Semarak International Journal of Mechanical Precision Engineering

Journal homepage: https://semarakilmu.my/index.php/sijmpe/index
ISSN: 3083-9564

Mechanical Properties of Friction Stir Welding Assisted Cooling

Ahmad Syahrazi Anuar[1], Mohammad Kamil Sued[1,*], Muhammad Izzul Najmi[1], Joseph Sahaya Anand[2], Maged Mustafa Abdulatef[1], Tham Sook Chan[1], Mohd Fauzi Mamat[1]

[1] Faculty of Technology and Engineering Industry and Manufacturing, Universiti Teknikal Malaysia Melaka, 76100 Durian Tunggal, Melaka, Malaysia
[2] MIT Vishwaprayag University, Solapur, 413255, India

ARTICLE INFO

Article history:
Received 24 March 2025
Received in revised form 20 April 2025
Accepted 22 May 2025
Available online 30 June 2025

Keywords:
FSW; AA6061; assisted cooling; MQL; machine coolant; mechanical properties

ABSTRACT

Friction Stir Welding (FSW) is a solid-state joining technique widely used for aluminium alloys due to its ability to produce high-quality welds without melting the base material. However, excessive heat generation during the process can deteriorate the microstructure, leading to reduced mechanical properties. Despite various advancements, limited research has focused on optimizing cooling strategies to enhance weld strength and quality. Therefore, this study addresses this gap by investigating the effects of assisted cooling on the mechanical properties of FSW joints using the Taguchi optimization method to identify the optimal welding parameters. A series of nine experiments were conducted on AA6061 aluminium alloy, varying tool rotation speeds between 900rpm to 1400 rpm, different coolant compositions, and varied coolant flow rates between 10 mL/min to 30 mL/min. The axial force and travel speed are constant at 5 kN and 108 mm/min respectively. The results demonstrated that assisted cooling significantly influenced the weld quality. The highest tensile strength was recorded at a tool rotation speed of 1150 rpm with a coolant flow rate of 30 mL/min, showing a 19.53% improvement over the Parent material without cooling. Hardness measurements indicated that welds produced under assisted cooling exhibited higher microhardness values in the weld zone, particularly at a 1:1 coolant-water mixture with a 30 mL/min flow rate. From the study that we found using machine coolant during welding assisted cooling, its mange to increase 24% in joint strength from the parent material. These findings highlight the critical role of cooling in enhancing FSW joint properties and provide valuable insights into optimizing process parameters for industrial applications. By mitigating heat-related issues, this study contributes to the advancement of FSW technology, promoting its adoption in sectors requiring high-strength aluminium welds, such as aerospace, automotive, and marine industries.

1. Introduction

Friction stir welding technology (FSW) involves solid-state bonding by a non-consumable tool that rotates and mechanically travels through the workpieces to be joined. The technology was originally

[*] *Corresponding author.*
E-mail address: kamil@utem.edu.my

https://doi.org/10.37934/sijmpe.3.1.118

patented by TWI, UK, and has been applied to shipbuilding [1], automotive [2], and aerospace [3] industries. It represents an alternative welding technology, over fusion welding, e.g. Tungsten inert gas welding (TIG) [4] and Metal inert gas welding (MIG) [5]. These traditional joining techniques often demand large amount of energy and require considerable manual labor. Despite these efforts, they can still produce weaker weld joints that necessitate additional post-processing. These limitations, however, can be effectively overcome with Friction Stir Welding (FSW). Additionally, FSW enhances weld quality and structural integrity while reducing material wastage and operational costs. Because of these benefits, it is widely recognized as a sustainable and energy-efficient welding method [6].

The joining process commercially used in local industries in Malaysia still relies on fusion-based methods. The primary reason for this is the lower cost of technology, the availability of skilled and semi-skilled workers, and the well-established nature of the process. Additionally, it offers several advantages, including minimal defect formation, faster welding times, and lightweight joints due to the absence of additional filler material [7]. Moreover, it consumes significantly less energy compared to fusion welding techniques such as laser and gas metal arc welding. Research by *et al.,* [8] indicates that Conventional Friction Stir Welding (CFSW) consumes only 2.5% of the total energy used in laser welding. In Conventional FSW, a non-consumable tool with a pin and shoulder rotates to generate heat, softening the material and enabling it to be stirred together as the tool advances along the joint. According to Li *et al.,* [9], the amount of heat generated is also influenced by process parameters such as travel speed and tool rotation. Welding efficiency can be optimized by controlling transverse and rotational speeds, as precise adjustments to these parameters significantly influence weld quality and overall performance [10]. Jadav *et al.,* [11] observed that rotational speed directly affects the weld's mechanical properties, with higher rotational speeds leading to improved tensile strength. Similarly, Alimadadi *et al.,* [12] found that traverse speed plays a crucial role in regulating heat input by determining the duration of the tool's interaction with the material, where an increase in traverse speed reduces heat input during welding. Studies by Uday *et al.,* [13] further demonstrated that raising the tool's traverse speed from 20 to 25 mm/min resulted in a 59% increase in ultimate tensile strength for dissimilar aluminum 6061 composite joints. Jia *et al.,* [14] reported that axial force decreases with increasing rotational speed but rises with higher traverse speed and plunge depth. Their findings suggest that while rotational and traverse speeds have only a minor impact on axial force overall, maintaining the right balance is crucial for minimizing tool wear and preventing defects, ultimately ensuring consistent weld quality. A fundamental advantage of Conventional FSW is its capability to join materials that are challenging to weld using traditional methods. This includes high-melting-point materials such as aluminium [15], titanium [16], and copper [17], as well as dissimilar metal combinations. Numerous studies have examined the FSW process across various materials, highlighting its versatility and effectiveness as a solid-state joining technique.

In FSW, heat generation plays a crucial role in determining the weld's quality and properties. As a solid-state joining process, FSW relies on heat generated through the frictional interaction between the rotating tool and the workpieces [18]. Research by Nie *et al.,* [19] indicates that the highest temperature is concentrated in the tool's stir zone and shifts forward as the tool progresses. Proper heat generation in FSW is essential as it affects material flow, microstructure development, and the weld's mechanical properties. However, controlling this heat is equally important to prevent defects such as excessive grain growth, voids, or thermal distortions. According to Huang *et al.,* [20], reducing heat input and applying forced cooling can effectively minimize the thermal cycles on the surrounding nugget zone (NZ), helping to prevent softening in the thermo-mechanically affected zone (TMAZ) and the heat-affected zone (HAZ).

Recent studies have emphasized the importance of temperature control in Friction Stir Welding (FSW) to enhance weld mechanical properties. Researchers [21,22] demonstrated that incorporating cooling techniques, such as compressed air or water, during FSW of aluminium alloys significantly improved weld tensile strength and hardness. Similarly, a study by Derazkola *et al.,* [23] examined the effects of different cooling rates on the microstructure and mechanical properties of Friction Stir Welded (FSW) joints in high-strength aluminum alloys. Their findings revealed that the application of rapid cooling rates led to finer grain structures and improved mechanical properties compared to conventional FSW without cooling assistance.

The effect of cooling methods on the Ultimate Tensile Strength (UTS) during welding varies depending on the method employed. Among them, in-situ cooling has shown the most promising results in enhancing UTS. However, this approach often requires specialized equipment, which can be costly, complex to implement, and may raise safety concerns. Various studies on FSW have highlighted difference impacts of cooling methods on tensile strength. For instance, Cho *et al.,* [24] reported a 28.3% increase in tensile strength when water cooling was applied to aluminium alloy A6082. Al-Wajidi *et al.,* [25] found a 28% increase in UTS using Minimum Quantity Lubrication (MQL) with 6061-T651 alloy. Bocchi *et al.,* [21] observed a remarkable 137% improvement with air cooling on AA5754.

Furthermore, Wang *et al.,* [26] demonstrated that liquid CO2 cooling could enhance tensile strength by 4.8% to 110.7% with AA2014 showing the greatest improvement. Cooling method selection is influenced by factors such as cost, setup complexity, and target performance. Gas-based cooling often yield higher strength but at greater cost, while water-based methods are more accessible but may deliver modest improvements. Despite advancements, there remains limited research specifically focusing on machine coolant combined with MQL, which may provide a cost-effective yet performance enhancing alternative. Further investigation into this hybrid method could lead to significant advancements in welding technology and methodologies.

2. Methodology

2.1 Material

Aluminium alloy 6061 was selected as the workpiece material due to its widespread use in various industries, including aerospace and structural applications. The workpieces will be prepared with dimensions of 120mm × 120mm × 6mm to ensure uniformity in the experimental setup. These dimensions were chosen to facilitate a controlled investigation into the effects of assisted cooling in friction stir welding while maintaining consistency in weld quality assessment. The chemical composition is provided in Table 1, and the mechanical properties of the base metal (BM) are presented in Table 2.

Table 1
The chemical composition of base metal

Components	Si	Fe	Cu	Mn	Mg	Cr	Zn	Al
wt%	0.6	0.5	0.3	0.15	1.0	0.2	0.2	Bal

Table 2
Mechanical Properties of base metal

UTS (MPa)	Elongation (%)	Hardness (HV)
310	12%	95-107

2.2 Welding Parameters

This welding process was performed using an FSW machine. Before starting the process, several sets of parameters were determined after conducting a detailed study of the appropriate process parameters. The parameters included tool-rotating speed (spindle speed), coolant composition, and liquid flow rate. The spindle speed was set at three different values: 1400, 1150, and 900 rpm. These values were selected based on previous research by Mamgain *et al.,* [27] which indicated that the optimal rotational speed for achieving high tensile strength ranged for joining Aluminium Alloy that are between 800–1700 rpm. The coolant composition was varied in three different ratios of coolant to water that are 1:0, 7:3, and 1:1. While the cooling flow rate used in this experiment was set at 10, 20, and 30 mL/min. These parameters are a pilot study since there are very few researchers exploring this approach. The lubricant used in the experiment was ECOCOOL 700 NBF, a machine coolant. This coolant is used because it is the most common coolant in machining. Table 3 below presents the experimental sets and their corresponding parameters.

Table 3
Welding parameter sets

Experiment No.	Parameters		
	Tool Rotation Speed (RPM)	Coolant Composition (Coolant: Water)	Coolant Flow Rate (mL/min)
1	1400	1: 0	10
2	1150	7: 3	20
3	900	1: 1	30

2.3 Method and Experimental Procedures
2.3.1 Cooling system setup

To start the experiment, the necessary equipment for welding, mist spraying, and measuring weld responses was set up. The jig specifically designed for conducting FSW experiments was securely clamped onto the platform inside the machine. Proper clamping of the jig was essential to prevent unwanted vibrations that could lead to tool breakage or defects in the welding material. Next, the mist-spraying tube was attached to the machine, positioning its nozzle directly behind the FSW tool to spray mist onto the finished weldment path. A machine coolant source was connected to its valve to enable mist spraying. During this process, the air pressure was measured and maintained at 6 bar. Once the air pressure was properly adjusted, the welding plates were securely clamped onto the jig. Ensuring the plates were tightly secured was crucial to preventing vibrations that could not only damage the tools and plates but also introduce welding defects. The final step involved measuring the liquid flow rate using a beaker, with different flow rates recorded for each experimental setup. The joining process was conducted in a butt configuration using a CNC FSW machine as shown in Figure 1. The welding process was initiated from left to right along the joint line. The FSW tool was made from H13 tool steel, featuring a tapered profile with three flats and a threaded pin of 4 mm length, which was utilized throughout the experiments.

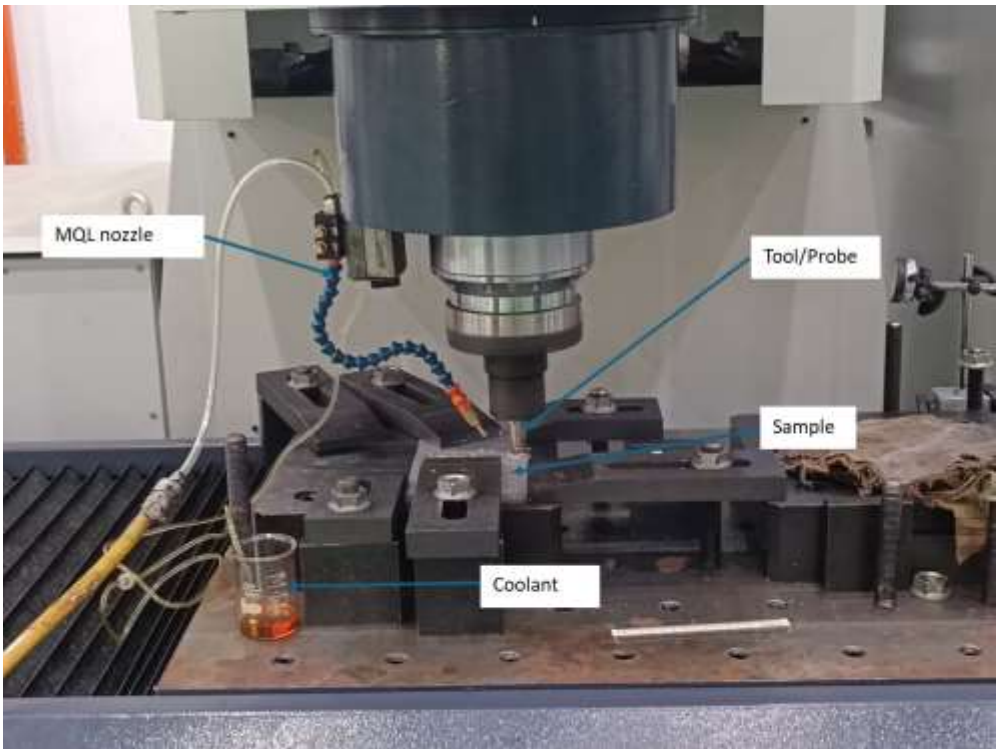


Fig. 1. Cooling system setup

The welding experiments were conducted using the previously mentioned parameters. A total of three parameters; tool rotation speed, coolant composition, and liquid flow rate were utilized in the experiment. Before starting the actual experiment, welding trials were conducted as a pilot test and served as reference plates without using coolant. These trials were performed to ensure that proper welding joints would form. If defects appeared on the workpieces during this phase, the test rig was adjusted to achieve the desired welding results. These trials also functioned as benchmarks for comparison with the actual welding experiments. The results obtained during the actual experiment were compared side by side with the trial welds to determine which welding conditions produced superior outcomes. In the experiment, one welding trial was conducted as a reference for the actual experiment. These trials helped in identifying welding defects and observing the welding process when mist cooling was introduced into the experiment.

2.3.2 Mechanical testing

Two mechanical tests were conducted to evaluate the mechanical properties of the welded joints in this experiment. Since the FSW experiments involved spraying different quantities of mist, it was essential to determine whether the cooling effect contributed to improved weld quality. The mechanical tests performed on the welded joints included tensile strength and hardness tests to assess the overall strength and durability of the welds.

2.3.2.1 Tensile testing

To perform this test, the welded joint specimens were prepared according to the American Society for Testing and Materials (ASTM) E8 standard test method for tensile testing as shown in Figure 2. The specimens followed a standardized dog bone design, which featured two shoulders and a gauge section in between. The shoulders had a larger cross-section to ensure a better grip during testing, while the gauge section had a smaller cross-section to allow for controlled deformation and failure. The specimens maintained a thickness of 6 mm. The workpieces were cut and shaped into the dog bone design using a CNC machine. Tensile tests were then conducted at room temperature with a crosshead speed of 1 mm/min. The tensile testing was performed using a Shimadzu AGS-X Universal Testing Machine, which has a maximum load capacity of 100 kN.

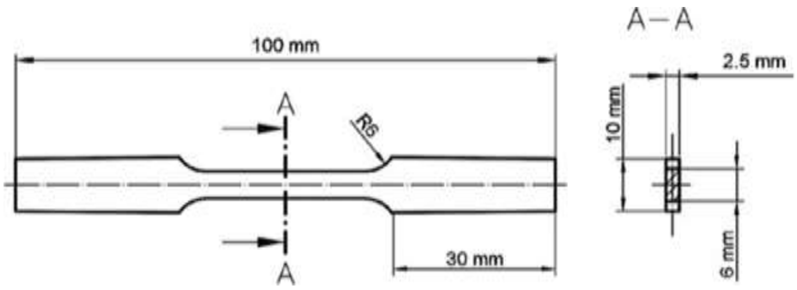


Fig. 2. Dimension of the dog bone according to the ASTM E8

2.3.2.2 Microhardness testing

The American Society for Testing and Materials (ASTM) standard guide was used to conduct this test. The guide required a simple test method, E384, with a load of 300 gram-force using a Vickers hardness indenter (gf). The experiment was carried out at room temperature. Figure 4 shows the Hardness Testing Machine model FV-100S, which was used for this test. Hardness tests were performed to evaluate the material's resistance to deformation. The test involved penetrating a diamond indenter at the desired load to create an indentation on the surface. For fastening method, the microhardness check was usually conducted on the cross section of the plate. This cross-section included the stir zone of the weld joint, the heat-affected zone, and the base metal. Performing this test on the welded specimen helped determine the joint's ability to resist deformation. A higher hardness value indicated a higher-quality welding joint. In this study, the microhardness test was conducted for each experimental set, with hardness values measured at 20 points along the center area of the cross-section.

2.4 Design of Experiment (DOE)

The Taguchi method was identified as a structured and systematic approach in the design of experiments (DOE) to optimize processes and improve quality by analyzing a strategic subset of possible component level combinations. Unlike the full factorial technique, which examines every possible combination, the Taguchi method employs orthogonal arrays to study a representative sample of the experimental space, significantly reducing the number of experiments required. This approach allows researchers to determine the primary effects of factors and their interactions by systematically examining selected combinations. For example, using two factors (A and B) with two levels each (Low and High), the Taguchi method strategically selects pairings such as (Low A, Low B), (Low A, High B), (High A, Low B), and (High A, High B) to efficiently evaluate the impact on the response variable. This method effectively reveals the influence of various factors on the response variable, both independently and interactively, helping researchers determine optimal conditions to achieve the desired outcomes.

The Taguchi method is a powerful tool for analyzing complex systems with multiple interacting variables, aiding in decision-making, improving quality standards, and optimizing workflows while minimizing experimental effort and cost. In this study, three factors were considered: tool rotation speed, coolant composition, and coolant flow rate as shown in Table 4. Each factor had three levels, making the L9 orthogonal array the most suitable choice for this experiment. The L9 array is specifically designed for experiments involving three factors at three levels each. Following the experiment, statistical methods were applied to analyze the results using Minitab software. The signal-to-noise (S/N) ratio was then calculated for each experiment. The S/N ratio helps determine the robustness of the parameters and identify the optimal parameter settings. The S/N ratio can be calculated using the following Larger-the-Better formula:

$$\text{S/N Ratio} = -10 \log \left(\frac{1}{n}\sum_{i=0}^{n}\frac{1}{yi^2}\right) \quad (1)$$

Table 4
The list of experiments by using Taguchi Method

Experiment no.	Tool rotation speed (rpm)	Coolant composition (Coolant: Water)	Coolant flow rate (mL/min)
1	1400	1:0	10
2	1400	7:3	20
3	1400	1:1	30
4	1150	1:0	20
5	1150	7:3	30
6	1150	1:1	10
7	900	1:0	30
8	900	7:3	10
9	900	1:1	20

3. Results

3.1 Tensile Test Result

The results from the tensile strength testing of friction stir welded joints under different assisted cooling conditions are presented and analyzed. This analysis evaluates the effects of tool rotation speed, coolant composition, and coolant flow rate on the ultimate tensile strength (UTS), strain, and fracture characteristics. The findings provide valuable insights into optimizing cooling-assisted FSW to achieve enhanced mechanical properties. The tensile test results for the welded samples under various cooling conditions are summarized in Table 5. Key mechanical properties, including ultimate tensile strength (UTS), maximum strain, break stress, and break strain, are analyzed to assess the impact of assisted cooling on weld performance. Figure 3 presents a graph of UTS (MPa) and Break Strain/Elongation (%) under different cooling conditions, providing a visual representation of the effects of cooling parameters on weld strength and ductility

Table 5
Results of tensile testing for every sample

Experiment no.	Tool rotation speed (rpm)	Coolant composition (Coolant: Water)	Coolant flow rate (mL/min)	Max stress (MPa)	Max strain (%)	Break stress (MPa)	Break strain (%)
Sample 1	1400	1:0	10	201.649	11.7971	187.500	13.9886
Sample 2	1400	(Pure Coolant)	20	197.135	12.4814	176.389	15.5743
Sample 3	1400	7:3	30	189.149	12.9457	165.972	16.9086
Sample 4	1150	1:1	20	189.149	13.5371	170.747	17.0971
Sample 5	1150	1:0	30	206.684	13.2600	189.583	16.0629
Sample 6	1150	(Pure Coolant)	10	164.410	12.3543	146.875	13.5371
Sample 7	900	7:3	30	159.462	11.7229	143.316	14.7286
Sample 8	900	1:1	10	132.205	7.41429	123.958	8.11714
Sample 9	900	1:0	20	104.948	7.47571	89.3229	8.38000
Parent Material	1000	(Pure Coolant)	0	172.917	10.9257	154.080	15.0657
Optimized Sample	1150	7:3	10	213.976	13.3914	185.503	15.8343

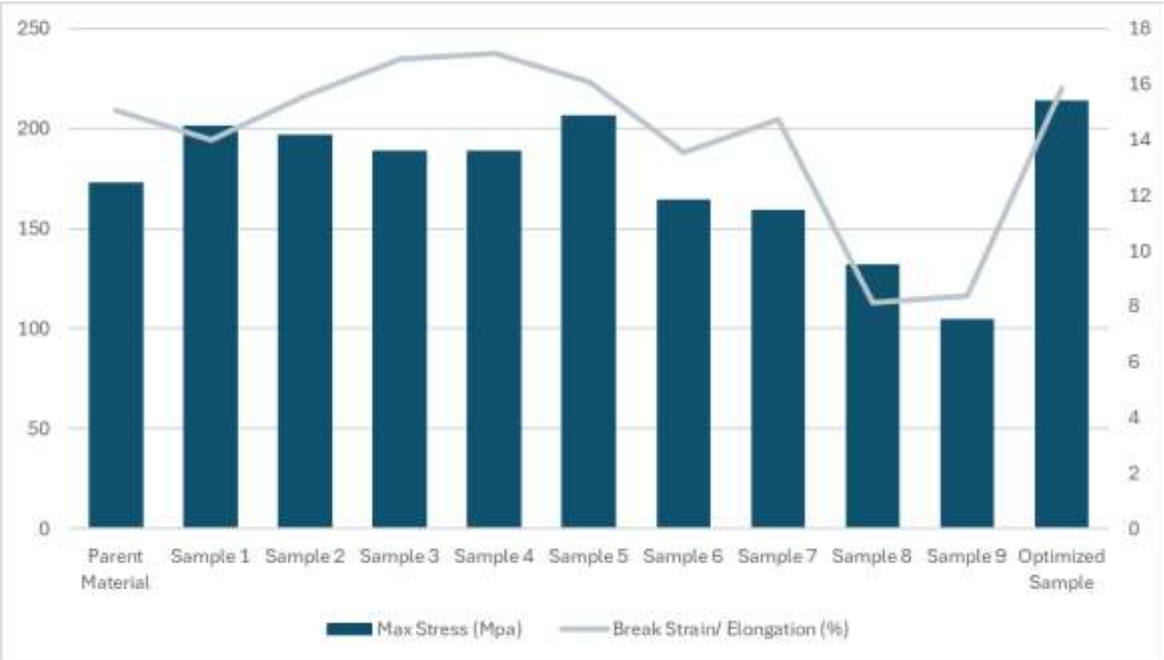


Fig. 3. Graph UTS (MPa) and and Break Strain/Elongation (%)

The experimental results indicate that cooling conditions, including tool rotation speed, coolant composition, and coolant flow rate, significantly influence the ultimate tensile strength (UTS) of friction stir welded joints. Properly optimized cooling enhances mechanical performance by refining grain structure, reducing residual stresses, and preventing excessive thermal softening. However, excessive or insufficient cooling can negatively impact weld integrity, leading to poor tensile strength. Tool rotation speed played a crucial role in determining heat input and weld strength. From Figure 4.1, the highest UTS (206.684 MPa) among the main samples was recorded at 1150 rpm (Sample 5, 7:3 coolant-water, 30 mL/min), while the lowest UTS (104.948 MPa) was observed at 900 rpm (Sample 9, 1:1 coolant-water, 20 mL/min). Moderate rotation speeds (1150 rpm) provided the best balance between frictional heat generation and cooling, promoting better material flow and grain refinement. At higher speeds (1400 rpm, Sample 1-3), the UTS values were slightly lower than at 1150 rpm, likely due to excessive heat input leading to grain coarsening. Conversely, at lower speeds (900 rpm, Sample 7-9), inadequate heat generation resulted in weak material bonding and increased defects, reducing UTS. The Parent material (1000 rpm, no coolant, UTS = 172.917 MPa) performed better than overcooled samples but underperformed compared to optimally cooled samples, indicating that moderate cooling enhances weld strength but must be carefully controlled.

Coolant composition significantly affected heat dissipation and tensile properties. The highest UTS values were obtained with a 7:3 coolant-water ratio, particularly in Sample 5 (206.684 MPa) and Sample 2 (197.135 MPa), demonstrating that controlled cooling prevents overheating while allowing sufficient heat for proper grain growth. In contrast, the 1:1 coolant-water ratio led to lower UTS values (Sample 3, 6, and 9), suggesting that excessive cooling causes rapid heat loss, increasing internal stresses and promoting a brittle microstructure. Pure coolant (1:0) produced moderate tensile strength values, with Sample 1 (201.649 MPa) performing better than Sample 7 (159.462 MPa), indicating that pure coolant is more effective at higher rotation speeds but less effective at lower speeds, where heat input is already minimal. Compared to the Parent material (172.917 MPa UTS, no coolant), overcooled samples with a 1:1 coolant ratio exhibited weaker mechanical properties, confirming that excessive cooling is detrimental to weld integrity.

Coolant flow rate also played a significant role in weld strength. A low flow rate (10 mL/min) preserved heat input, enhancing weld quality, as seen in Sample 1 (201.649 MPa UTS). Moderate flow rates (20–30 mL/min) produced the best mechanical performance, particularly in Sample 5 (206.684 MPa, 7:3, 30 mL/min), where controlled cooling allowed optimal material flow and grain refinement. However, at high flow rates (30 mL/min), UTS values dropped significantly, as seen in Sample 9 (104.948 MPa, 900 rpm, 1:1, 20 mL/min), where excessive cooling disrupted heat retention, leading to poor fusion and increased microstructural defects. The Parent material (1000 rpm, no coolant, 172.917 MPa UTS) further supports these findings, as it outperformed overcooled samples but underperformed compared to moderately cooled samples, reinforcing the importance of controlled coolant flow rates for enhancing tensile strength. A notable result was obtained from the optimized sample (1150 rpm, 1:0 pure coolant, 10 mL/min), which achieved the highest UTS of 213.976 MPa, surpassing all other samples. This confirms that pure coolant at a low flow rate combined with a moderate rotation speed provides an optimal balance between heat dissipation and grain refinement, leading to superior weld strength. The optimized parameters minimized thermal softening while maintaining adequate heat for strong material bonding, making it the best-performing configuration in this study.

Overall, the results confirm that optimizing cooling conditions in friction stir welding is essential for achieving high tensile strength. The best mechanical properties were obtained at 1150 rpm with a 7:3 coolant-water ratio and a coolant flow rate of 30 mL/min, demonstrating that moderate cooling effectively balances heat dissipation and material flow, resulting in superior weld quality. However, the optimized sample (1150 rpm, 1:0 pure coolant, 10 mL/min, UTS = 213.976 MPa) outperformed all other samples, suggesting that fine-tuned cooling strategies can further improve weld strength. In contrast, excessive cooling, particularly with high water content and high flow rates, led to weakened joints due to rapid heat loss and increased brittleness. The Parent material provided an intermediate performance, highlighting that while cooling-assisted FSW can enhance mechanical properties, improper cooling conditions can degrade weld strength.

3.1.1 Influence of cooling on ductility (strain at maximum stress and break strain)

Ductility, represented by strain at maximum stress and break strain, is a crucial mechanical property that reflects a material’s ability to deform before failure. The experimental results indicate that cooling conditions, including tool rotation speed, coolant composition, and coolant flow rate, significantly influence the ductility of friction stir welded joints. Optimized cooling enhances ductility by promoting grain refinement and reducing internal stresses, whereas excessive cooling can lead to embrittlement, increasing the likelihood of brittle fracture. The highest strain at maximum stress from Table 4.1 was recorded in Sample 4 (1150 rpm, 1:0, 20 mL/min, 13.5371%), followed closely by Sample 5 (1150 rpm, 7:3, 30 mL/min, 13.2600%). These results suggest that moderate cooling allows sufficient heat retention, enabling grain growth control and better plastic deformation capacity. On the other hand, the lowest strain at maximum stress was observed in Sample 9 (900 rpm, 1:1, 20 mL/min, 7.47571%), confirming that excessive cooling, combined with insufficient heat generation, limits plasticity and increases material brittleness. The optimized sample (1150 rpm, 1:0 pure coolant, 10 mL/min) recorded a strain at maximum stress of 13.3914%, closely matching the highest values, further reinforcing that controlled cooling enhances ductility.

Similarly, break strain values followed a similar trend, with Sample 4 (17.0971%) and Sample 3 (16.9086%) exhibiting the highest ductility at failure, suggesting that moderate heat input combined with controlled cooling results in an optimal microstructure that enhances plastic deformation before fracture. In contrast, the lowest break strain values were recorded in Sample 9 (8.38000%) and Sample 8 (8.11714%), indicating that rapid cooling and reduced heat input increased internal stresses, causing premature fracture. The optimized sample exhibited a break strain of 15.8343%, outperforming the Parent material and further confirming that proper cooling enhances ductility without excessive embrittlement. The Parent material (1000 rpm, no coolant, strain at max stress = 10.9257%, break strain = 15.0657%) provides a key benchmark for assessing cooling effects. Compared to highly cooled samples such as Sample 9, the Parent material exhibited significantly better ductility, confirming that excessive cooling reduces strain capacity and promotes early failure. However, compared to optimally cooled samples (Sample 3, 4, 5, and the optimized sample), the Parent material had slightly lower strain values, suggesting that controlled cooling can enhance ductility by refining grain structure and preventing excessive hardening.

Overall, these findings confirm that ductility in FSW joints is highly dependent on the balance between heat input and cooling rate. The best ductility was observed at moderate tool rotation speeds (1150 rpm), controlled coolant compositions (7:3 or 1:0), and moderate coolant flow rates (20–30 mL/min), which provided an ideal thermal cycle for plastic deformation. The optimized sample (1150 rpm, 1:0 pure coolant, 10 mL/min) exhibited a well-balanced ductility profile, with a strain at max stress of 13.3914% and a break strain of 15.8343%, making it one of the best-performing configurations. While cooling can significantly improve the tensile strength of FSW joints, excessive or overly aggressive cooling may lead to undesirable effects, particularly in terms of reduced ductility. When heat is removed quickly, it can create uneven temperature gradients and interfere with the natural grain refinement process that occurs during welding. In some alloys, this may cause the formation of brittle phases or promote over-aging of strengthening precipitates, ultimately making the weld more prune to cracking or early failure. Excessive cooling can also limit the extent of dynamic recrystallization, leaving behind a coarser microstructure than desired. So, while cooling is important, it’s intensity must be carefully controlled to maintain a favourable combination of strength and ductility in FSW joints.

3.2 Hardness Test Result

The hardness testing results provide valuable insights into the relationship between cooling rates, heat input, and the resulting microstructural features. A detailed comparison of the hardness values in each zone across different experiments enables a comprehensive understanding of how variations in welding parameters affect the overall integrity of the weld. The following section presents the findings from the hardness testing and discusses the influence of tool rotation speed, coolant composition, and coolant flow rate on the mechanical properties of friction stir welded joints, as summarized in Table 6 and Figure 4.

Table 6
Results of hardness testing for every sample

Experiment no.	Tool rotation speed (rpm)	Coolant composition (Coolant: Water)	Coolant flow rate (mL/min)	Hardness stir zone (HV)	Hardness HAZ (HV)	Hardness base material (HV)
Sample 1	1400	1:0	10	70.27	63.49	81.58
Sample 2	1400	(Pure Coolant)	20	70.01	56.47	81.00
Sample 3	1400	7:3	30	60.59	56.74	88.69
Sample 4	1150	1:1	20	86.04	77.68	91.3
Sample 5	1150	1:0	30	75.72	74.29	97.89
Sample 6	1150	(Pure Coolant)	10	66.07	60.78	99.16
Sample 7	900	7:3	30	84.63	70.21	98.33
Sample 8	900	1:1	10	65.14	70.81	99.89
Sample 9	900	1:0	20	74.57	74.56	110.15
Parent material	1000	(Pure Coolant)	0	64.26	60.14	96.15
Optimized Sample	1150	7:3	10	54.33	51.64	77.42

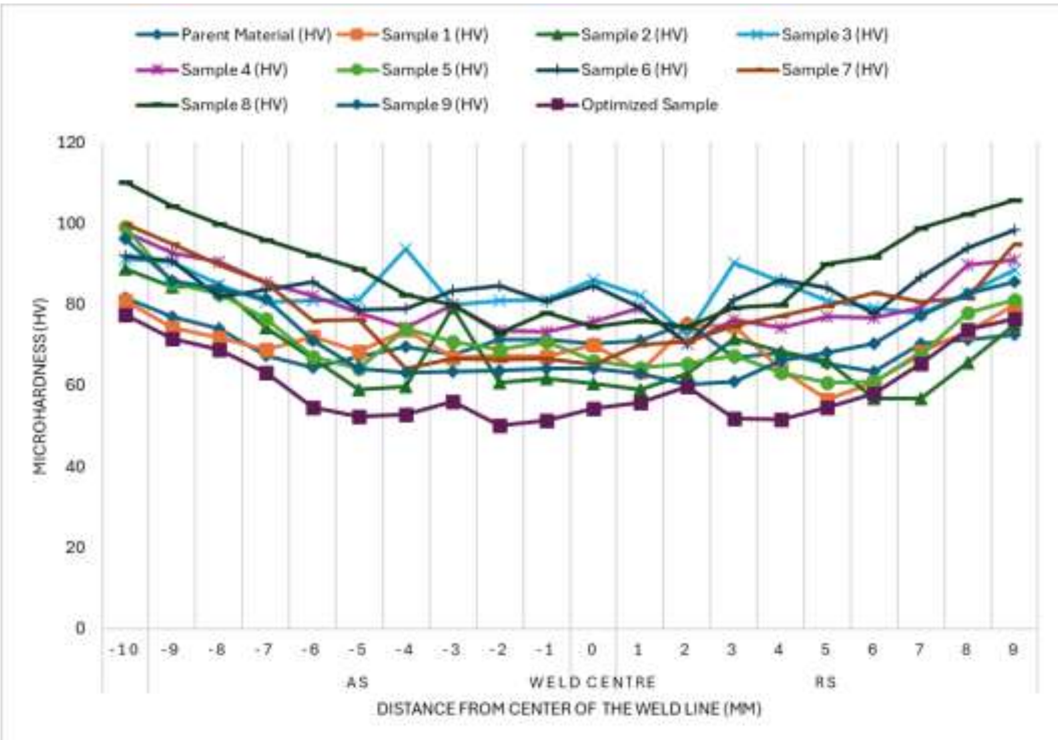


Fig. 4. Graph of microhardness (HV) vs distance from centre of the weld line

The hardness testing findings, as illustrated in Table 5 and Figure 7, highlight the influence of various welding parameters, including tool rotation speed, coolant composition, and coolant flow rate, on the mechanical properties of friction stir welded joints. The hardness was evaluated in three key regions: the stir zone, heat-affected zone (HAZ), and base material. The Parent material, which was not subjected to welding, exhibited relatively uniform hardness values of 70.27 HV in the stir zone, 63.49 HV in the HAZ, and 81.58 HV in the base material. These values serve as a benchmark for assessing the effects of different welding conditions. The graph in Figure 7 illustrates that hardness generally decreases with increasing distance from the weld centre. The stir zone typically shows the highest hardness, as it undergoes direct thermal and mechanical influence during welding. Sample 3, characterized by a tool rotation speed of 1400 rpm, a coolant composition of 1:1, and a coolant flow rate of 30 mL/min, recorded the highest stir zone hardness at 86.04 HV. This suggests that the combination of high rotation speed and coolant flow rate contributed to finer grain refinement, thereby improving the material's mechanical strength. In contrast, Sample 2 (1400 rpm, 7:3 coolant composition, 20 mL/min flow rate) exhibited a lower stir zone hardness of 60.59 HV, likely due to slower cooling from the higher water content in the coolant, which led to a coarser grain structure and reduced hardness.

In the heat-affected zone (HAZ), Sample 3 displayed a higher hardness (77.68 HV) than Sample 2 (56.47 HV), indicating that better thermal control in Sample 3 resulted in a more refined microstructure. Additionally, Sample 6 (1150 rpm, 1:1 coolant composition, 10 mL/min flow rate) showed a notably high stir zone hardness of 84.63 HV, suggesting that this parameter combination effectively improved weld hardness. Conversely, Sample 7 (900 rpm, 7:3 coolant composition, 20 mL/min flow rate) exhibited the lowest hardness values, with 65.14 HV in the stir zone and 70.81 HV in the HAZ, likely due to reduced cooling rates and lower heat input during welding. The base material hardness tended to be higher in experiments with either faster cooling or increased heat input. Sample 8 (900 rpm, 7:3 coolant composition, 20 mL/min flow rate) recorded the highest base material hardness at 110.15 HV, likely due to efficient cooling that refined the grain structure. In contrast, Sample 1 (1400 rpm, 1:0 coolant composition, 10 mL/min flow rate) exhibited a lower base material hardness of 99.16 HV, indicating that inadequate cooling negatively affected base material properties.

The Optimized Sample (1150 rpm, 1:0 coolant composition, 10 mL/min flow rate) yielded notable results. The stir zone hardness was 54.33 HV, which was lower than other samples. However, its HAZ hardness (51.64 HV) was the lowest among all experiments, while the base material hardness stood at 77.42 HV. These results suggest that although the optimized sample produced a refined microstructure in the base material, the cooling rate and heat input were insufficient in the stir zone and HAZ to achieve higher hardness. The overall trend shows that hardness decreases as the distance from the weld centre increases, which is consistent across all samples. The HAZ tends to experience reduced hardness due to thermal cycling, leading to grain coarsening and material softening. The results indicate that higher tool rotation speeds, appropriate coolant compositions, and optimal coolant flow rates improve mechanical properties in both the stir zone and HAZ. The Parent material provides a baseline for hardness in untreated material, while the welded samples exhibit variations based on cooling rate and heat input. Faster cooling rates generally lead to higher hardness values, particularly in the stir zone and base material, while slower cooling results in coarser grains and reduced hardness, particularly in the HAZ.

These findings highlight the importance of carefully controlling welding parameters, specifically tool rotation speed, coolant composition, and coolant flow rate, to enhance the hardness and overall mechanical performance of friction stir welded joints. A combination of higher rotation speeds, optimized coolant mixtures, and faster coolant flow rates yielded the highest hardness values, indicating improved material properties and a refined microstructure in the welded joints.

3.2 Statistical Analysis

The Taguchi method is widely used for optimizing process parameters by analyzing their effects on output performance using the signal-to-noise (S/N) ratio. In this study, the Larger is Better criterion was chosen because higher mechanical properties, such as tensile strength and hardness, are preferred. The analysis was conducted using Minitab software to evaluate the impact of three key parameters: Tool Rotation Speed (rpm), Coolant Composition (Coolant: Water Ratio), and Coolant Flow Rate (mL/min). Figure 5 show the Graph of Main Effects Plot above represents the influence of each factor on the mean S/N ratio. For Tool Rotation Speed, the plot shows an increase in the S/N ratio from 900 rpm to 1150 rpm, followed by a decline at 1400 rpm.

This indicates that 1150 rpm provides the best performance in terms of mechanical properties. In the case of Coolant Composition, the 7:3 ratio (0.7) yields the lowest S/N ratio, while the pure coolant (1.0) results in the highest, suggesting that using pure coolant is more beneficial. Similarly, the Coolant Flow Rate significantly affects the S/N ratio, with the highest value observed at 10 mL/min, a sharp decline at 20 mL/min, and a rise again at 30 mL/min. This trend suggests that an excessive coolant flow rate may negatively impact the mechanical properties. Figure 6 show the Response Table for S/N Ratios above provides a comparative ranking of the parameters based on their impact on mechanical properties. The Delta value, which represents the difference between the highest and lowest S/N ratio for each factor, helps determine the significance of each parameter. The Coolant Flow Rate has the highest Delta value (0.73), making it the most influential factor (Rank 1), followed by Tool Rotation Speed with a Delta value of 0.60 (Rank 2). The Coolant Composition has the least impact, with a Delta value of 0.20 (Rank 3). This ranking confirms that coolant flow rate is the most critical parameter affecting the welding quality, while coolant composition has the least influence.

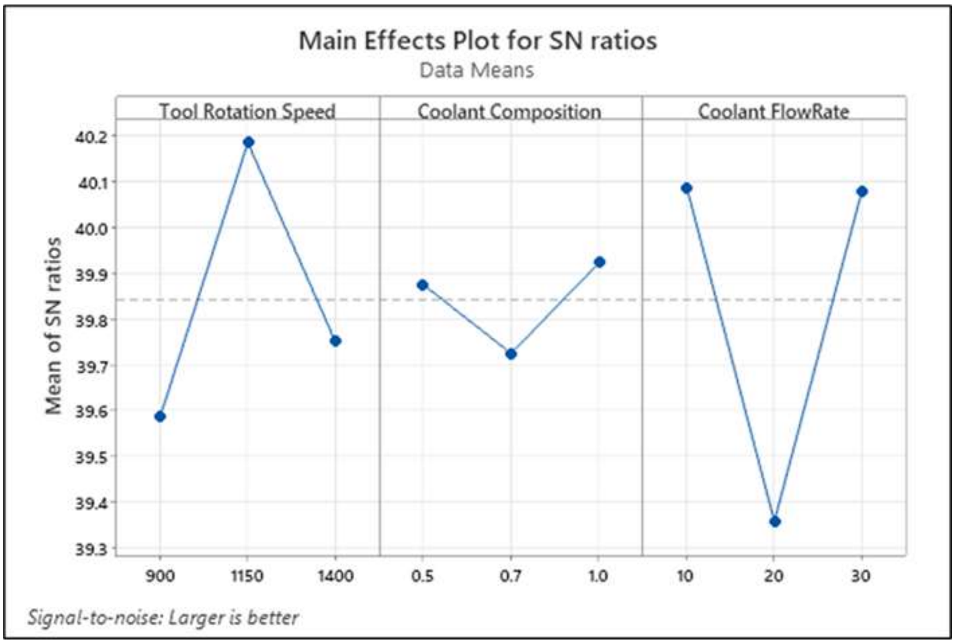


Fig. 5. 3 Graph of main effects plot for SN ratios by Minitab software

Response Table for Signal to Noise Ratios

Larger is better

Level	Tool Rotation Speed	Coolant Composition	Coolant FlowRate
1	39.59	39.88	40.09
2	40.19	39.72	39.36
3	39.75	39.92	40.08
Delta	0.60	0.20	0.73
Rank	2	3	1

Fig. 6. Response table for signal to noise ratios

Based on the Taguchi analysis, the optimal parameter combination for achieving improved mechanical properties is Tool Rotation Speed = 1150 rpm, Coolant Composition = 1.0 (pure coolant), and Coolant Flow Rate = 10 mL/min. Among the three parameters, the Coolant Flow Rate has the most significant impact on performance, followed by Tool Rotation Speed, whereas Coolant Composition has the least effect. This analysis helps in identifying the best conditions to achieve superior tensile strength, hardness, and microstructural properties in Friction Stir Welding Assisted Cooling.

3.2.1 Analysis of Variance for Tensile Testing

The Analysis of Variance (ANOVA) from the Figure 7 was conducted to assess the influence of various process parameters on tensile strength in Friction Stir Welding Assisted Cooling using the Taguchi Method. The parameters analyzed in this study included Tool Rotation Speed, Coolant Composition, and Coolant Flow Rate, with the aim of understanding how these factors impact the tensile properties of the welded joints. The ANOVA table generated by Minitab includes critical statistical values such as Degrees of Freedom (DF), Adjusted Sum of Squares (Adj SS), Adjusted Mean Squares (Adj MS), F- Value, and P-Value, which help determine the significance of each parameter.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	7902.8	2634.3	7.78	0.025
Tool Rotation Speed	1	6100.4	6100.4	18.02	0.008
Coolant Composition	1	1260.2	1260.2	3.72	0.112
Coolant FlowRate	1	542.1	542.1	1.60	0.261
Error	5	1692.5	338.5		
Total	8	9595.3			

Fig. 7. Analysis of variance for tensile testing

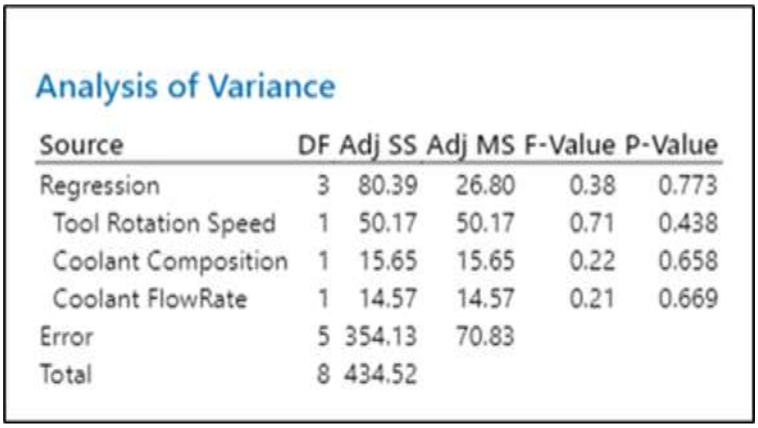
The overall regression model shows an F-value of 7.78 and a P-value of 0.025, which indicates that the model is statistically significant at the 95% confidence level. This suggests that at least one of the three factors have a significant effect on tensile strength. In terms of individual factors, Tool Rotation Speed is the most influential parameter, with the highest F-value of 18.02 and the lowest P-value of 0.008. This indicates that Tool Rotation Speed has a highly significant effect on tensile strength, contributing the most to the variation in the data, as reflected by its Sum of Squares (SS) value of 6100.4.

Coolant Composition, with an F-value of 3.72 and a P-value of 0.112, shows a moderate effect on tensile strength. However, since the P-value is greater than 0.05, it indicates that the effect of Coolant Composition is not statistically significant at the 95% confidence level. Nevertheless, it could still have some influence on the mechanical properties, albeit to a lesser degree compared to other factors. On the other hand, Coolant Flow Rate has the lowest F-value of 1.60 and the highest P-value of 0.261, suggesting that it has no statistically significant effect on tensile strength in this experiment. The Error term in the ANOVA results, which accounts for unexplained variations, has a Sum of Squares (SS) value of 1692.5, indicating that most of the variation in tensile strength is explained by the parameters under study rather than by random error.

In conclusion, the ANOVA analysis highlights that Tool Rotation Speed is the most significant parameter affecting tensile strength, with a statistically significant effect, while Coolant Composition and Coolant Flow Rate have lesser or negligible effects. This finding emphasizes the importance of optimizing Tool Rotation Speed when conducting Friction Stir Welding for enhanced tensile strength.

3.2.1 Analysis of variance for hardness testing

The Analysis of Variance (ANOVA) from the Figure 8 was performed to evaluate the influence of different process parameters on the hardness of the welded joint in Friction Stir Welding Assisted Cooling. The factors considered in this study were Tool Rotation Speed, Coolant Composition, and Coolant Flow Rate. The ANOVA results generated by Minitab include essential statistical values such as Degrees of Freedom (DF), Adjusted Sum of Squares (Adj SS), Adjusted Mean Squares (Adj MS), F-Value, and P-Value, which help determine the significance of each factor in influencing hardness.


Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	80.39	26.80	0.38	0.773
Tool Rotation Speed	1	50.17	50.17	0.71	0.438
Coolant Composition	1	15.65	15.65	0.22	0.658
Coolant FlowRate	1	14.57	14.57	0.21	0.669
Error	5	354.13	70.83		
Total	8	434.52			

Fig. 8. Analysis of variance for tensile testing

The overall regression model has an F-value of 0.38 and a P-value of 0.773, which is greater than 0.05. This indicates that the selected process parameters do not have a statistically significant effect on hardness at the 95% confidence level. This suggests that variations in Tool Rotation Speed, Coolant Composition, and Coolant Flow Rate do not play a dominant role in determining the hardness of the welded joint under the experimental conditions used in this study. Among the individual parameters, Tool Rotation Speed has the highest F-value of 0.71 and a P-value of 0.438, which is still much higher than 0.05, indicating that its effect is not statistically significant. Similarly, Coolant Composition has an F-value of 0.22 and a P- value of 0.658, while Coolant Flow Rate has an F-value of 0.21 and a P-value of 0.669, both of which confirm that these parameters do not significantly impact hardness. The error term has a Sum of Squares (SS) value of 354.13, which is considerably high compared to the regression sum of squares (80.39). This suggests that most of the variation in hardness is due to uncontrolled factors or noise rather than the selected process parameters.

Based on this ANOVA analysis, Tool Rotation Speed, Coolant Composition, and Coolant Flow Rate do not have a statistically significant impact on hardness in Friction Stir Welding Assisted Cooling. The high error variance suggests that other factors, such as material properties, tool design, or additional process conditions, may play a more dominant role in affecting hardness. These findings indicate that optimizing these parameters alone may not lead to a substantial improvement in hardness, and further investigation may be required to identify additional influential factors.

3.3 Applicability of The Findings in Real-World Industrial Settings

The findings on cooling methods in FSW present valuable opportunities for industries aiming to enhance joint performance, particularly in sectors such as aerospace, automotive, and marine, where high-strength lightweight material like aluminium alloys is commonly used. Integrating controlled cooling such as MQL can lead to significant improvements in tensile strength, while maintaining acceptable level of ductility. These methods are especially attractive due to their cost effectiveness, environmental advantages, and compatibility with automation, making them suitable for high throughput manufacturing environments.

However, implementing these methods on a large scale is not without challenges. The setup and calibration of cooling systems require precise control over coolant flow rate, direction, and timing to avoid issues such as thermal shock or excessive grain hardening. Additionally, retrofitting existing FSW equipment with cooling modules may involve modifications to the machine design, added maintenance requirements, and operator training. There is also a need to carefully select the cooling medium based on the material being welded and the desired mechanical properties. Therefore, while the benefits are promising, industrial adoption must be approached strategically, with consideration for both performance gains and operational feasibility.

4. Conclusions

This study successfully met its objective of evaluating the effects of assisted MQL cooling using the machine coolant on the mechanical properties of friction stir welded (FSW) joints. The findings demonstrated that integrating cooling techniques significantly impacts weld quality by enhancing tensile strength and increasing hardness. The experimental results confirmed that controlled coolant flow and composition are critical in optimizing the mechanical performance of aluminium welds. Tensile testing results indicated that the highest tensile strength was achieved at a tool rotation speed of 1150 rpm with a coolant flow rate of 30 mL/min, representing a 19.53% improvement compared to the Parent material without cooling. Similarly, microhardness testing revealed that samples subjected to assisted cooling exhibited higher hardness values, with the most favourable results observed at a coolant composition of 1:1 and a flow rate of 30 mL/min. These findings highlight the effectiveness of assisted cooling in friction stir welding by minimizing excessive heat accumulation and improving mechanical performance. This study provides valuable insights for optimizing FSW parameters in industrial applications, particularly in sectors that require high-strength aluminium welds. Building upon the current findings, future research should focus on optimizing cooling parameters such as flow rate, nozzle positioning, and coolant composition for specific material types and joint configurations. There is considerable potential in exploring hybrid cooling techniques, particularly the combination of Minimum Quantity Lubrication (MQL) with conventional machine coolants or gas-based systems. Additionally, real-time thermal monitoring and numerical simulations could help refine process control and predict outcomes more accurately. Long-term studies on fatigue behaviour, corrosion resistance, and microstructural stability under varying cooling conditions would also provide valuable insights for industries seeking durable and high-performance welds. Encouraging collaboration between academia and industry can accelerate these advancements, paving the way for more efficient, and application specific cooling methods in FSW.

Acknowledgement
Authors would like to thank Universiti Teknikal Malaysia Melaka (UTeM) for financial support under the research grant of FRGS/1/2023/TK10/UTEM/02/3 and UTeM Kesidang Scholarship.

References

[1] da Cunha, Pedro Henrique Costa Pereira, Guilherme Vieira Braga Lemos, Luciano Bergmann, Afonso Reguly, Jorge Fernandez dos Santos, Ricardo Reppold Marinho, and Marcelo Torres Piza Paes. "Effect of welding speed on friction stir welds of GL E36 shipbuilding steel." Journal of Materials Research and Technology 8, no. 1 (2019): 1041-1051. https://doi.org/10.1016/j.jmrt.2018.07.014

[2] Karmakar, Souvik, Rishabh Swarnkar, and Surjya Kanta Pal. "A novel zero tool defect accelerated friction stir thin sheet welding technique for automotive light-weight structural component fabrication with dissimilar material." Materials Chemistry and Physics 316 (2024): 129075. https://doi.org/10.1016/j.matchemphys.2024.129075

[3] Anandan, B., and M. Manikandan. "Effect of welding speeds on the metallurgical and mechanical property characterization of friction stir welding between dissimilar aerospace grade 7050 T7651-2014A T6 aluminium alloys." Materials Today Communications 35 (2023): 106246. https://doi.org/10.1016/j.mtcomm.2023.106246

[4] Zhang, Huijing, Baosong Guo, Wenbo Du, Xinyue Cong, and Chao Chen. "Study on the weld formation, microstructure and mechanical properties of AZ31B Mg alloy in AC/DC mixed gas tungsten arc welding process." Journal of Materials Research and Technology 18 (2022): 3664-3672. https://doi.org/10.1016/j.jmrt.2022.04.065

[5] Braun, Moritz, Jan Schubnell, Ardeshir Sarmast, Harihara Subramanian, Lutz Reissig, Felix Altenhöner, Shahram Sheikhi, Finn Renken, and Sören Ehlers. "Mechanical behavior of additively and conventionally manufactured 316L stainless steel plates joined by gas metal arc welding." Journal of materials research and technology 24 (2023): 1692-1705. https://doi.org/10.1016/j.jmrt.2023.03.080

[6] Shrivastava, Amber, Manuela Krones, and Frank E. Pfefferkorn. "Comparison of energy consumption and environmental impact of friction stir welding and gas metal arc welding for aluminum." CIRP Journal of Manufacturing Science and Technology 9 (2015): 159-168. https://doi.org/10.1016/j.cirpj.2014.10.001

[7] Sproesser, Gunther, Sebastian Schenker, Andreas Pittner, Ralf Borndörfer, Michael Rethmeier, Ya-Ju Chang, and Matthias Finkbeiner. "Sustainable welding process selection based on weight space partitions." Procedia CIRP 40 (2016): 127-132. https://doi.org/10.1016/j.procir.2016.01.077

[8] Sued, M. K., S. S. M. Samsuri, M. K. A. M. Kassim, and S. N. N. M. Nasir. "Sustainability of welding process through bobbin friction stir welding." In IOP Conference Series: Materials Science and Engineering, vol. 318, no. 1, p. 012068. IOP Publishing, 2018. https://doi.org/10.1088/1757-899X/318/1/012068

[9] Li, W. Y., T. Fu, L. Hütsch, J. Hilgert, F. F. Wang, J. F. Dos Santos, and N. Huber. "Effects of tool rotational and welding speed on microstructure and mechanical properties of bobbin-tool friction-stir welded Mg AZ31." Materials & Design 64 (2014): 714-720. https://doi.org/10.1016/j.matdes.2014.07.023

[10] Dashatan, Saeid Hoseinpour, Taher Azdast, Samrand Rash Ahmadi, and Arvin Bagheri. "Friction stir spot welding of dissimilar polymethyl methacrylate and acrylonitrile butadiene styrene sheets." Materials & design 45 (2013): 135-141. https://doi.org/10.1016/j.matdes.2012.08.071

[11] Jadav, Harshadkumar H., Vishvesh Badheka, Daulat Kumar Sharma, and Gautam Upadhyay. "Effect of pin diameter and different cooling media on friction stir welding of dissimilar Al-Mg alloys." Materials Today: Proceedings 42 (2021): 362-369. https://doi.org/10.1016/j.matpr.2020.09.553

[12] Alimadadi, Mehrshad, Mahdi Mahmoudiniya, Massoud Goodarzi, and S. M. A. Boutorabi. "Effect of tool transverse speed and pin offset on the properties of friction stir welding Al6061-St52 dissimilar joint." Journal of Advanced Joining Processes 5 (2022): 100116. https://doi.org/10.1016/j.jajp.2022.100116

[13] Uday, K. N., and G. Rajamurugan. "Influence of tool rotational and transverse speed on friction stir welding of dissimilar aluminum 6061 composites." Materials Letters 329 (2022): 133182. https://doi.org/10.1016/j.matlet.2022.133182
[14] Jia, Hepeng, Kai Wu, Yu Sun, Fengfeng Hu, and Gang Chen. "Evaluation of axial force, tool torque and weld quality of friction stir welded dissimilar 6061/5083 aluminum alloys." CIRP Journal of Manufacturing Science and Technology 37 (2022): 267-277. https://doi.org/10.1016/j.cirpj.2022.02.003
[15] Ogunsemi, B. T., T. E. Abioye, T. I. Ogedengbe, and H. Zuhailawati. "A review of various improvement strategies for joint quality of AA 6061-T6 friction stir weldments." Journal of Materials Research and Technology 11 (2021): 1061-1089. https://doi.org/10.1016/j.jmrt.2021.01.070
[16] Chen, Y. C., and K. Nakata. "Microstructural characterization and mechanical properties in friction stir welding of aluminum and titanium dissimilar alloys." Materials & Design 30, no. 3 (2009): 469-474. https://doi.org/10.1016/j.matdes.2008.06.008
[17] Yaghoubi, Mohammad Amin, Nozar Anjabin, Hosein Eslamian, and Yousef Mazaheri. "Corrosion behavior of AA2024/pure copper bimetal manufactured by friction stir welding with a hybrid zinc-graphite interlayer." Journal of Materials Research and Technology 31 (2024): 935-956. https://doi.org/10.1016/j.jmrt.2024.06.067
[18] Gao, Fuyang, Yufan Guo, Wei Yu, Peng Jiang, and Zhiqian Liao. "Microstructure evolution of friction stir welding of Ti6321 titanium alloy based on the weld temperature below microstructure transformation temperature." Materials Characterization 177 (2021): 111121. https://doi.org/10.1016/j.matchar.2021.111121
[19] Nie, Lin, Yunxin Wu, and Diqiu He. "A novel slip rate model for determining the interfacial contact state in friction stir welding." Journal of Materials Research and Technology 29 (2024): 2293-2305. https://doi.org/10.1016/j.jmrt.2024.01.253
[20] Huang, Guoqiang, Jie Wu, and Yifu Shen. "A strategy for improving the mechanical properties of FSWed joints of non-heat-treatable Al alloys through a combination of water cooling and particle addition." Journal of Manufacturing Processes 34 (2018): 667-677. https://doi.org/10.1016/j.jmapro.2018.07.014
[21] Bocchi, Sara, Gianluca D’Urso, Claudio Giardini, and Giancarlo Maccarini. "Effects of cooling conditions on microstructure and mechanical properties of friction stir welded butt joints of different aluminum alloys." Applied Sciences 9, no. 23 (2019): 5069. https://doi.org/10.3390/app9235069
[22] Behtaripour, Esmat, Hamid Reza Jafarian, Seyed Hossein Seyedein, Nokeun Park, and Ali Reza Eivani. "Impact of in-process cooling and tool rotation speed on the mechanical and microstructural characteristics of friction stir processed AA2024." Journal of Materials Research and Technology 30 (2024): 5842-5854. https://doi.org/10.1016/j.jmrt.2024.05.006
[23] Aghajani Derazkola, Hamed, Eduardo García, Arameh Eyvazian, and Mohammad Aberoumand. "Effects of rapid cooling on properties of aluminum-steel friction stir welded joint." Materials 14, no. 4 (2021): 908. https://doi.org/10.3390/ma14040908
[24] Cho, Jae-Hyung, Sang Ho Han, and Chang Gil Lee. "Cooling effect on microstructure and mechanical properties during friction stir welding of Al-Mg-Si aluminum alloys." Materials Letters 180 (2016): 157-161. https://doi.org/10.1016/j.matlet.2016.05.157
[25] Al-Wajidi, Wisam, Ibrahim Deiab, Fantahun M. Defersha, and Abdallah Elsayed. "Effect of MQL on the microstructure and strength of friction stir welded 6061 Al alloy." The International Journal of Advanced Manufacturing Technology 101 (2019): 901-912. https://doi.org/10.1007/s00170-018-2957-y
[26] Wang, Jian, Ke Yang, Yang Zhang, Ya-lin Lu, Zhi-hao Bai, and Xing-cheng Li. "Investigation on variations of microstructures and mechanical properties along thickness direction of friction stir processed AA2014 aluminum alloy via ultra-rapid cooling." Materials Characterization 179 (2021): 111352. https://doi.org/10.1016/j.matchar.2021.111352
[27] Mamgain, Aditya, Vivek Singh, and A. Pratap Singh. "Influence of welding parameters on mechanical property during friction stir welded joint on aluminium alloys: a review." J. Kejuruter 35, no. 1 (2023): 13-28. https://doi.org/10.17576/jkukm-2023-35(1)-02