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Investigation of the Effect of Rotational Speed on the Hardness of Aluminium Alloy (AA6063) Weldment in Rotary Friction Welding

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ABSTRACT

The study presents an innovative approach to join materials and focuses on optimizing the mechanical performance of aluminium alloy (AA6063) weldments using a semi- automated rotary friction welding machine (RFWM). The Taguchi L9 orthogonal array was employed to systematically investigate the effects of three key input parameters: Rotational speed, forge pressure and friction time. Vickers hardness tests were conducted on the welded joints to evaluate the performance. The results revealed that the highest hardness value (96.3 HV) was achieved at 900 rpm, 40 bar forge pressure and 20 seconds friction time. The analysis indicated that increasing rotational speed improved hardness up to an optimal point beyond which the hardness began to decline. These findings highlight the potential of process parameter optimization in enhancing the structural integrity and mechanical properties of aluminium alloy joints contributing to materials development in solid-state joining technologies. The study demonstrates the effectiveness of data- driven experimental design techniques in advancing welding practices in the metals and materials industry.

Keywords: Friction welding, rotational speed, aluminium, hardness

1.0 INTRODUCTION

Advancement in materials processing have become central to sustainable manufacturing, particularly in industries dealing with metals and alloys. Rotary friction welding (RFW) is an innovative solid- state welding process and a form of friction welding (FW) widely used in joining cylindrical components without melting. The welding heat is produced by the friction between the two surfaces in contact. When the spinning is stopped, a bond is formed by applying a forging force [1]. It is the most commonly used process among the FW techniques. RFW can be carried out in two ways; continuous drive and inertia friction welding [2]. This method does not require melting and as such there is no risk of solidification defects in the welded joint [3]. FW processes solves a number of fusion welding problems such as porosity, segregation, and liquation cracking in the heat affected zone [4]. Furthermore, RFW offers advantages such as energy efficiency, environmental friendliness and it is among the few methods up to date that can effectively weld similar and dissimilar metals [5]. RFW can be applied in industries such as the aerospace industry to join turbine shafts, automotive industries to join piston rods, oil and gas industry to join drill pipes and great potentials in the medical industry to join surgical equipment and implants such as stents [6]. However, RFW has the limitations for its restriction to cylindrical cross- section [7]. The stages of the process are in the following steps as shown in Figure 1.

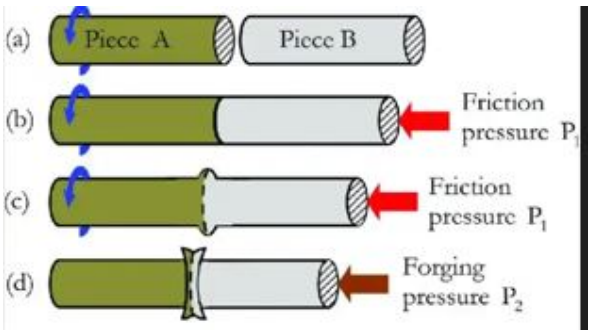


Figure 1: Stages in Rotary friction Welding [7].

In RFW certain welding parameters have been reported to have an effect on the welded joints these include rotational speed, friction duration, forge duration, friction pressure and forge pressure. The optimization of these parameters is crucial to achieving desired mechanical properties such as hardness and tensile strength. However, despite widespread industrial relevance of RFW, optimization of its parameters for different materials especially aluminium- remains a subject of active research. In particular, aluminium alloy AA6063, known for its excellent strength- to- weight ratio and corrosion resistance is widely used in structural and automotive applications. However, its weldability via friction based- process demands careful parameter control to achieve desirable mechanical properties.

Various investigations have been documented on these process parameters and optimization techniques to achieve desired mechanical properties such as [8], who studied the RFW of steel to aluminum and reported that the mechanical microstructural characteristics of joints are significantly influenced by the forge pressure, friction time and friction pressure. In the investigation of RFW of aluminum alloy to stainless steel, [9] demonstrated how friction duration and other welding parameters had an effect on the weld joint strength. Studies on process optimization have also been carried out for the friction welding process. For example, [10] carried out optimization of process parameters of RFW of low alloy steel using response surface methodology and found out that the frictional force and the forge pressure has an effect after the rotational speed in controlling the tensile properties of the friction welded joint and also established that the maximum tensile strength (TS), yield strength (YS), elongation (EL), notch tensile strength (NTS) and notch strength ratio (NSR) that could be attained in the low alloy steel joint RFW joints are 488 MPa, 378 MPa, 40.01%, 630 MPa and 1.29% under the welding conditions of Friction force of 0.851 MPa/s, forging pressure of 0.81 MPa/s and rotational speed of 3600 rpm. [11] Carried out RFW on austenitic stainless steel AISI321 and ferritic stainless steel AISI430 with varying process parameters. The studies revealed that higher upset pressure yielded fine grain size and increased friction pressure aided in grain coarsening. It was also discovered that lower friction pressure resulted in lower hardness at the interface and higher upset pressure yielded higher hardness value. [12], optimized RFW parameters using response surface methodology for high speed steel and carbon steel and reported that rotational speed dramatically affects the mechanical behaviour of the material. [9], studied RFW of AA 1050 aluminium alloy to AISI 304 austenitic stainless steel and reported that the strength of the weldment varied with friction time and other welding parameters. [13] carried out RFW of AISI 4340 austenitic- stainless steel with AA6061 aluminium alloy using silver interlayer as a diffusion barrier for Fe. They discovered that silver interlayer avoids the formation of brittle IMC layer and increase the tensile strength of welds. [14] investigated the rotary friction welding parameters of similar austenitic stainless steel (SS316) welded joints. The effect of temperature, pressure and time of weld on the hardness, microstructure and heat affected zone were analysed. It was observed that as the grain size increases, strength of the material decreases. Finer grain size yielded higher hardness and tensile strength.

From the above review, these process parameters have been identified as one of the key parameters influencing the thermal cycle, microstructural evolution and mechanical behaviour of welded joint. The objective of this research therefore is to evaluate the influence of varying rotational speed on the hardness of rotary friction

welded AA6063 aluminium alloy joints and to identify the optimal results in the highest hardness. This is achieved using the Taguchi L9 orthogonal design while also considering pressure and friction time as secondary variables. The focus is to enhance the mechanical properties through process parameter optimization.

2.0 MATERIALS AND METHODS

2.1 Materials

The base materials used for the study was AA6063 aluminum alloy and was machined to a length 55 mm and diameter 18 mm. The milled specimen is shown in Figure 2 while the chemical composition is presented in Table 1.



Figure 2: The Milled Specimen

Table 1: Chemical Composition of Base Material (AA6063) Aluminum Alloy

Element	Fe	Si	Mg	Cu	Zn	Ti	Mn	Pb	Sn	Al
Composition (%)	0.510	0.446	0.480	0.084	0.135	0.150	0.262	0.009	0.025	98.51

2.2 Equipment

A semi- automated RFW was developed and used for all welds. The machine features an AC motor drive, adjustable rotational speed, hydraulic pressure application system and braking system as shown in Figure 3. A Vickers hardness testing machine was employed to determine the hardness value of the welded joints.



Figure 3: Rotary Friction Welding Machine

2.3 Experimental Design

The Taguchi L9 orthogonal array was used to design the experiments with three levels for each parameter. The welding factor levels are shown in Table 2. A total of nine (9) experiments were obtained using Minitab 17 software as shown in Table 3.

Table 2: Factor Levels for Process Parameters

Parameter	-1	1	0
Rotational Speed	900	1000	1100
Forge Pressure	20	30	40
Friction Time	10	15	20

Table 3: Experimental Design Matrix

Experimental Runs	Rotational speed (rpm)	Forging pressure (Bar)	Friction time (Sec)
1	900	20	10
2	900	30	15
3	900	40	20
4	1000	20	15
5	1000	30	20
6	1000	40	10
7	1100	20	20
8	1100	30	10
9	1100	40	15

2.4 Welding Procedure

The material used in this experimental work is aluminum AA6063 of 18 mm in diameter and 55 mm in length. The welding process was carried out using the developed RFWM shown in Figure 3. Before the welding process, the ends of the samples were cleaned with grit silicon carbide paper and washed with acetone to remove grease and other contaminations which can affect the quality of the joints. One of the specimens was fixed in the jaw chuck (rotating specimen) while the other specimen was fixed on the drill chuck mounted on a tail stock. Figure 4 shows a 3- D representation of the arrangement of specimens in the about to weld state. The arrow in Figure 2 points in the direction of axial movement of the non- rotating specimen advancing to make contact the rotating specimen.

The power of the machine was activated and the axially moving specimen on the tail stock was brought in contact by the hydraulic ram with the rotating specimen and the welding was carried out. Figure 5 shows the experimental set up.

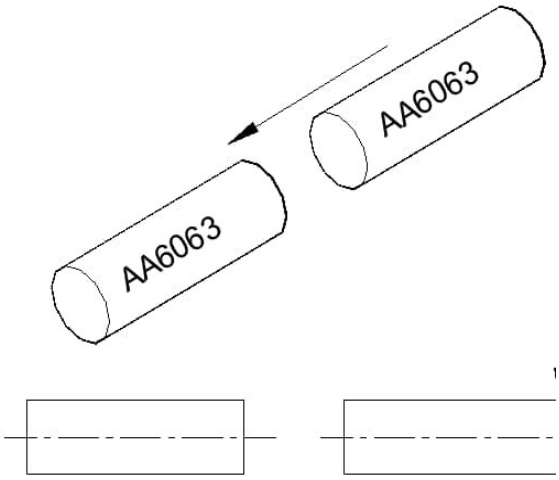


Figure 4: 3- D Representation of the Specimens

The welding process was in two stages; the friction stage and the forging stage. In the friction stage, the two materials were brought in contact with each other with one rotating and the other fixed and the forge stage which occurs when the rotation is suddenly stopped and a forge pressure is applied from the end of the non-rotating specimen and in the process, a bond is formed. During the friction stage, the specimens gain sufficient heat which plastically deforms without melting the two specimens. The weldment was then allowed to cool before removing from the fixtures. Figure 6 shows the welded joints.



Figure 5: Experimental Set Up

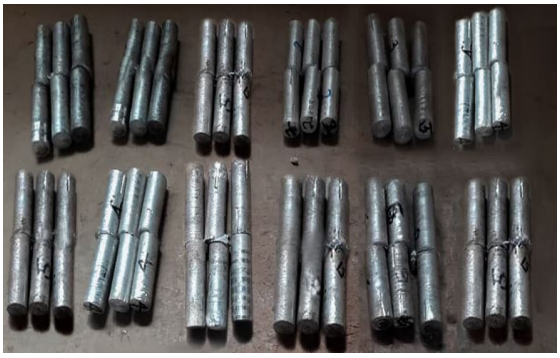


Figure 6: Welded Joints

2.5 Hardness Test

The Vickers hardness testing to determine the resistance of the welded joint to indentation was carried out using a Digital Micro Vickers Hardness Tester (Model: HVS- 1000Z). The sample was prepared by cutting with an abrasive wheel. A water-based coolant was used to prevent overheating and possible thermal damage. The surface was then ground and polished to achieve a scratch- free mirror- like surface. The prepared sample was then subjected to pressure with a test load of 200g and a dwell time of 10 seconds using a diamond pyramid type indenter. The average hardness of each sample was recorded. Figure 7 shows the hardness test specimen in mm.

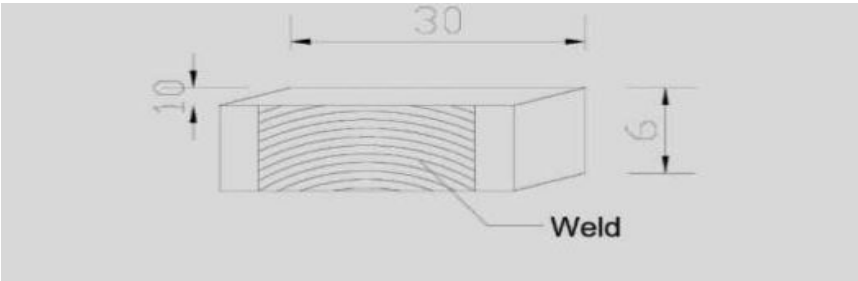


Figure 7: Microhardness Test Specimen in mm

3.0 RESULTS AND DISCUSSION

3.1 Experimental Data

The results from the experiment are shown in Table 4.

Table 4: Experimental Results for Hardness Value

Experimental Runs	Rotational Speed (rpm)	Forge pressure (Bar)	Friction Time (Sec)	Hardness (HV)
1	900	20	10	78.7
2	900	30	15	85.7
3	900	40	20	96.3
4	1000	30	10	89.2
5	1000	40	15	85.3
6	1000	20	20	86.3
7	1100	40	10	86.9
8	1100	20	15	89.4
9	1100	30	20	87.0

3.2 Effect of rotational speed on average hardness for each level run

From Table 4, the hardness value increased from 78.7 HV (Run 1: 900 rpm, 20 bars, 10 sec) to 96.3 (Run 3: 900 rpm, 40 Bar, 20 sec). The mean hardness value was 87.2 HV. The rotational speed is a critical parameter and has several effects on the welding process [15]; [16] by influencing the heat generation and the weld quality. An extremely low rotational speed results in incomplete weld and poor bond formation between the workpiece. Whereas on the other hand if the rotational speed is too high, in can lead to defects such as flash, voids, porosity or formation of wormholes [17]. From the trend of the results, moderate speed led to better hardness. High rotational speeds during rotary friction welding of AA6063 aluminium alloy can had detrimental effect on the hardness. This trend is due to the fact that elevated rotational speeds increase frictional heat generation leading to excessive heat input. [18]; [19], reported that this excessive heat can lead to grain coarsening within the weld zone while [20] found out that increased rotational speed in FSW, the coarsening of precipitate particles is increased owing to higher peak temperatures generated during the welding process which consequently reduce the hardness of the welded joint. Additionally, [21], in the publication joining aluminium to steel by friction stir welded observed that the magnesium in the aluminium alloy burned at higher rotational speed which resulted in an unsound joint. The authors reported that there is always an optimum rotational speed for obtaining sound joints, this would depend on materials to be joined and the effect of the combination of other process parameters. [22], reported studies carried out by Zhou *et al*. whom considered spindle speed as the most dominant parameter and investigated its effect on the mechanical properties of Ti- 6Al-4V. From the research, it was observed that an increase in rotational speed reduced the hardness in the weld zone. It was concluded from the studies that optimum rotational speed to establish a sound joint ranged between 400 to 600 rpm. Research on 6061- T6 aluminium alloy found that excessive speeds resulted in reduced viscous friction and poor weld metal bonding, leading to fractures at the weld centre [23]. Figure 8 shows the effect of varying rotational speed on the average hardness for each of the levels.

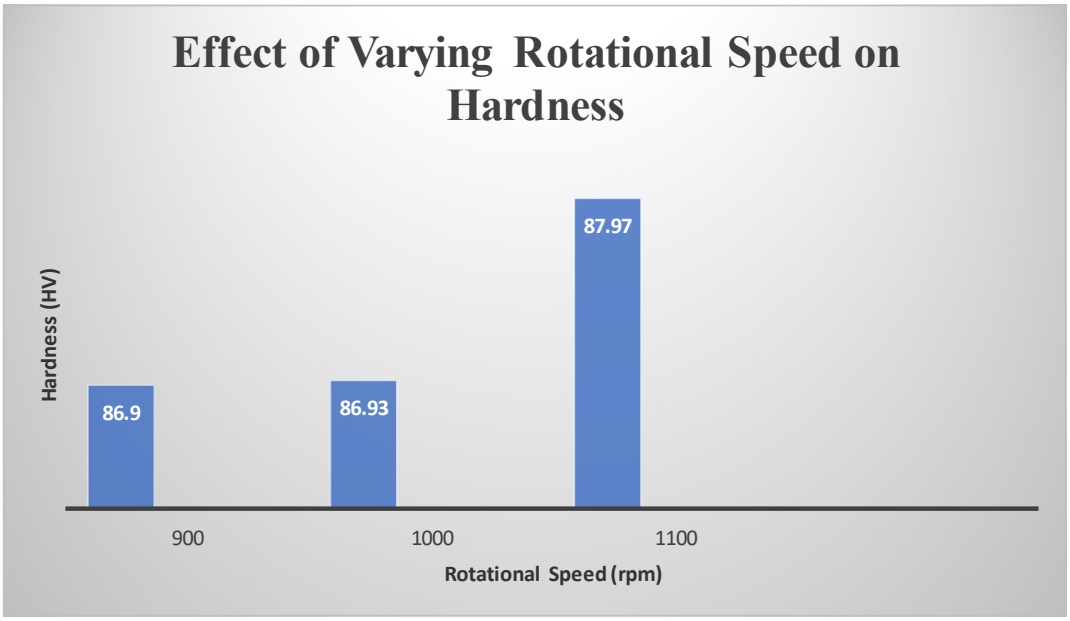


Figure 8: Effect of Varying Rotational Speed on the Average Hardness for each level

3.3 Interaction with Other Parameters

3.3.1 Rotational Speed vs Forge Pressure on Hardness

The interactive plot of rotational speed against forge pressure on hardness is shown in Figure 9. It illustrates that at 900 rpm, increasing forge pressure from 20 to 40 bar consistently improves the hardness. At 1000 rpm, pressure effects are less consistent, hardness peaks at 30 bar but drops at 40 bar. At 1100 rpm pressure flattens indicating reduced sensitivity.

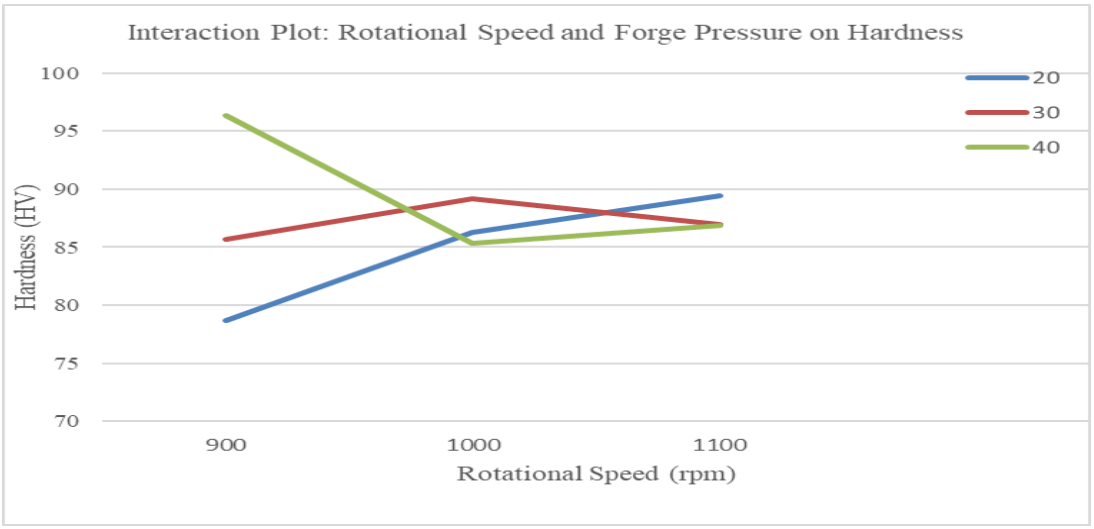


Figure 9: Interactive Plot of Rotational Speed and Forge Pressure on Hardness

3.3.2 Rotational Speed vs Friction Time on Hardness

The interactive plot of rotational speed vs friction time on hardness is shown in Figure 10. The plot shows that at 900 rpm, increasing friction time from 10 to 20 seconds steadily improves the hardness. At 1000 and 1100 rpm, hardness shows less improvement with longer friction time. The friction time contributes to the total heat input

and plastic deformation at optimal rotational speed (900 rpm), longer friction time promotes grain refinement and bond quality.

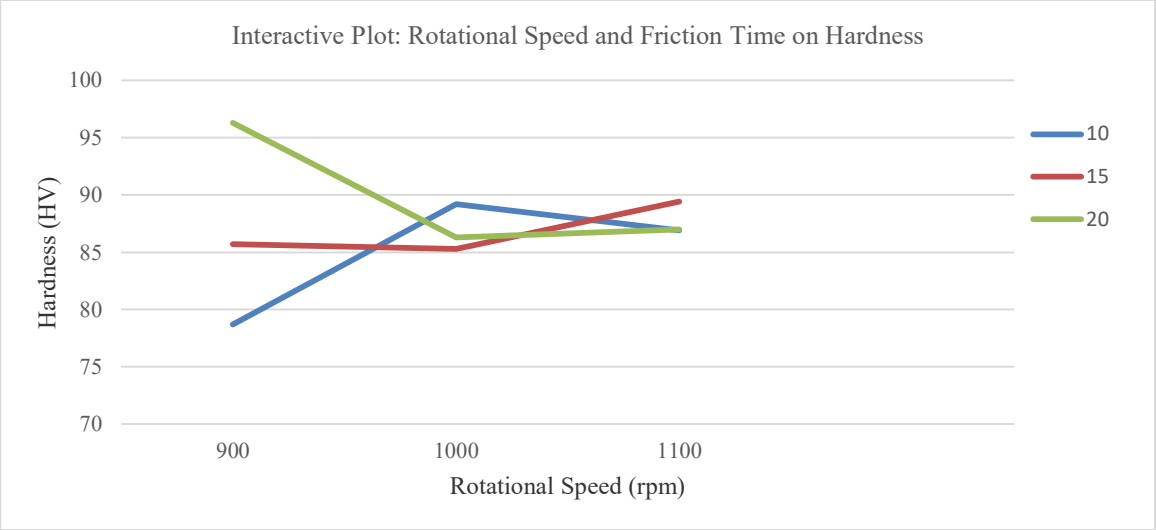


Figure 10: Interactive Plot of Rotational Speed Vs Friction Time on Hardness

3.3.3 Analysis of Variance for Hardness

As shown in Table 5, the most significant factor was the forging pressure which contributed 39.403% emphasizing its role in plastic deformation and grain refinement which increases hardness. Friction time (37.005%) follows. The least contributing factor was the rotational speed (18.497%) which suggests that temperature increase alone does not directly corelate with hardness unless supported by adequate forge pressure. The error recorded in this analysis was 5.096%

Table 5: ANOVA for Hardness

Factor	DOF	SS	MS	F	P%
Rotational Speed (rpm)	2	31.475	15.378	3.630	18.497
Forging Pressure (Bar)	2	67.05	33.525	7.733	39.403
Friction time (Sec)	2	62.97	31.485	7.262	37.005
Error	2	8.671	4.336		5.096
Total	8	170.166	21.271		100

4. CONCLUSION

The study investigated the influence of process parameters, particularly rotational speed on the hardness of AA6063 aluminium alloy welded by rotary friction welding. The findings revealed that a rotational speed of 900 rpm is the optimum speed for maximizing hardness in AA6063 rotary friction welding under the parameter range. The forge pressure has a stronger influence at lower speeds, while at high speeds, heat input dominates thereby reducing its effectiveness. At moderate speeds friction time enhances hardness effectively. Beyond this moderate speed, its benefits are detrimental. The study confirmed that rotational speed has a significant effect on the hardness of aluminium alloy weldments produced by RFW. However, excessive rotational speeds led to thermal softening and reduced hardness probably due to grain coarsening and material slippage. These results emphasise the need for careful optimization of process parameters to achieve high- quality welded joints. This aligns with the primary objective of the study which seeks to identify the optimal rotational speed and process conditions that enhances the hardness of AA6063 aluminium weldments.

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