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Article

Tool Force Monitoring for Efficient Friction Stir Welding of AA5754 Aluminum Alloy Joints with Enhanced Mechanical Performance

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Abstract

Friction stir welding (FSW) is a solid-state joining process widely used for aluminum alloys due to its low heat input, reduced distortion, and ability to produce high-quality joints. However, excessive tool forces generated during the welding process can increase machine loading, accelerate tool wear, and negatively affect the process efficiency. Therefore, understanding the relationship between welding parameters, tool forces, and the joint performance is essential for achieving high-quality welds while avoiding unnecessary mechanical loads. In this study, 4 mm thick AA5754 aluminum alloy plates were joined using the FSW process, and the feasibility of using tool force measurements for process optimization was investigated. A comprehensive experimental matrix consisting of nine different rotational speeds and ten different tool travel speeds was established based on preliminary studies and previous literature. During each welding operation, forces acting on the tool in the F_x, F_y, and F_z directions were continuously recorded. The welded joints were evaluated through tensile testing (Zwick Z300 universal testing machine, ZwickRoell, Ulm, Germany), hardness measurements, and microstructural characterization using scanning electron microscopy (SEM) (ZEISS Merlin scanning electron microscope, Carl Zeiss Microscopy GmbH, Oberkochen, Jena, and Göttingen, Germany). A Pearson correlation analysis and a two-way analysis of variance (ANOVA) were performed at a 95% confidence level to quantify the relationships and statistical significance of the process parameters. The results showed that F_z was the dominant force component during welding. The rotational speed had a statistically significant effect on the tensile strength, yield strength and hardness ($p < 0.05$), accounting for 99.39% of the total variation in hardness. For the mean tool force, both the rotational speed and the tool travel speed were statistically significant ($p < 0.0001$), contributing 38.48% and 47.16% of the total variation, respectively. The rotational speed also accounted for 81.55% of the variation in the maximum axial force. The Pearson correlation analysis showed a strong negative correlation between the rotational speed and hardness (r = −0.73), whereas the tool travel speed showed positive correlations with F_x (r = 0.61), F_z (r = 0.62), and the mean tool force (r = 0.68). Despite the increased tool loading associated with higher travel speeds, no corresponding improvement in the mechanical performance was observed. The results demonstrated that appropriately selected welding conditions produced joints with a yield strength and hardness exceeding 90% of the corresponding base material properties while maintaining relatively lower tool forces. SEM observations confirmed grain refinement in the stir zone. Overall, the combined correlation and ANOVA results demonstrate that real-time tool force monitoring can provide a quantitative basis for selecting FSW parameters that achieve an adequate mechanical performance while minimizing unnecessary machine and tool loading.

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1. Introduction

Joining is a critical process used to connect both similar and dissimilar materials in manufacturing.

Over the years, numerous conventional welding techniques have been employed to successfully join different materials. Friction stir welding (FSW) is an advanced solid-state welding process that offers significant advantages over traditional fusion-welding methods. This process was developed and patented by The Welding Institute (TWI) in 1991 for the butt and lap welding of ferrous and non-ferrous metals, as well as plastics. The process involves the insertion of a specially designed rotating tool between the abutting surfaces of the workpieces. The frictional heat generated by the interaction between the rotating tool and the workpieces, combined with their relative motion, induces localized plasticization, forming a softened region around the tool's plunged section [1].

Unlike conventional welding methods that involve melting the material, FSW uses a non-consumable rotating tool to generate heat through friction, which softens the material and allows the tool to join the workpieces [2]. The tool rotation speed and travel speed are the key process parameters that affect the welding outcome. The tool moves along the joint line, and the friction generated at the tool interface leads to localized heating, causing the material to soften and flow, resulting in a solid-state bond.

FSW has several advantages over fusion-welding methods, including better control over the heat-affected zone (HAZ) and a reduced risk of defects such as porosity and cracking, which are often observed in fusion welding. Additionally, FSW is considered more energy-efficient and environmentally friendly since it does not require filler metals or produce harmful emissions. These qualities make FSW particularly suitable for the aerospace and automotive industries, where the precision and strength of the welded joint are critical. The absence of melting also prevents solidification cracks, which are common in the fusion welding of aluminum alloys. Moreover, FSW is versatile and can be used to join dissimilar materials and composites, making it a powerful tool in advanced manufacturing processes [3].

The quality of FSW joints depends heavily on the process parameters, including the tool rotation speed, travel speed, and material properties. These parameters influence the material flow around the tool, which in turn affects the microstructure of the welded region. The welded zone is typically divided into four regions: the unaffected material zone (A), the heat-affected zone (B), the thermomechanically affected zone (C), and the weld nugget zone (D). Each of these regions exhibits different microstructural characteristics, with the nugget zone typically showing fine, equiaxed grains due to the recrystallization process during welding. Researchers have extensively studied these regions to better understand the relationship between the process parameters, microstructure, and mechanical properties [4–6].

One of the challenges in FSW, particularly for aluminum alloys, is maintaining a consistent and uniform microstructure throughout the weld [7]. Variations in the process parameters, such as the tool rotation speed and travel speed, can lead to inhomogeneities in the material, affecting the final mechanical properties of the joint. However, studies have shown that optimizing the FSW parameters can produce joints with superior mechanical properties, including a high tensile strength and fatigue resistance, compared to conventional fusion-welded joints [8].

FSW tools follow the same basic trends in terms of their shapes and geometries. They generally comprise three generic features: a shoulder; a probe, also known as a pin; and

any external features. The heat input, forging action, and stirring action of the tool induce a plastic flow in the material, forming a solid-state weld. It was realized early in the development of the FSW method that the tool's design is critical in producing sound welds [9]. The selection of the tool material is very important. The weld quality and tool wear are two important considerations in the selection of the tool material, the properties of which may affect the weld quality by influencing heat generation and dissipation. The interaction between the base materials and an eroded tool material may also affect the microstructure of the produced weld. Reliable friction stir welds require an understanding of how the tool design can influence the process parameters, which in turn can provide a high joint strength and performance [10].

Over the years, researchers have conducted much work on friction stir welding using similar and dissimilar base materials. In the last decade, most of the studies have been focused on aluminum and copper materials. The FSW process of aluminum and copper still remains a relatively underexplored area, and further scientific research is required to achieve a comprehensive understanding of its mechanisms [11]. However, although most FSW research has focused on aluminum, further studies are needed to broaden the interest in this joining technique, which could ultimately promote its use across a wider range of industries.

In conclusion, friction stir welding has emerged as a key technology for joining aluminum alloys, offering numerous advantages over traditional fusion-welding methods. The ability to join aluminum alloys without melting the material not only prevents common welding defects, but also leads to improved mechanical properties and a greater energy efficiency. AA5754 was specifically selected in the present study because it is a widely used Al-Mg alloy with a good formability and weldability; thus,, the selection of 5754 was intended to provide a representative aluminum alloy for investigating the relationship between the process parameters and the tool forces and the joint performance. Given the ongoing research into optimizing FSW parameters and exploring new techniques such as splat cooling, friction stir welding will continue to play a vital role in industries where aluminum alloys are crucial, particularly in aerospace and automotive applications.

2. Materials and Methods

2.1. Friction-Stir-Welding Process

Aluminum 5754 is a lightweight, corrosion-resistant, and highly weldable alloy, making it suitable for a wide range of applications. It is widely used in the automotive, marine, and construction industries due to its high mechanical strength, excellent corrosion resistance, and good formability. It is particularly well-suited for FSW, with minimal strength reduction after welding. The mechanical properties of aluminum 5754 under the H32 condition include a tensile strength of approximately 200–250 MPa, a yield strength of around 110–160 MPa, and an elongation of 12–18%, indicating a good strength, moderate resistance to yielding, and a decent ductility [12].

So, 5754-series aluminum plates were selected as the workpiece for the experiments. The chemical composition of 5754 aluminum alloy consists of at least 95.2% aluminum (Al) and 2.6–3.6% magnesium (Mg). Other trace elements, including iron (Fe), silicon (Si), manganese (Mn), zinc (Zn), copper (Cu), and titanium (Ti), each account for less than 1% [13].

Plates of 4 mm thick aluminum AA 5754 were prepared in 75 × 75 mm dimensions as FSW test specimens. A fixture was designed to secure the parts on the CNC milling machine during operation and to measure the forces during the joining process using a dynamometer.

A Kistler brand 9265B model 3-axis cutting force dynamometer (Kistler Group, Winterthur, Switzerland)was used to measure the forces acting on the tool tip. The device has a

piezoelectric force measurement system; thus, forces acting on the tool can be measured in each weld on the x, y and z axes.

A tool with conical and triflat pin geometries showed a different performance in the FSW process in terms of the heat density and mechanical properties [13].

In Figure 1, the dimensions of the tool can be seen, which were designed for experiments using tool steel. In this design, the tool pin includes a tapered top section with sharp edges to interact with the material during welding. This tapering ensures efficient heat generation and material flow. To isolate the operational variables, this single tool configuration was held constant throughout all experiments, allowing the study to focus specifically on monitoring the resulting tool forces and their relationship with the final joint performance. Using this test setup, 9 different rotational speeds and 10 different travel speeds were welded as the test parameters, based on those employed in previous studies. To determine the optimal parameters, such as the rotational and traverse speed, for the friction-stir-welding (FSW) process, a detailed review of various studies in the literature was conducted [14–20].

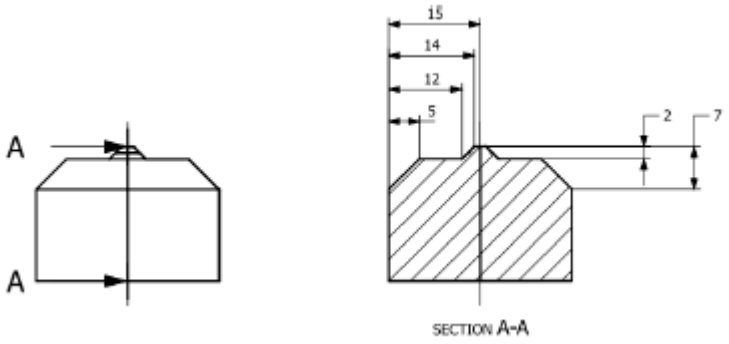


Figure 1. Tool geometry used in friction-stir-welding process. The arrow indicates the cross section. All dimensions are in mm.

Most of these studies provided insights into the commonly used machine settings for aluminum 6000-series alloys, particularly for aluminum 5754, which served as a reference for parameter selection. However, the investigation focused on identifying the feasible ranges of machine parameters to achieve successful welding while considering the limitations of the available equipment. The welding experiments were conducted on a CNC milling machine (Vision Wide Co., Ltd., Taichung, Taiwan), which had a maximum rotational speed limit of 3500 rpm. During the experimental trials, it was observed that welding was unsuccessful at rotational speeds lower than 500 rpm and travel speeds exceeding 120 mm/min. Consequently, 500 rpm was set as the minimum speed and 120 mm/min was as the maximum toll travel speed for further experimentation. A range of parameters, including the tool travel speed and rotational speeds seen in Table 1, were tested based on the most frequently used parameters reported in the literature [21–26].

Table 1. Friction-stir-welding parameters.

Rotational Speed, rpm	Tool Travel Speed, mm/min
500, 700, 900, 1100, 1300, 1500, 2000, 2500, 3500	10, 20, 30, 40, 50, 60, 80, 100, 120

The numerical simulation of the friction-stir-welding (FSW) process is not yet sufficient for process optimization. However, the growing body of knowledge on the process, along with advancements in computational resources, may enable the use of numerical simulations to predict optimal process parameter combinations [27]. In this context, defining process limits through experimentally obtained data remains crucial at this stage.

Numerous review articles have been published on the joining of similar and dissimilar materials using FSW [28,29]. While these studies have examined the effects of the process parameters and tool geometries on the weld mechanical properties, defects, and microstructure, as well as intermetallic formation and growth, they have largely ignored the detailed analysis of forces acting on the tool during the welding process. This deficiency represents a significant gap in fully understanding the FSW process.

2.2. Tests and Measurements (Analysis of Samples)

According to previous studies in the literature, nine different rotational speeds and ten different travel speeds were used for FSW operations, and the forces acting on the tool were measured and recorded during the process. To investigate the effects of these parameters on tool forces and product properties, various tests and analyses were conducted.

2.2.1. Force Measurements

The forces acting on the tool in friction stir welding (FSW) are critical for several reasons, as they directly influence the weld quality, tool wear, and overall process efficiency. These forces include the axial force, traverse force, and lateral force. If the forces are too low, insufficient material stirring can cause defects like voids or kissing bonds. Excessive forces can lead to excessive flash formation or thinning of the weld. Excessive forces can cause premature failure of the tool, especially in high-strength materials like aluminum alloys or steel. Optimizing the forces reduces tool wear, extending the tool life and reducing costs [30].

As previously discussed, the Kistler 9265B dynamometer (Kistler Instrumente AG, Winterthur, Switzerland)was used for force measurements under varying process parameters for all welded samples. A sample measurement can be seen in Figure 2.

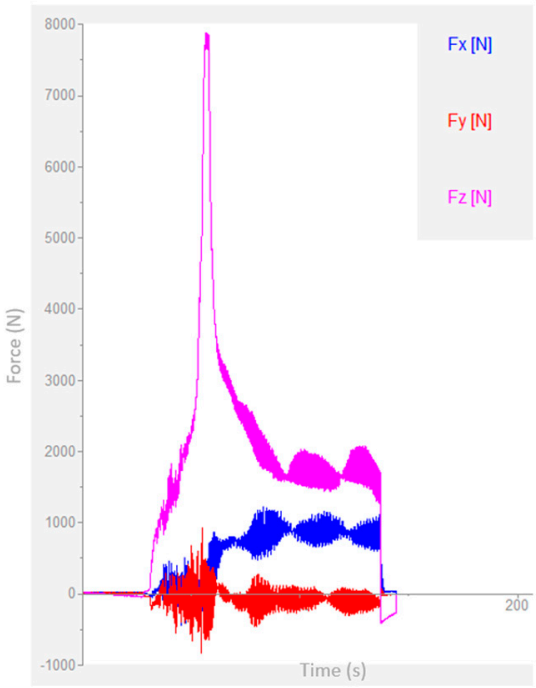


Figure 2. Force measurements were conducted at a rotational speed of 1500 rpm and a travel speed of 40 mm/min.

The variation in the tool forces with the transverse speed and rotational speed can be observed in Figures 3 and 4, respectively.

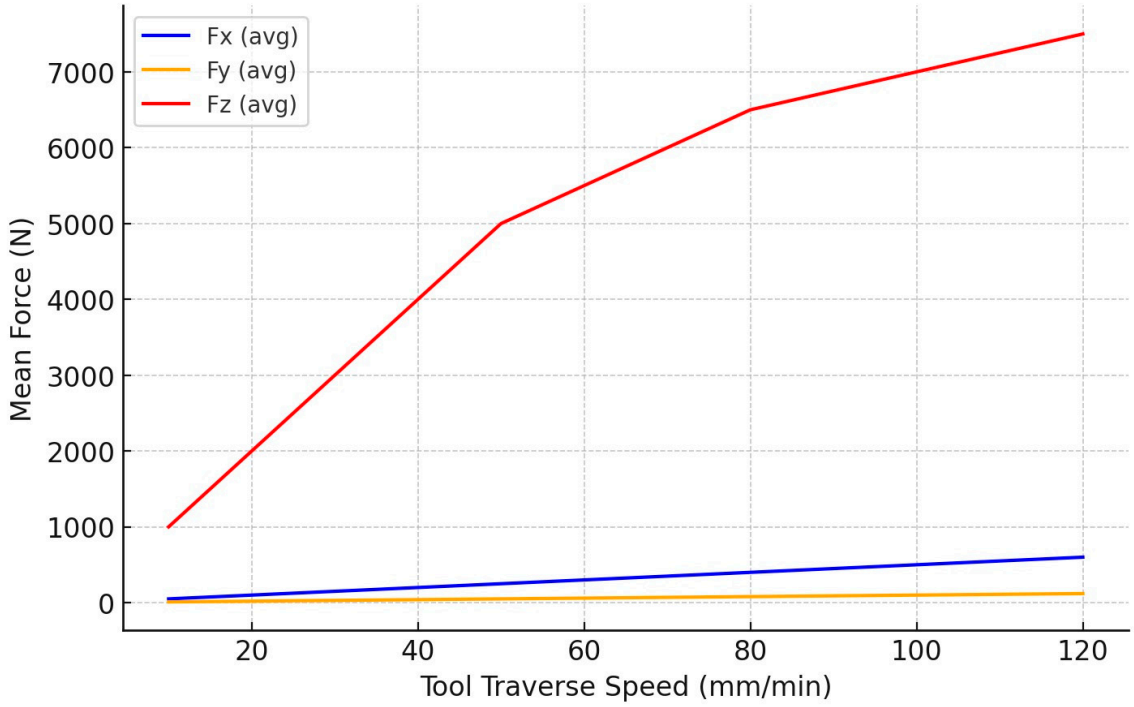


Figure 3. Change in tool forces with tool transverse speed.

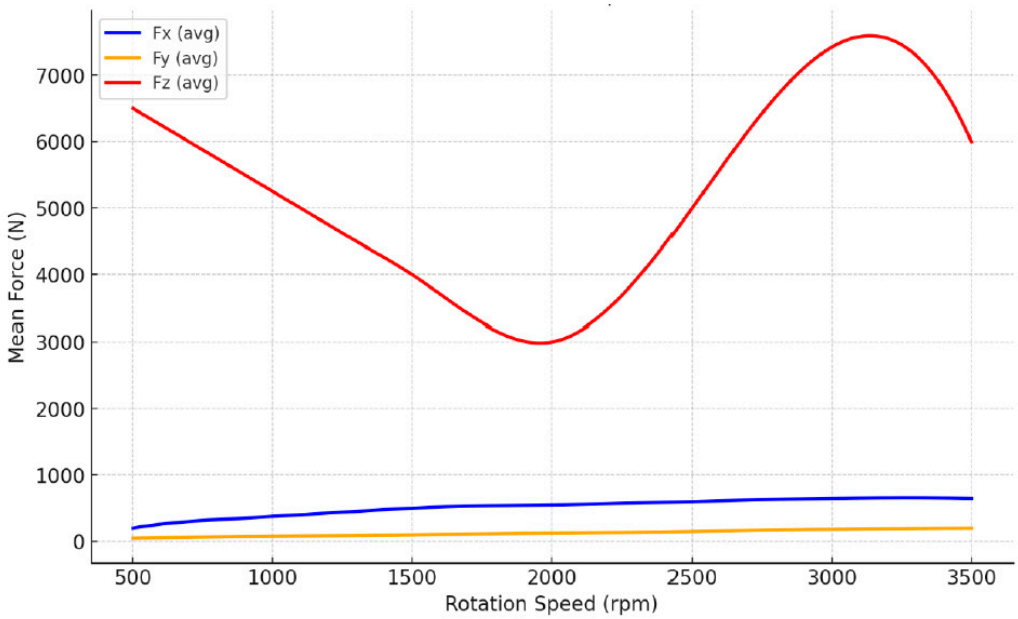


Figure 4. Change in tool forces with tool rotational speed.

The total force can also be calculated by the use of three measured force components, F_x, F_y and F_z, using the following relationship:

$$F_{Total} = \sqrt{{F_x}^2 + {F_y}^2 + {F_z}^2}$$

2.2.2. Hardness Tests

In the friction-stir-welding process, the strength, wear resistance, and overall quality of the weld can be evaluated through hardness testing of the samples. By carefully controlling the hardness, FSW can produce high-quality, durable, and strong welded joints that are free from defects and perform well under stress.

Brinell hardness shown in Figure 5 tests were performed using a Zwick/Roell hardness testing machine (Zwick/Roell, Ulm, Germany)in accordance with the ISO 6506-1 standard [31]. The diameter of the ball usually varied between 1 and 10 mm. The ball was pressed against the surface of the material with a certain force and the penetration diameter was measured to obtain the hardness value. The measurements were carried out under an HBW 2.5/10 configuration, employing a 2.5 mm tungsten carbide ball indenter with a load dwell time of 12 s. Prior to testing, the target area was marked as the exact center point of the entire specimen, located directly behind the welded surface.

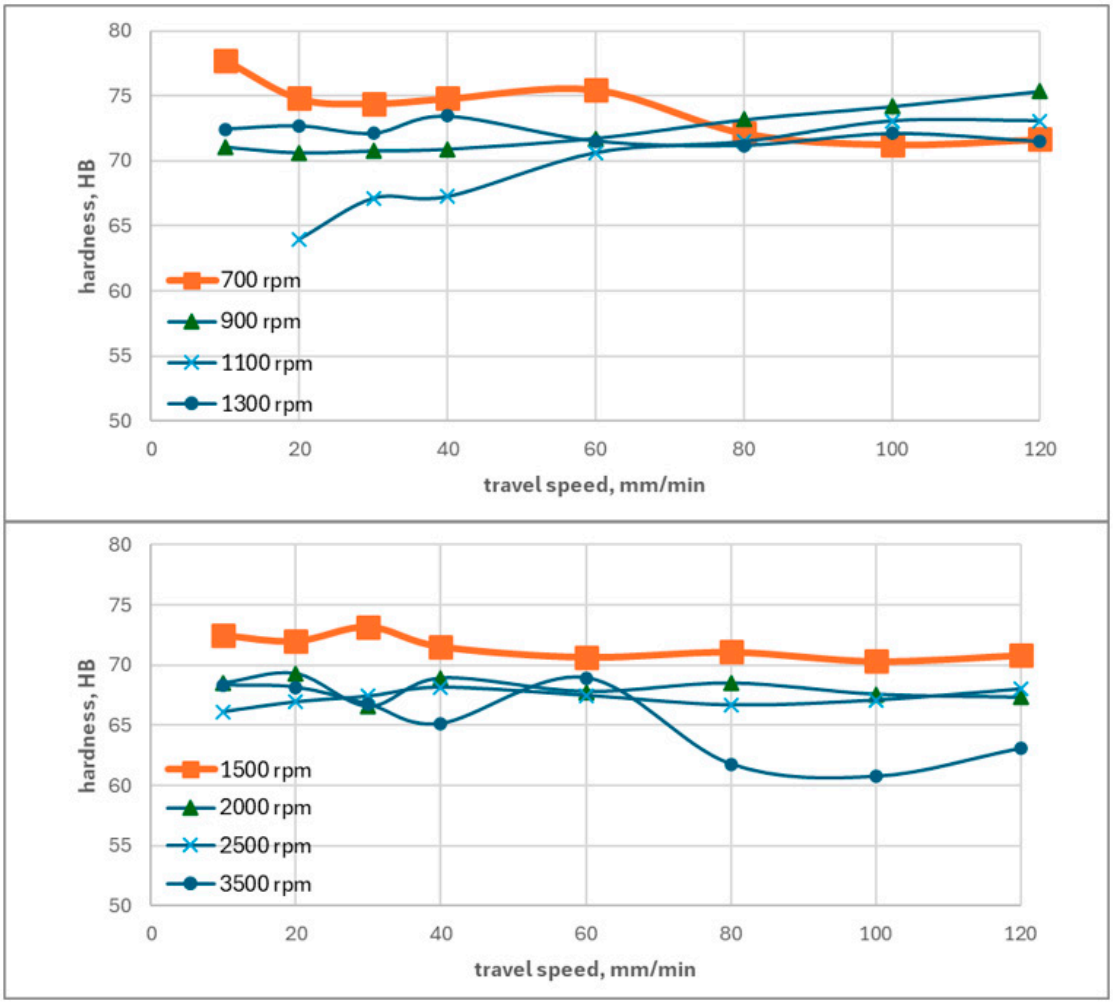


Figure 5. Hardness measurements under different transverse speeds and rotational speeds.

2.2.3. Tensile Tests

The strength, ductility, and integrity of the welds are crucial parameters for ensuring that they meet the required standards for their intended applications. To evaluate these parameters, tensile tests were conducted on all welded samples.

Tensile tests were performed using the Zwick Z300 Tensile testing machine (Zwick-Roell GmbH & Co. KG, Ulm, Germany) according to the "ISO 6892-1 Tensile Test on Metals at Ambient Temperature" standard [32]. The tensile test samples shown in Figure 6 were prepared using EDM (electro-discharge machining) utilizing specimens with a total length of 103 mm, a thickness of 4 mm, a grip width of 12.70 mm, a gauge width of 6.35 mm, a gauge length of 10 mm, and a transition radius of 12.70 mm. The yield strength values obtained from these tensile tests at different tool traverse speeds and rotational speeds are presented in Figure 7.



Figure 6. Tensile test samples.

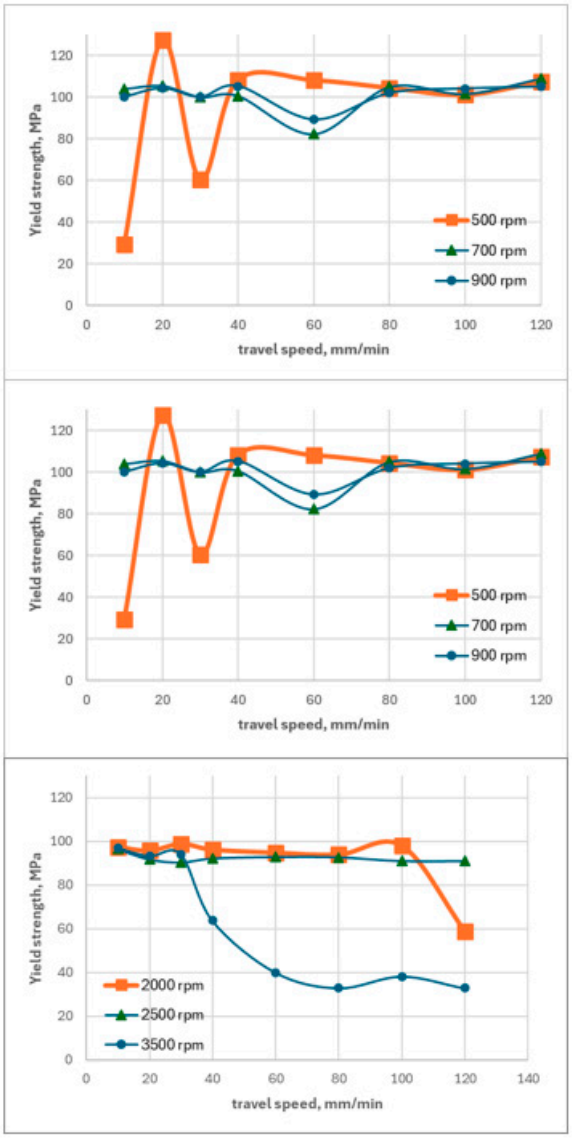


Figure 7. Yield strength measurements under different transverse speeds and rotational speeds.

2.2.4. SEM Analysis

The scanning electron microscopy (SEM) (ZEISS Merlin scanning electron microscope, Carl Zeiss Microscopy GmbH, Jena, Germany).analysis provided high-resolution, detailed images of the weld microstructure and offered a deeper understanding of the material's behavior during and after the welding process. Therefore, it is crucial to determine the success of FSW.

The SEM analyses were performed for microstructure analyses of the welded joints. After the tensile test, the fractured surfaces of the samples were used, and SEM analyses were performed.

The samples were cut perpendicular to the joint surface and their surfaces were sanded with 320–1200-mesh sandpaper to examine the structural differences formed on the joint surface, and polished with 9-3-1 µm diamond paste, respectively. Keller chemical etchant was prepared for the microstructure analyses and etching was performed.

As can be clearly seen in Figure 8a, there were no gaps, cracks or disconnected areas in sample number 136, which had the best tensile strength. In addition, in Figure 8b, when the microstructure of the material had the lowest tensile strength, for sample number 356, there was a gap in the welding region.

In Figure 9, it can be seen that fine grains and oriented grains were formed because of the axial load on the samples. Also, the weld line can be easily seen in these images. Also in Figure 10, the SEM images can be compared with the base material and welded sample. The base metal showed a uniform grain structure and weld center, displaying refined grains and grain alignment along the welding direction.

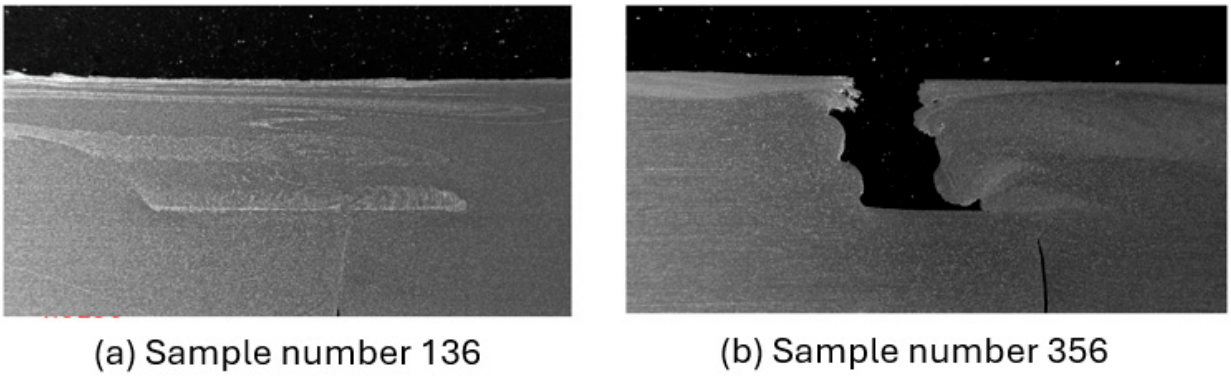


Figure 8. SEM images.

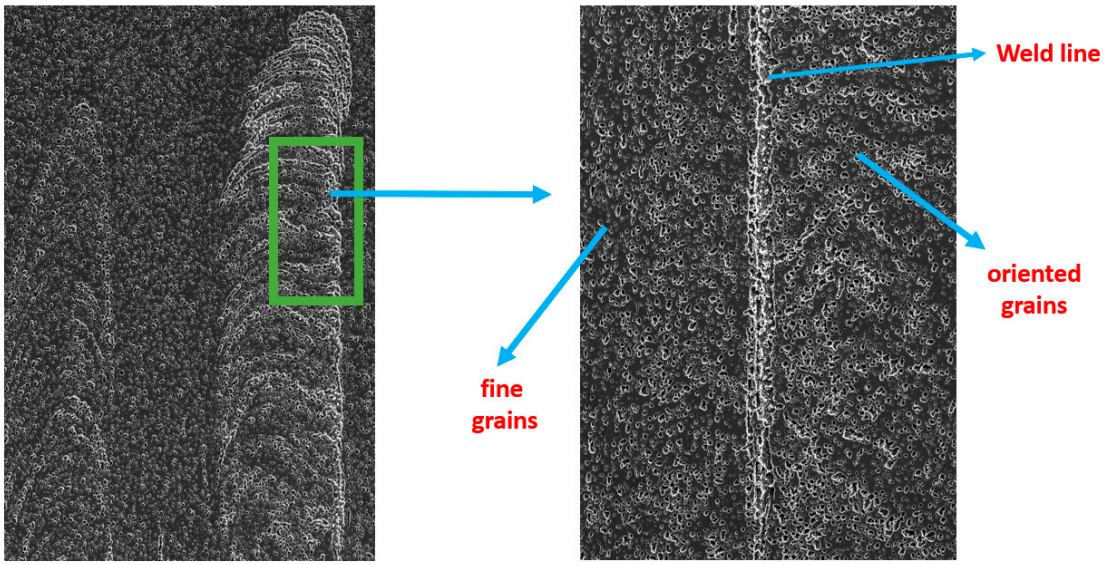
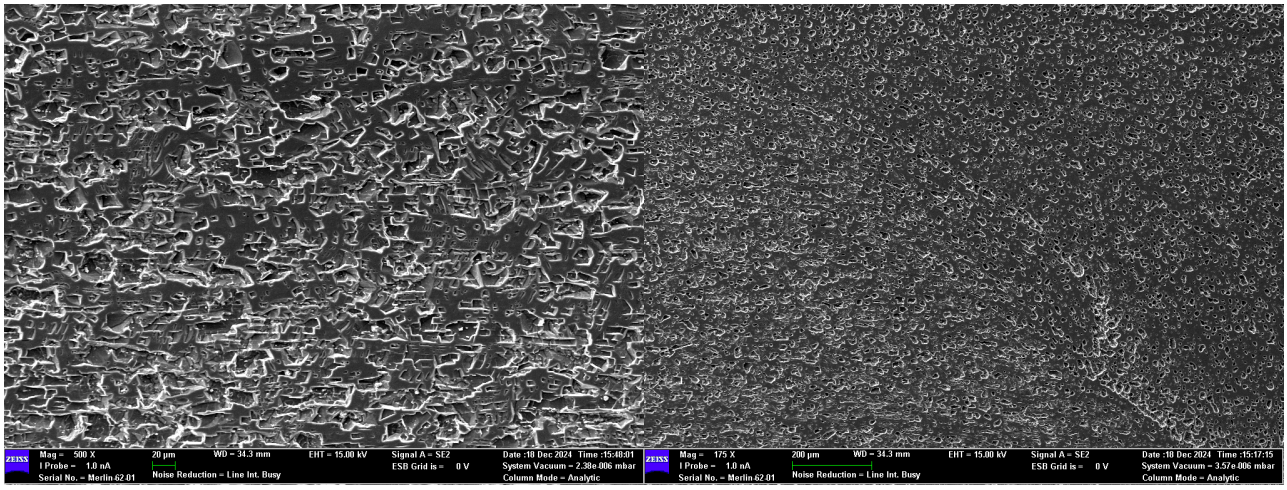


Figure 9. Microstructural analysis of sample number 136.



(**a**) Base metal (**b**) Sample Number 136

Figure 10. SEM images comparing the microstructure of the base metal and welded sample.

3. Results and Discussion

In this study, the relationship between the welding parameters, tool forces, and mechanical performance of AA5754 friction-stir-welded joints was investigated. The main objective was to determine whether tool force measurements can be used as an effective indicator for selecting appropriate welding conditions that provide a sufficient mechanical performance while avoiding excessive machine loading and tool stress. The preliminary results showed that increasing the rotational speed negatively affected the mechanical properties, particularly the hardness and yield strength. However, a comprehensive analysis was required to evaluate the combined effects of the process parameters, tool forces, and mechanical responses.

A Pearson correlation analysis was employed to quantify the linear relationships between the welding parameters, tool forces, and mechanical properties. The correlation coefficient (r) ranged between −1 and +1, where positive and negative values indicate direct and inverse relationships, respectively. The correlation heatmap obtained from the experimental data is presented in Table 2.

Table 2. Correlation heatmap of FSW experiments.

	Rot. Speed	Tool Speed	Hardness	Yield St.	Tensile St.	Elongation	F_x	F_y	F_z	F_x max	F_y max	F_z max	F Mean
Rot. Speed	1	0	−0.73	−0.5	−0.27	0.04	−0.26	0.34	−0.33	−0.8	0.05	−0.45	−0.31
Tool Speed	0	1	−0.02	−0.13	−0.23	−0.19	0.61	0.36	0.62	0	0.14	0.05	0.68
Hardness	−0.73	−0.02	1	0.55	0.38	0.18	0.32	−0.43	0.03	0.65	−0.1	0.28	0.04
Yield St.	−0.5	−0.13	0.55	1	0.93	0.57	−0.14	−0.77	−0.03	0.22	0.03	0.32	−0.1
Tensile St.	−0.27	−0.23	0.38	0.93	1	0.73	−0.27	−0.75	−0.19	−0.02	0.03	0.25	−0.26
Elongation	0.04	−0.19	0.18	0.57	0.73	1	−0.28	−0.52	−0.25	−0.28	0.01	0.19	−0.31
F_x	−0.26	0.61	0.32	−0.14	−0.27	−0.28	1	0.25	0.22	0.09	0.03	0.01	0.34
F_y	0.34	0.36	−0.43	−0.77	−0.75	−0.52	0.25	1	0.36	0.03	0.08	−0.01	0.44
F_z	−0.33	0.62	0.03	−0.03	−0.19	−0.25	0.22	0.36	1	0.55	−0.03	0.55	0.99
F_x max	−0.8	0	0.65	0.22	−0.02	−0.28	0.09	0.03	0.55	1	−0.09	0.49	0.53
F_y max	0.05	0.14	−0.1	0.03	0.03	0.01	0.03	0.08	−0.03	−0.09	1	−0.02	−0.02
F_z max	−0.45	0.05	0.28	0.32	0.25	0.19	0.01	−0.01	0.55	0.49	−0.02	1	0.51
F Mean	−0.31	0.68	0.04	−0.1	−0.26	−0.31	0.34	0.44	0.99	0.53	−0.02	0.51	1

The correlation analysis revealed that increasing the rotational speed negatively affected the mechanical properties of the welded joints. A strong negative correlation was observed between the rotational speed and the hardness (r = −0.73), while the yield strength showed a moderate negative correlation (r = −0.50). These results indicate that excessive rotational speeds may increase the heat input and adversely influence the mechanical performance of AA5754 joints.

In contrast, the tool travel speed exhibited significant positive correlations with the measured tool forces, particularly F_x (r = 0.61), F_z (r = 0.62), and the mean force values (r = 0.68). However, the correlation between the tool travel speed and the mechanical properties was relatively weak, with the yield strength and tensile strength showing correlation coefficients of -0.13 and -0.23, respectively. This indicates that increasing the welding speed increases the mechanical load acting on the tool without providing a significant improvement in the joint performance.

The relationship between the axial force and the other process variables provides further insight into the mechanical loading of the FSW system. The axial force, F_z, exhibited a very strong correlation with the mean tool force (r = 0.99), confirming that F_z is the dominant component of the measured tool loading. However, the correlations between F_z and the mechanical properties were weak, with r values of 0.04 for the hardness, -0.10 for the yield strength, and -0.26 for the tensile strength. Therefore, higher axial loading cannot be directly associated with an improved joint mechanical performance. This finding is particularly important from an industrial perspective because conditions that generate higher tool forces may increase machine and tool loading without necessarily producing stronger joints.

To further determine whether the observed trends were statistically significant, a two-way analysis of variance (ANOVA) was performed using the rotational speed and the tool traverse speed as independent factors. The tensile strength, yield strength, hardness, elongation, and process forces were considered response variables. The analysis was conducted at a 95% confidence level ($\alpha = 0.05$). The ANOVA results provided statistical evidence supporting the trends identified by the Pearson correlation analysis.

The ANOVA results demonstrated that the rotational speed was the dominant process parameter governing the mechanical properties of the AA5754 joints. The rotational speed was statistically significant ($p < 0.05$) for the tensile strength, yield strength, elongation, and hardness, whereas the tool traverse speed did not show a statistically significant effect on these mechanical responses. The particularly strong influence of the rotational speed on the hardness is noteworthy, as it accounted for 99.39% of the total variation in hardness. This result is consistent with the strong negative correlation between the rotational speed and the hardness (r = -0.73) and confirms that the thermal conditions associated with rotational speed play a dominant role in determining the hardness response of the welded joints.

From a process mechanics perspective, these observations can be explained by the competing effects of heat generation, material flow, and mechanical loading during FSW. Increasing the rotational speed increases frictional and plastic-deformation-related heat generation around the tool, which promotes thermal softening and reduces the flow stress of the material. Although this softening facilitates material flow and can reduce the instantaneous mechanical resistance acting on the tool, excessive thermal exposure can also modify the microstructure of the welded region and reduce the hardness and strength. The statistically significant effect of rotational speed obtained from the ANOVA therefore supports the negative correlations observed between the rotational speed and the hardness and yield strength.

The ANOVA results also demonstrated that the process forces were governed by a different combination of parameters. For the mean force (Fmean), both the rotational speed and the tool traverse speed had statistically significant effects ($p < 0.0001$). Their contributions to the total variation were 38.48% and 47.16%, respectively. The relatively high contribution of the traverse speed is consistent with its positive correlation with Fmean (r = 0.68). Increasing the traverse speed reduces the time available for heat generation per unit length while requiring the tool to deform and displace the material at a higher

rate. Consequently, the material offers a greater instantaneous resistance to tool movement, resulting in increased F_x and F_z values.

A particularly important finding was obtained for the maximum axial force. The rotational speed accounted for 81.55% of the total variation in the maximum axial force, indicating that it was the primary parameter controlling the vertical loading experienced by the tool. This result further emphasizes the importance of the rotational speed in controlling both the joint mechanical properties and tool loading. However, the weak correlations between F_z and the hardness, yield strength, and tensile strength demonstrate that the axial force should not be interpreted as a direct predictor of the mechanical performance. Rather, it provides valuable information regarding the mechanical loading state of the FSW system.

The combination of the Pearson correlation and ANOVA results therefore provides a more comprehensive interpretation of the experimental findings. A Pearson correlation analysis identifies the direction and strength of linear relationships, whereas an ANOVA determines whether the effects of the process parameters are statistically significant. The agreement between these two approaches strengthens the reliability of the observed trends. In particular, the strong negative correlation and statistically significant ANOVA result for the rotational speed versus the hardness, as well as the strong positive correlation and statistically significant ANOVA results for the traverse speed versus the process forces, demonstrate that the observed relationships are not merely qualitative trends.

Overall, the results indicate that the mechanical performance and tool loading are influenced by different process parameters. The rotational speed has a dominant influence on the mechanical properties, particularly the hardness, while both the rotational speed and the traverse speed significantly affect the process forces. Therefore, selecting FSW parameters should involve a balance between achieving adequate mechanical properties and minimizing unnecessary machine and tool loading. In this context, the real-time monitoring of tool forces, particularly the axial force, can provide useful process information for identifying unfavorable welding conditions. The present results consequently demonstrate the potential of force-based monitoring as a practical approach for selecting and maintaining suitable FSW conditions, while avoiding excessive loading that does not contribute to an improved joint mechanical performance.

4. Conclusions

This study demonstrated that tool force monitoring can be effectively utilized to optimize the friction-stir-welding process of AA5754 aluminum alloy joints by balancing the mechanical performance and machine loading. A comprehensive experimental investigation was conducted using nine different rotational speeds and ten different tool travel speeds, while the F_x, F_y, and F_z forces were continuously measured during welding.

The results showed that the axial force (F_z) was the dominant force component during the FSW process, reaching significantly higher values compared with F_x and F_y. Increasing the tool travel speed caused a considerable increase in the axial force; however, higher tool loads did not provide additional improvement in the joint mechanical properties. This finding indicates that excessive mechanical loading of the tool and machine system is not necessary to achieve high-quality welds.

The statistical analysis provided further evidence of the dominant role of the rotational speed. The two-way ANOVA showed that the rotational speed had a statistically significant effect on the tensile strength, yield strength, elongation, and hardness ($p < 0.05$). In particular, the rotational speed accounted for 99.39% of the total variation in hardness. For the mean tool force (Fmean), both the rotational speed and the tool travel speed had statistically significant effects ($p < 0.0001$), with contributions of 38.48% and 47.16%,

respectively. Furthermore, the rotational speed accounted for 81.55% of the variation in the maximum axial force, confirming its dominant influence on tool loading.

The Pearson correlation analysis supported these findings by identifying strong relationships between the rotational speed, mechanical properties, and process forces. The combination of the correlation and ANOVA analyses demonstrated that the mechanical performance and tool loading are governed by different aspects of the FSW process. While the rotational speed predominantly controls the mechanical response, both the rotational speed and the tool travel speed significantly influence the forces acting on the tool.

The mechanical characterization results revealed that properly selected welding parameters produced joints with yield strength and hardness values exceeding 90% of the base material properties. The obtained results also identified the welding conditions that provided a high mechanical performance while maintaining relatively lower tool forces.

The SEM observations confirmed grain refinement in the stir zone after FSW, contributing to the enhanced mechanical properties of the welded joints. Furthermore, the correlation analysis revealed significant relationships between the welding parameters, tool forces, and mechanical performance, demonstrating that tool force measurements can provide valuable information for selecting suitable FSW parameters.

Overall, this study highlights the potential of real-time tool force monitoring as an effective approach for improving the FSW process efficiency, reducing unnecessary tool loading and wear, and achieving high-performance AA5754 aluminum alloy joints.

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