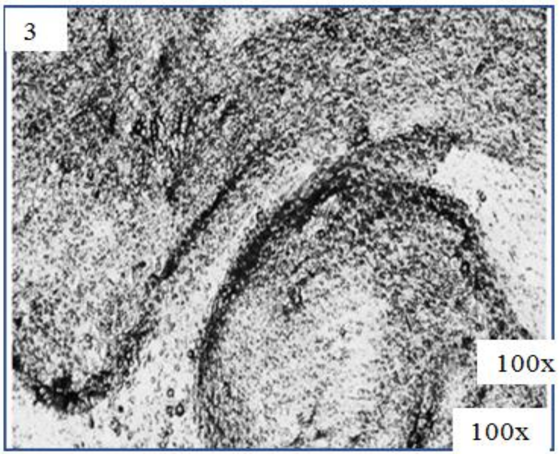

Figure 6.3: Microstructure Observation FSW 1800 rpm

3.3 Mechanical Properties

In this study, tensile testing was conducted following ASTM D8 standards, with three tests performed for each tensile test sample in one variable. The results of these tests were averaged, showing that the parameter of 1400 rpm had the highest tensile strength value of 180.45 MPa, followed by the 1100 rpm parameter with an average value of 176.69 MPa, and the 1800 rpm parameter with an average value of 158.80 MPa. These results are presented in Table 2 and Chart 1 below, which show that the 1400 rpm parameter exhibits a high tensile strength due to the uniform material mixing and optimal temperature, resulting in fine and consistent grains that hinder dislocation of the grains.

Table 2: Result of Tensile Strength

Variation	Tensile Properties		
	UTS (Mpa)	Elongation (%)	Joint Efficiency (%)
1	176.69	6.90	78%
2	180.45	6.76	76%
3	158.80	6.47	69%

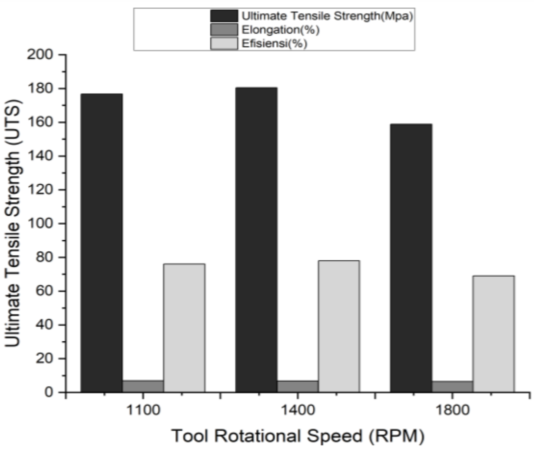

Figure 7: Chart of Tensile Properties

3.4 Micro Vickerss Testing

This test was conducted using the Vickers hardness testing method, which is used to measure the microhardness at various zones of the weld joint. This testing is essential for assessing the quality of the weld and can also detect microstructural changes resulting from the welding process. The focus of this test was on the Weld Nugget (WN) zone, as this is the mixing zone between aluminum 5083 and aluminum 6061, where it can be determined whether the hardness exceeds that of the base material (BM) or vice versa. In this study, three points were taken from the WN zone, with the midpoint located 1 mm apart, and a load of 1000 kgf was applied for 15 minutes. The results showed the highest hardness values at various tool rotational speeds of 100 rpm, 1400 rpm, and 1800 rpm, with the highest hardness values in the WN being 64 HV, 68 HV, and 61 HV, respectively. This occurred because the Friction Stir Welding (FSW) process on the AA5083 and AA6061 joints with the 1400 rpm parameter produced the best hardness test results. During the stirring process, the heat could be well-controlled, resulting in optimal material flow. The 1400 rpm tool rotational speed generated an optimal temperature to reach the dynamic recrystallization (DRX) phase in the FSW joint, which allowed for the formation of uniform, fine grains and more even distribution of metal chemical elements. This optimal recrystallization process resulted in the best joint hardness, as the smaller grains hindered dislocation movement, contributing to increased material strength. Furthermore, at 1400 rpm, the welding of both joints (AA5083 and AA6061) was more homogeneous, producing a stable and strong microstructure without significant element segregation.

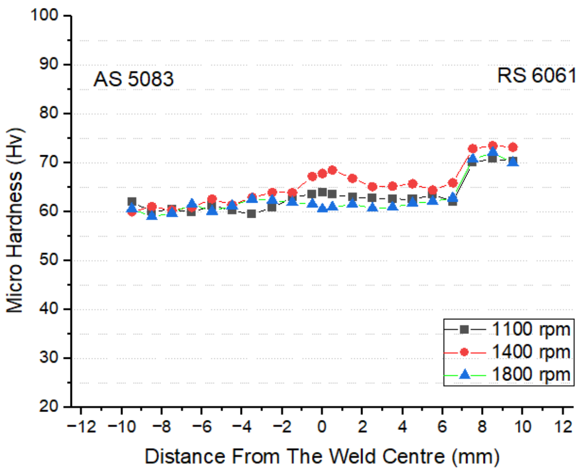

Figure 8: Chart of Micro Vickers

However, at 1100 rpm, the lower tool rotational speed resulted in insufficient temperature to achieve effective recrystallization. The diffusion between the two joints was

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limited, leading to larger grains and less uniform element distribution, resulting in lower hardness values. At 1800 rpm, the higher tool rotational speed caused excess heat, leading to overheating, grain growth, and softening of the material, which reduced hardness. The following is the hardness test graph based on the Vickers hardness testing results.

IV. CONCLUSION

Based on the research results related to FSW welding between aluminum 5083 and 6061, the following conclusions can be drawn:

The best welding parameters are a tool rotational speed of 1400 rpm, travel speed of 30 mm/s, and a tilt angle of 1°. This is because these parameters provide a balanced amount of heat, ensuring proper material flow and uniform grain structure, allowing for dynamic recrystallization (DRX) to occur more efficiently.

Based on visual observations, the weld at 1400 rpm is very clean with no defects. Additionally, the microstructure testing revealed that the grain quality and uniformity reached the recrystallization phase, making this parameter the best in the study. In tensile testing, the highest result was achieved at 180.45 MPa, with an efficiency of 78%. This occurred because the optimal parameters promoted better mixing, which resulted in stronger and smoother material flow. In contrast, the 1100 rpm and 1800 rpm parameters generated suboptimal heating, leading to less favorable microstructures and defects that reduced the tensile strength of the weld joint.

The highest hardness value was obtained at 1400 rpm, with a hardness of 68 HV. This is because, at this speed, fine and uniform grains were able to form. The efficient recrystallization process improved the hardness of the joint, as the smaller, denser grains hindered dislocation movement, which positively affected the joint's strength.

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