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Improvement of Hardness on Butt Weld Joints Aluminium Alloy AA 6061 Using the Underwater Friction Stir Weld (UFSW) Method

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ABSTRACT

This study reveals the hardness improvement resulting from Underwater Friction Stir Welding (UFSW) on the butt joint method AA 6061. Underwater welding introduces complexity to the joint's hardness due to the presence of water, which affects the welding process and the quality of the joint formed. The objective of the UFSW study is to explore potential advantages in the aquatic environment, primarily to obtain the optimal machine tilt angle. The study used a conventional milling machine with various spindle speeds, feed rates, and tilt angles to get the best combination of parameters. The spindle speed of 750 rpm, welding speed of 20 mm/min, and machine head angle of 2° recorded show the Brinell hardness (HRB) of UFSW to be 98.8% better than Friction Stir Welding (FSW) on various parameters. This study revealed that a machine tilt angle of 2° increased the hardness of UFSW welding. The

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results show that UFSW can increase HRB through proper head tilt angle, which is even better than the existing method, which is FSW.

Keywords: *UFSW; Tilt Angle; Spindle Speed; Welding Speed; Brinell Hardness*

Introduction

The enhancement of hardness in butt weld joints of aluminium alloy AA 6061 using the Underwater Friction Stir Welding (UFSW) method addresses a critical challenge in welding aluminium alloys. AA 6061 is widely used in the marine, aerospace, and automotive industries due to its favourable strength-to-weight ratio and corrosion resistance. Basically, the conventional method of Friction Stir Welding (FSW), operating at temperatures below the melting point, offers advantages such as high-quality, solid-state joints with minimal distortion and is particularly well-suited for challenging materials like high-strength. Its environmentally friendly nature and energy efficiency contribute to its appeal in industries [1]-[2]. According to Yang et al. [3], conventional welding techniques often lead to defects, reduced mechanical properties, and significant residual stresses in aluminium alloys. A significant weakness and defect in FSW is the formation of hardness variations within the weld zone, leading to localised brittleness and reduced overall joint strength. The weakness of FSW is due to the influence of the tool traverse speed on the microstructure, hardness, and strength properties of FSW joints [2]. On the other hand, this study focuses on a new method, UFSW, which involves comparing HRB to various head tilt angles and other welding parameters during welding processes. UFSW is an area of research exploring the application of Friction stir welding techniques in underwater environments. The traditional challenges of welding in water, such as cooling effects and weld protection from environmental factors, are addressed in UFSW [5]. Research on the strength of weld joints usually tests Brinell hardness tests to gauge the strength and deformation resistance of FSW joints [6]-[7].

UFSW, a solid-state joining process, has emerged as a promising alternative, potentially enhancing weld quality and mechanical properties, especially hardness at the weld joint. However, the underwater environment presents unique variables that impact the welding process and its outcomes. It necessitates comprehensive studies to optimise parameters and understand the improvements in Brinell hardness (HRB) and overall weld integrity. In this paper, the goal is to enhance the hardness of butt weld joints in aluminium alloy AA 6061 through the optimisation of welding parameters by involving spindle speed, welding speed, and machine head tilt angle. A comprehensive approach was taken to accomplish the goal, starting with a literature review to establish a theoretical foundation. AA 6061 sample preparation was followed by systematic experimentation with varying welding parameters such as rotational speed, welding speed, and axial force. The samples undergo HRB testing, microstructural analysis, and grain size measurement to determine the effects of various parameters welding. Data analysis will determine the relationship between welding parameters and improvements in HRB, leading to the identification of optimal welding conditions. The findings will be compiled into a detailed report highlighting the successful parameters and observed improvements. The overall pipeline is shown in Figure 1.

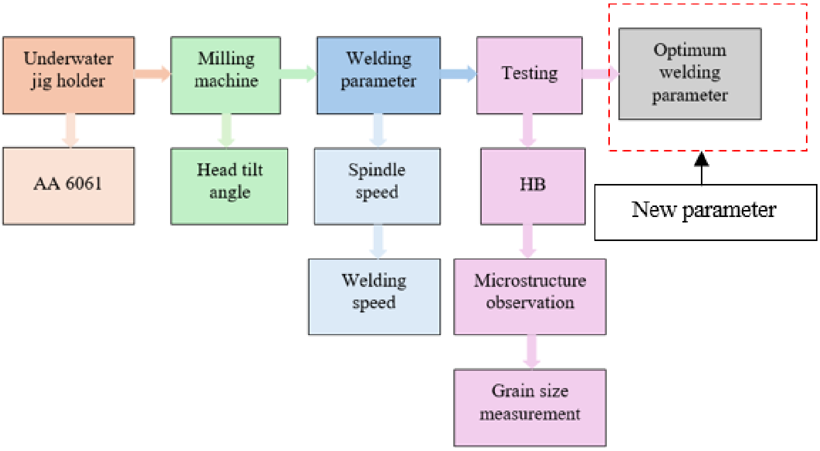


Figure 1: The pipeline of the study method

Experimental Procedure

The chosen foundational material for UFSW is an aluminium alloy AA6061 grade known for its high toughness, commendable toughness, lightweight nature, and favourable weldability. AA 6061 is one of the most versatile heat-treatable alloys and is popular for medium-to-high strength applications; it also has favourable toughness characteristics [9]. This material exhibits excellent corrosion resistance in atmospheric conditions, making it suitable for aerospace, marine, and automotive applications. The nominal chemical composition of the AA6061 aluminium alloy is detailed in Table 1, and Table 2 shows mechanical properties. Figure 2 shows two pieces of AA 6061 and the dimension specifications used for UFSW welding. AA 6061 provides as many as 9 pairs for each welding parameter.

Table 1: Chemical composition AA 6061

Chemical composition (wt.%)								
Mg	Si	Fe	Cu	Cr	Mn	Zn	Ti	Al
0.9	0.62	0.33	0.28	0.17	0.06	0.02	0.02	Rest

Table 2: Mechanical properties of AA 6061

Yield strength	**Ultimate strength**	**Elongation (%)**	**Reduction in cross-sectional area**	**Hardness (VHN)**
302 MPa	334 MPa	18	12.24	105

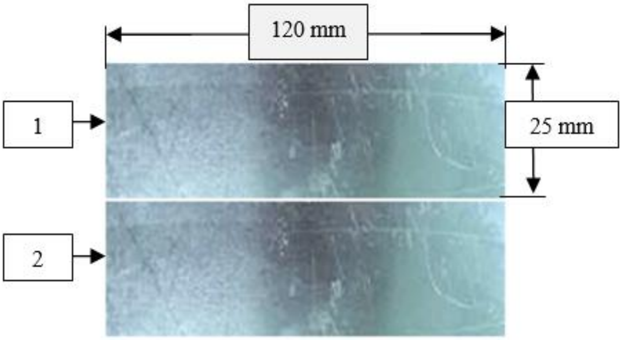


Figure 2: Two pieces of AA 6061 and dimensions for the UFSW

The essential aspects to consider during FSW processes are tool size, material, and welding parameters. Other than that, the tool material itself should be harder, and the higher melting point of the material must be stirred. Hence, this work selected the tool material as an H13 tool steel with 42 HRC due to its excellent wear resistance and deep hardening characteristics. Tool specifications as shown in Figure 3.

Custom fixtures were developed to secure the specimens to prevent vibrations arising from friction forces during the joining process in the underwater method, as shown in Figure 4. UFSW welding requires a jig and fixtures that are robust, strong, and can hold water during welding. 7mm thick acrylic-type material is used and attached using high-density silicon around the jig. Water flushing is considered for changing the water after the water has become contaminated by placing a water pipe on the side of the Jig. A butt FSW joint, a welding configuration formed through the friction stir welding process, involves joining two pieces of material by overlapping them and using a specialised tool to establish a durable and secure bond [28]. The conventional milling machine from the FULLMARK FVH 260S brand was employed for the friction stir welding (FSW) on the butt joint process, as shown in Figure 5.

Figure 3: Friction stir welding tool

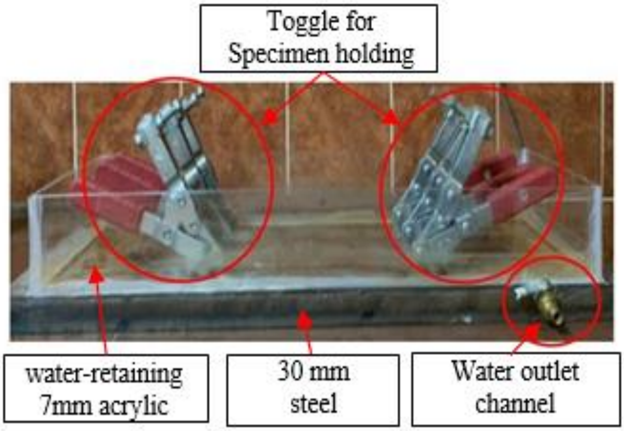


Figure 4: Jig for underwater friction stir welding

Table 3 shows the experimental parameter for evaluating the buttweld's HRB in the UFSW method on AA 6061. Apart from the UFSW process, this study also compared FSW methods for assessing the performance of the developed techniques. The range of parameter selection used is a pilot or initial study to evaluate weldability.

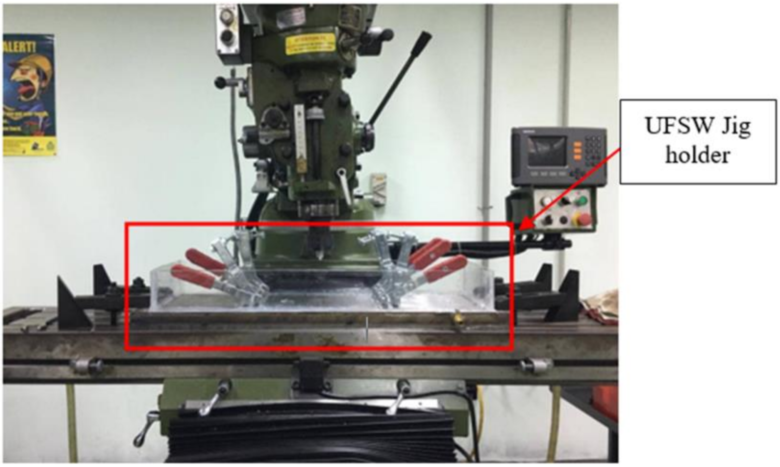


Figure 5: Conventional milling machine

Table 3: Experimental parameter

Experimental no.	Spindle speed (rpm)	Welding speed (mm/min)	Tool tilt angle (°)
1	660	15	1
2	660	20	2
3	660	25	0
4	750	15	1
5	750	20	2
6	750	25	0
7	910	15	1
8	910	20	2
9	910	25	0

Figure 6(a) shows a hardness testing machine brand Mitutoyo HR-400, and Figure 6(b) shows a 10 mm diameter hard steel ball indenter, which is pressed into the surface of the material sample for a defined period. The test is conducted according to standards ASTM E10, ensuring consistency and comparability of results [10]. Sample collection for the Brinell hardness test requires preparing specimens with smooth, flat surfaces free from oxides, scale, or other surface contaminants that might affect the indentation process. Three indentations were tested: the welded part's centre, left, and right parts. The reason is to account for any material inhomogeneity and to obtain an average hardness value, thus ensuring accurate and reliable measurement of the material's hardness properties.

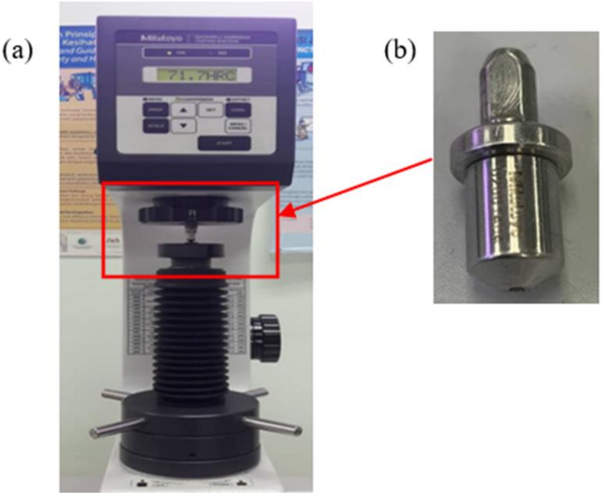


Figure 6: (a) Hardness Testing Mitutoyo HR-400 and (b) hard steel ball indenter

Results and Discussion

The findings demonstrate a significant enhancement in HRB compared to traditional friction stir welding (FSW) methods. The UFSW process produces a more refined and homogenous grain microstructure, leading to superior mechanical properties. The analysis includes comparing hardness measurements across different welding parameters, highlighting the optimal conditions that yield the best performance.

Hardness

Figure 7 shows the resultant hardness of the buttweld in underwater conditions with different parameters. From the result, the highest hardness value is 51.87 HRB, with parameters of 750 rpm spindle speed, 20 mm/min welding speed, and a 2° machine tilt angle. The machine tilt angle influences factors such as heat input and the geometry of the weld bead because the travel angle, or the angle between the welding direction and the axis of the weld, is another aspect that can impact welding [11]-[12]. On the other hand, the lowest hardness value based on underwater conditions is 9.1 HRB, which used parameters of 910 rpm spindle speed, 25 mm/min welding speed, and 0° head angle. According to Barenji [13], increasing traverse speed will decrease joint hardness. Increasing the traverse speed during welding decreases joint hardness because the faster movement reduces the heat input and the time available for the material to adequately fuse to form a strong, homogenous bond, leading to a less robust microstructure and lower resistance to deformation. Besides that, incorrect travel angles may lead to defects, such as a lack of fusion, that further affect the hardness of the welding point. Proper angles are crucial for avoiding such issues. According to Mehta and Badheka [14], the hardness in the stir zone increases as the tool tilt angle increases from 0° to 4°. The hardness increases due to improved mixing and material consolidation. However, an angle of 2° is optimal, providing the best balance between effective stirring and heat generation and resulting in superior hardness properties compared to lower and higher tilt angles. Based on the observation, experimental number five got the highest hardness value because the head angle was more significant than 1°. Proper consideration of welding angles can help optimise the distribution of residual stresses, reducing the risk of stress-related issues in the weld [15].

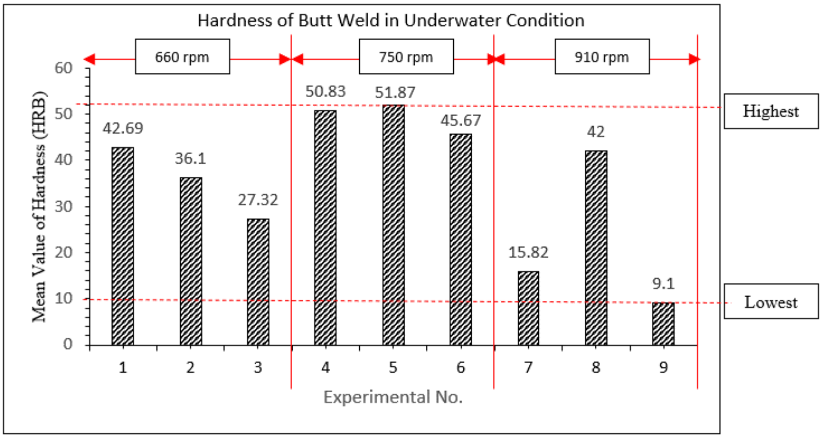


Figure 7: Result hardness of butt weld in underwater condition

FSW vs UFSW

Figure 8 compares hardness between dry and underwater conditions using the friction stir welding process. The result shows that, as an overall trend, the hardness value in UFSW conditions is higher than in dry conditions. Hardness results on the FSW method in experiment 4 obtained the highest hardness compared to other FSW parameters. However, compared to the UFSW method, experiment 5 shows a significantly lower hardness difference of 98.8%. This is because many errors when handling the operation, such as machine errors, incorrect settings, and jigs that are not tight, significantly reduce fatigue strength and occur with increasing gaps between plates [14]. According to Bocchi et al. [16], the Brinell testing indicated an improvement in the nugget hardness values in water-cooled welds compared to air-cooled welds. The weld nugget region, which is the stirred zone of the material created during the welding process, exhibited higher hardness values in welds that were cooled with water immediately after welding compared to cooling in the air, indicating enhanced material properties and potentially greater strength. The hardness of the welded joint underwater is greater than that of the air-welded joint. The hardness values of the water-cooled SZ are much higher than those of the air-cooled sample [17].

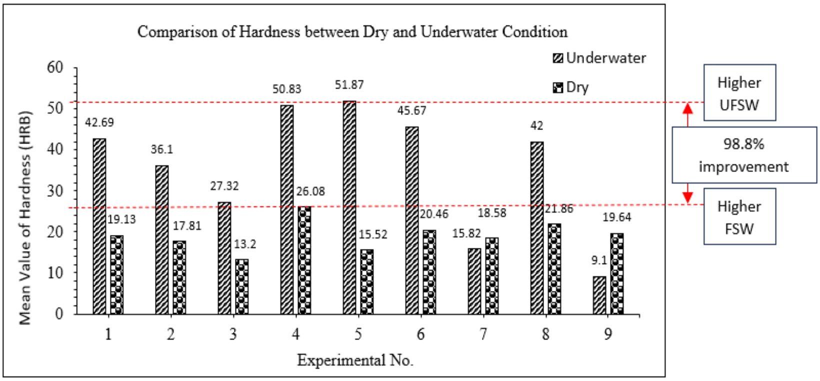
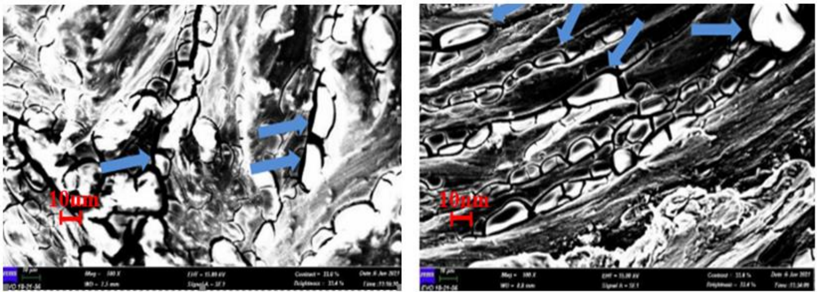


Figure 8: Comparison of hardness between dry and underwater conditions

Figures 9(a) and 9(b) reveal the distinct grain particles under 500x magnification for (a) parameter 5, 750 rpm spindle speed, 20 mm/min feed rate, and 2^o machine tilt angle, and (b) parameter 9, 910 rpm spindle speed, 25 mm/min feed rate, and 1^o machine tilt angle. Meanwhile, the blue arrows show part of the grain in the microstructure through scanning electron microscopy (SEM) observation. Figure 9(a) shows that the grains are more homogeneous than Figure 9(b). Homogeneous grain size, characterised by uniform grain dimensions throughout a material, is hypothesised to influence HRB significantly due to its impact on deformation mechanisms and resistance to indentation. Previous studies suggest that finer and more uniform grain structures typically enhance hardness due to the increased grain boundary area [18]-[19], which impedes dislocation motion—a phenomenon explained by the Hall-Petch relationship [20].

Parameters 5 and 9 were selected and compared in this paper because parameter 5 has the highest HRB, while parameter 9 is the lowest. So, it is suitable to compare by observing and analysing the gap between the two parameters. The SEM images offer a detailed view of the weld microstructure, enabling the identification and measurement of grain sizes critical for assessing the quality of the weld joint. Specifically, the average grain size of the specimen produced under parameter 5 is determined to be 10 μm in length and 2.3 μm^2 in area. This is compared to parameter 9, which recorded a length of 13 μm and an area of 2.9 μm^2, as shown in detail in

Table 4. In Friction Stir Welding (FSW), the size of the grain structure in the welded joint is generally not a direct indicator of the quality of the joint. However, smaller grain sizes are often desirable in welding because they can contribute to improved mechanical properties, such as increased strength and toughness [21]. A finer grain structure usually indicates a more homogeneous and uniform microstructure, which can enhance the mechanical properties of the joint [22]. Smaller grain sizes and homogeneous distribution in materials enhance mechanical properties by reducing stress concentrations and providing a more uniform response to applied forces, thereby increasing strength and toughness. Microscopic analysis is essential for evaluating the effectiveness of FSW joints in achieving desired material properties, such as weld strength and integrity. It provides valuable insights for optimising welding parameters and improving the hardness of butt joint welded structures in underwater environments [23].



(a) (b)

Figure 9: SEM of UFSW comparison between (a) parameter 5 and (b) parameter 9

The difference in average grain size between parameters 5 and 9 is attributed to variations in the welding conditions associated with each parameter. In FSW, welding parameters such as rotational speed, traverse speed, and tilt angle significantly influence the thermal and mechanical conditions experienced by the material during the welding process [24]. Parameter 5 might be associated with specific conditions that lead to a slower cooling rate or other factors favouring the formation of smaller grains. According to Zheng et al. [25], a lower traverse speed could result in a slower cooling rate. Slower cooling rates encourage the formation of a more significant number of small grains than a smaller number of larger grains [26]-[27]. A combination of parameters influences the overall heat input during the welding process. Therefore, higher heat input can lead to smaller grain structures. Besides that, the rotational speed of the welding tool can influence the material's microstructure. Based on observation, a 2° head angle could influence the material flow pattern around the tool, promoting better material mixing. A combination of parameters influences the overall heat input during welding [28].

Table 4: Average grain size between parameters 5 and 9

	Parameter 5	
	Area (um^2)	**Length**
1	3.951	17.645
2	3.901	13.311
3	1.679	7.279
4	2.37	10.539
5	2.469	10.979
6	1.679	7.238
7	2.568	11.403
8	4.099	18.271
9	1.481	6.46
10	0.494	1.912
11	4.938	22.045
12	4.296	19.111
13	2.074	9.068
14	1.185	5.183
15	1.778	7.713
16	0.988	4.24
17	2.864	12.668
18	2.37	10.356
19	1.235	5.311
20	1.136	4.978
21	2.42	10.704
22	1.136	4.969
23	1.827	7.966
24	2.667	11.809
25	1.284	5.52
	2.27556	10.02712

	Parameter 9	
	Area (um^2)	**Length**
1	4.718	20.896
2	4.966	22.06
3	5.909	26.341
4	3.873	17.182
5	2.731	12.128
6	2.036	8.8383
7	2.88	12.77
8	3.128	13.724
9	2.036	8.905
10	1.986	8.779
11	5.015	22.382
12	3.178	13.952
13	2.086	9.161
14	1.341	5.832
15	2.185	9.538
16	1.937	8.377
17	2.533	11.178
18	2.086	9.188
19	2.979	13.108
20	2.533	11.064
21	3.079	13.643
22	2.235	9.828
23	3.029	13.328
24	3.228	14.182
25	2.23	9.808
Avg	2.95748	13.04768

Future research could focus on optimising process parameters and understanding the microstructural transformations induced by the underwater environment. Specific areas of investigation could include the effects of varying rotational and traverse speeds on hardness and mechanical properties, the role of cooling rates in the underwater setting on grain refinement and phase distribution, and the comparative analysis of UFSW with conventional FSW in terms of hardness, tensile strength, and corrosion resistance. Additionally, advanced characterisation techniques such as Electron Backscatter Diffraction (EBSD) and Transmission Electron Microscopy

(TEM) could elucidate the detailed mechanisms behind microstructural evolution and its correlation with hardness improvements. This research could also explore the scalability of UFSW for industrial applications, ensuring the reproducibility and consistency of enhanced mechanical properties in AA 6061 weld joints.

Conclusion

The findings from this study reveal that a tilt angle of 2° is optimal for achieving the highest HRB in AA6061 aluminium alloy welds, particularly at spindle speeds of 750 rpm and 910 rpm, highlighting the critical role of tilt angle in enhancing hardness outcomes. This result emphasises the importance of precise control over welding parameters to optimise mechanical properties. Moreover, the UFSW method substantially improved hardness, recording an HRB 98.8% higher than FSW at their respective peak performance points. Furthermore, the study observed that the average grain size at parameter 5 was 22.97% smaller than that at parameter 9, indicating that specific parameter configurations promote a more homogeneous and uniform microstructure. These results underscore the interplay between welding parameters and microstructural evolution, providing valuable insights for optimising FSW processes for superior material performance.

Contributions of Authors

The authors confirm the equal contribution in each part of this work. All authors reviewed and approved the final version of this work.

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Conflict of Interests

All authors declare that they have no conflicts of interest.

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