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Effect of Tool Geometry in Stir Zone for Hook Formation of Dissimilar Aluminium Alloys: A Parametric Investigation on Metallurgical and Mechanical Characteristics

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A recently developed solid-state joining technique called "friction stir spot welding" (FSSW) is used to combine metal alloys with low weldability. Significant experimental work for this study is concentrated on the FSSW of AA6063 and AA5083. The study involved fixture setup and welding pattern parameters for the sizes of the material, all of which were done on a milling machine. A cylindrical shoulder with a concave (10°) square pin profile was taken into consideration using various process parameters. The tool material is heat-treated high-carbon steel. The Taguchi L9 orthogonal array is employed for the experimental model. The influence of FSSW factors including spindle speed, time, and depth was studied, along with the relationship between tensile strength, hardness at the contact region, and hook development, which would be a nominal metallurgical pledge established in the welding zone among the interacting sheet plate. The hook structure was found in the area of contact, and thermomechanical effects were seen in the spot-welding area. It has been determined that the influencing variables are spindle speed and plunge depth. As a consequence, it was determined that a tool spindle speed of 1200 rpm, a time of 25 seconds, and a plunge depth of 0.10 mm offer better mechanical properties. The microstructural analysis of welded region was carried out using a scanning electron microscope (SEM).

Keywords: microstructure, hook geometry, stir zone, multiple regression, ANOVA

Highlights

- *FSSW operating parameters, including the spindle speed, time, and depth of penetration, were considered.*
- *The mechanical properties, such as tensile strength and hardness of the FSSW-welded region, were obtained.*
- *The formation of the hook structure was observed during the FSSW process using SEM.*
- *Percentages of the contribution of each process parameter were obtained based on the ANOVA results.*

0 INTRODUCTION

The most important factor in the current automobile sector is fuel efficiency, and losing weight is one of the simplest ways to reduce fuel usage. Lighter components such as aluminium and magnesium alloys are helping to improve fuel efficiency. In contrast, flame-curable Al alloys require more complicated fusion welding techniques. As a result, TWI's friction stir spot welding (FSSW) has drawn much interest since it offers a variety of advantages, including minor welding faults, relatively low stresses, an electrodeless weld, weight reduction, and the ability to use less power. Recent years have seen an increase in the utilization of aluminium body welds for FSSW.

Al 6082-T6 sandwich plates' mechanical performance during FSSW was examined using a square pin instrument by Ravi, et al. [1]. Sandwich plates can be attached using a squared pattern tool that has a solid pin and plain joint, as well as a tool with a curved shoulder, although at the price of joint output. Siddhartha and Senthilkumar [2] studied FSSW apertures in order to produce Al 5086 boards of equal quality. ANOVA analysis has been utilized to confirm the applicability of the established model at a response rate of more than 95 %. Rana et al. [3] investigated the mechanical properties, hook structure, particle shape, toughness, and heat radiation of aluminium plates. The hook size widens and the hook length lengthens with increased spindle speed. The hook topologies are defined by the heat generated, and the device's rotating speed affects the quantity of energy generated. This length of plunge demonstrates a change in product blending at the link surface and is inversely proportional to the ultimate tensile fatigue strength.

Research by Garg and Bhattacharya [4] examines how spindle speed, longer waiting times, and different pin profile configurations affect the lap strength qualities of welding effectiveness. However, employing the rectangular shape pattern results in an increased elastic modulus, which significantly increases stress in the base materials. The lap-shear fracture load increases as welding limitations are raised up to a certain degree and then decreases as welding constraints are raised further, according to Tashkandi et al. [5]. The load for lap-shear fracture increased if the spindle speed was increased to 1120

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rpm. Shubhavardhan and Rahman [6] investigated the hook structure and fracture power of Al6060-T5/ Al6060-T5. As the tool spindle speed increased from 500 rpm to 1000 rpm, a rise in contact region especially increased hooked length. Hook length remained constant as spindle speed increased from 1000 rev/min to 2000 rev/min. Satheesh et al. [7] investigated the various friction stir welding input process parameters, such as traverse speed, tool rotational speed, axial force and pin profile using response surface methodology and found the optimal process parameters which exhibited improvement in mechanical properties.

Cao et al. [8] investigated the relationship between the shape of the hook and the hooks' maximum tensile strength as well as the direction of the hook effect in relation to plunge height. Increases in spindle speed, join duration, or plunge distance resulted in longer hooks and inefficient welding. According to Piccini and Svoboda [9], effective binding increases the chance when welding with small pin instruments and improves device propagation distance. In this regard, the decrease in the distance between the attachment and the low position of the shoulder has shown an improvement in the thermo-mechanical impact of the welding device. According to Piccini and Svoboda [10], the thermo-mechanical impact of the workpiece is primarily related to the thickest low distance between the controller and the shoulder layer. When the equipment depth is raised for lap welding, the Al 6063 (top) / Al5052 (bottom) configuration performs fairly well.

The primary objective of the research is to investigate the weld performance of the aluminium alloys 6063-T6 and 5083-O-H111 in terms of ultimate tensile toughness, stiffness, and hook shape under different processing conditions. The predicted values of tensile shear stress, stiffness, and hook shape are determined using regression analytical techniques. ANOVA is used to evaluate the impact of various features and effects on the outcome, and Taguchi's approach is used to determine the appropriate test parameter.

1 MATERIALS AND METHOD

1.1 Selection of Material

The marine-grade aluminium alloys used in this work are AA6063-T6 and AA5083-O-H111. Compared to other aluminium alloys, it is the most corrosion-resistant. The matrix-consistent deposition of a subsequent phase strengthens the thermal metal AA6063-T6. According to T6, the metal must be heated to a certain temperature before being extruded for corrosion resistance. Table 1 displays AA 6063's chemical composition. Another alloy employed in the research is AA5083-O-H111, in which the O symbol denotes total softness and the updated diagnosis ranges from 345 °C to 650 °C, with subsequent cooling to such an uncontrolled back level. The last number and the second digit, which is defined as 1/8, are typically utilised on rotational forms that need to be streamlined after welding to meet stiffness requirements. The strain toughened without treatment, as seen in H111. Table 2 contains a summary of Al5083-O-chemical H1's composition.

Table 1. *Chemical content of AA 6063*

Elements	Mg	Fe	Si	Si	Zn	Ti	Cr	Cu	Al
%	0.45	0.35	0.2	0.2	0.1	0.1	0.1	0.1	rest

Table 2. *Chemical content of AA 5083*

Elements	Mg	Mn	Fe	Si	Cr	Zn	Ti	Cu	Al
%	4.9	1	0.4	0.4	0.25	0.25	0.15	0.1	rest

1.2 Experimental Design

Significant influencing parameters in FSSW were discovered to be spindle speed, dwell time, and plunge depth. Therefore, it is necessary to investigate the ideal settings for productive joint processing. The pin wears out very quickly due to a lower spindle speed that results in an insufficient rise in heat at the weld. The dwell period is determined by the heat transfer into the samples. Axial force is caused by the depth of the drop on the top and bottom sheets [11]. When analysing the effects of multiple parameters simultaneously, Taguchi optimization techniques are efficient and simple to utilize. This approach is ideally suited to the use of a mean output characteristic quality that is close to the goal level rather than a rating that is subject to those calculation restrictions. The efficiency and quality of the materials will therefore increase. Numerous samples must be taken even as the number of input variables increases. The samples were converted to the initial number of experiment samples using a special orthogonal array structure. A signal-to-noise ratio, an evaluation of the desired valuation standard's capabilities, was created from the modified valuation data. Three input parameters and three levels were used in this investigation's design, and the operational parameters are displayed in Table 3.

Table 3. *Welding operating parameters and their levels*

Parameters	Unit	Level 1	Level 2	Level 3
Spindle speed (N)	rpm	1000	1100	1200
Dwell time (t)	s	20	25	30
Plunge depth (D)	mm	0.10	0.15	0.20

1.3 Experimental Details

The studies were carried out on a semi-automated vertical milling machine with such a tool mounted on an axle with a suitable collet and samples set up in a fixture and weld template. The vertical tool head could be pushed along the horizontal Z-axis while the longitudinal bed could be moved along the X- and Y-axes. The investigation used 3 mm thick plates of the aluminium alloys that were chosen (AA6063-T6 and AA5083-O-H111). The welding surfaces of the trial plates are mounded in the longitudinal bed to the smallest origin gaps connected to the centreline of the FSSW tool with the aid of a specially made fixture [12]. The backing plate and template need to be firmly fastened together. The experimental setup for clamping the FSSW plate is shown in Fig. 1. The spot-welded section's dimensions are plotted in a figure as illustrated in Fig. 2.

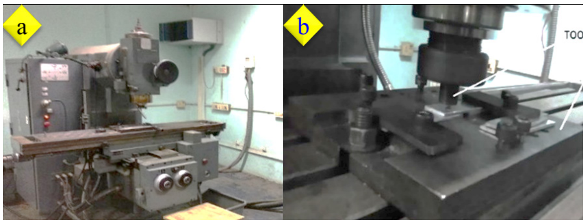

Fig. 1. *a) Semi-automated vertical milling machine, b) specimen fixture*

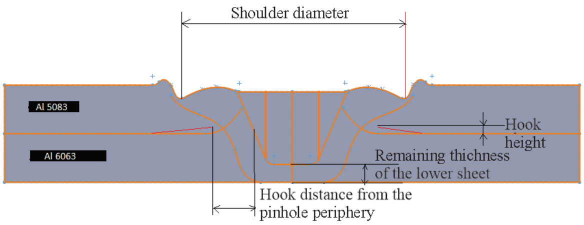

Fig. 2. *Schematic plot of the dimensions measured on the spot welded section*

1.4 Testing of Mechanical Properties

Samples prepared in accordance with ASTM-E8M requirements underwent tensile shear strength tests. The typical welding sample dimensions for shear strength testing are shown in Fig. 3. The computerized UTM 100 is used to estimate the TSS of the weld region. The FSSW of the AA6063 and AA5083 specimens used for TSS testing is shown in Fig. 4. A Vickers hardness measurement apparatus with a load of 5 kg is utilized for the hardness test. A diamond indenter is used to measure the hardness horizontally and perpendicular to the welding keyhole of 90-degree deviations around component attributes. Later, micrographic analysis was carried out at the touch region using optical techniques to determine the hooked distance and width from the pinhole boundary. Fig. 5 displays the FSSW of AA6063 and AA5083 samples for hardness analysis examination.

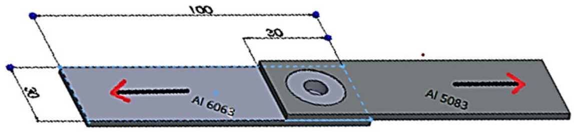

Fig. 3. *Standard dimension for tensile shear test, all dimensions are in mm, ASTM E8M*

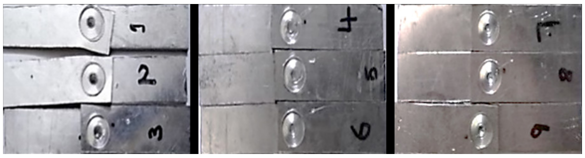

Fig. 4. *Tensile test welded specimens*

Fig. 5. *Hardness test welded specimens*

1.5 Microstructure Examination

The base metal and fuse field were compromised during the metallurgical categorization on the welded sample, utilizing an optical inverted microscope. The conventional microstructure method has been applied to prepare the sample for the test. The binding region significantly affects the weld zone's weight behaviour competence, particularly during shear strength testing. If the bonding region were wider, the breaking load would be higher. Hook morphology also determines how tough a joint is. Both the hook height and the distance can be used to depict it. A weaker joint result from hook insertion in the pinhole direction; conversely, a stronger joint follows from hook placement in the opposite direction. The joint's stability would increase with the size of the gap between the hooks and the pinhole boundary. At the same time, welding becomes weaker as hook size and length increase.

2 RESULTS AND DISCUSSION

2.1 Results of Mechanical Properties

The welded samples underwent a tensile test. To ascertain the tensile strength of the weld samples, they are loaded into the apparatus and subjected to a tensile load. Fig. 6 shows the topmost and bottommost portions of the weld zone after a maximum force has been applied to fracture it. Fig. 7 displays the bottom section of a weld sample following the tensile test. It has been noted that this zone's nugget zone area is larger than others' and that it has a sizable TMAZ area and HAZ area, both of which contribute to the generation of more frictional heat between the tool and the materials.

Fig. 6. *Welded specimen a) Al 6061 top view, and b) AL 5058 bottom view*

Table 4 shows the TSS for the samples obtained during the tests, with the sample from experiment 9 (1200 rpm, 30 s, 0.15 mm) with the highest TSS and the sample from experiment 1 with the lowest TSS (1000 rpm, 20 s, 0.10 mm). Fig. 8 demonstrates that experiment 9's tensile strength is higher than that of the other experiments. The experimental circumstances specimen had the lowest hardness of 81.74 at 1000 rpm, 25 s, and 0.15 mm, while the specimen from study 7 had the highest hardness at 1200 rpm, 20 s, and 0.20 mm). Fig. 8 shows the FSSW joints' tensile shear and Vickers hardness values.

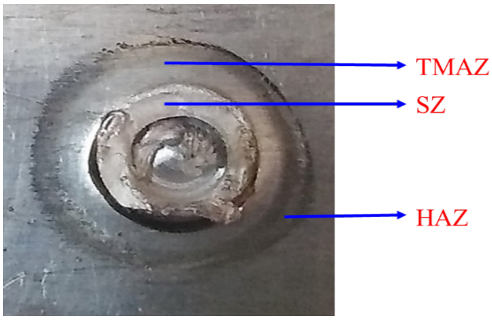

Fig. 7. *The bottom section of a weld (after tensile test)*

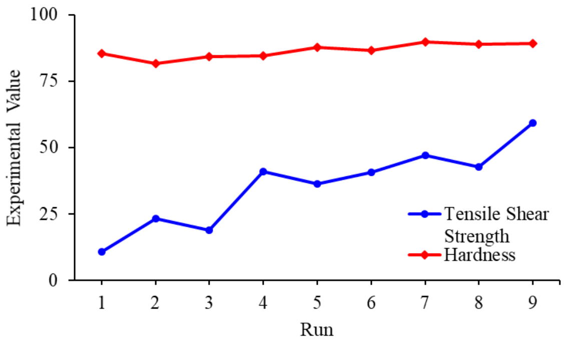

Fig. 8. *Experimental values of mechanical properties*

2.2 Results of Microstructure Study

The results of a microstructural analysis show that there are essentially three different sorts of regions

Table 4. *Experiment results with signal to noise (S/N) ratio for mechanical properties*

Run	Input parameters			Experimental results		S/N ratio	
	Spindle speed	Dwell time	Plunge depth	Tensile shear strength	Hardness	Tensile shear strength	Hardness
1	1000	20	0.1	10.9	85.33	20.7485	38.622
2	1000	25	0.15	23.3	81.74	27.3471	38.2487
3	1000	30	0.2	18.9	84.25	25.5292	38.5114
4	1100	20	0.15	40.9	84.5	32.2345	38.5371
5	1100	25	0.2	36.2	87.75	31.1742	38.8649
6	1100	30	0.1	40.6	86.5	32.1705	38.7403
7	1200	20	0.2	47	89.75	33.4420	39.0607
8	1200	25	0.1	42.6	89	32.5882	38.9878
9	1200	30	0.15	59.2	89.25	35.4464	39.0122

that occur during welding: the stir zone (SZ), the thermal mechanically affected zone (TMAZ), and the heat affected zone (HAZ), which are classified from the section's centre to its superiority. Fig. 9 shows that for the sample of experiments run at a spindle speed of 1200 rpm, dwell time of 30 s, and depth of 0.15 mm, the maximum hook height was 0.673 mm, and the smallest hook height was 0.239 mm for the specimen of experiments run at a spindle speed of 1200 rpm, dwell time of 25 s, and depth of 0.10 mm. The distance from the pinhole perimeter varies on the procedure parameters, as shown in Fig. 10. Table 5 shows that the greatest hook height was 0.673 mm for the welded specimen of trial 9 (1200 rpm, 30 s, 0.15 mm), while the minimum hook height was 0.239 mm for the specimen of experiment 8. Hook height and distance of the TSS discovered in microstructure analysis (1200 rpm, 25 s, 0.10 mm). that the sample

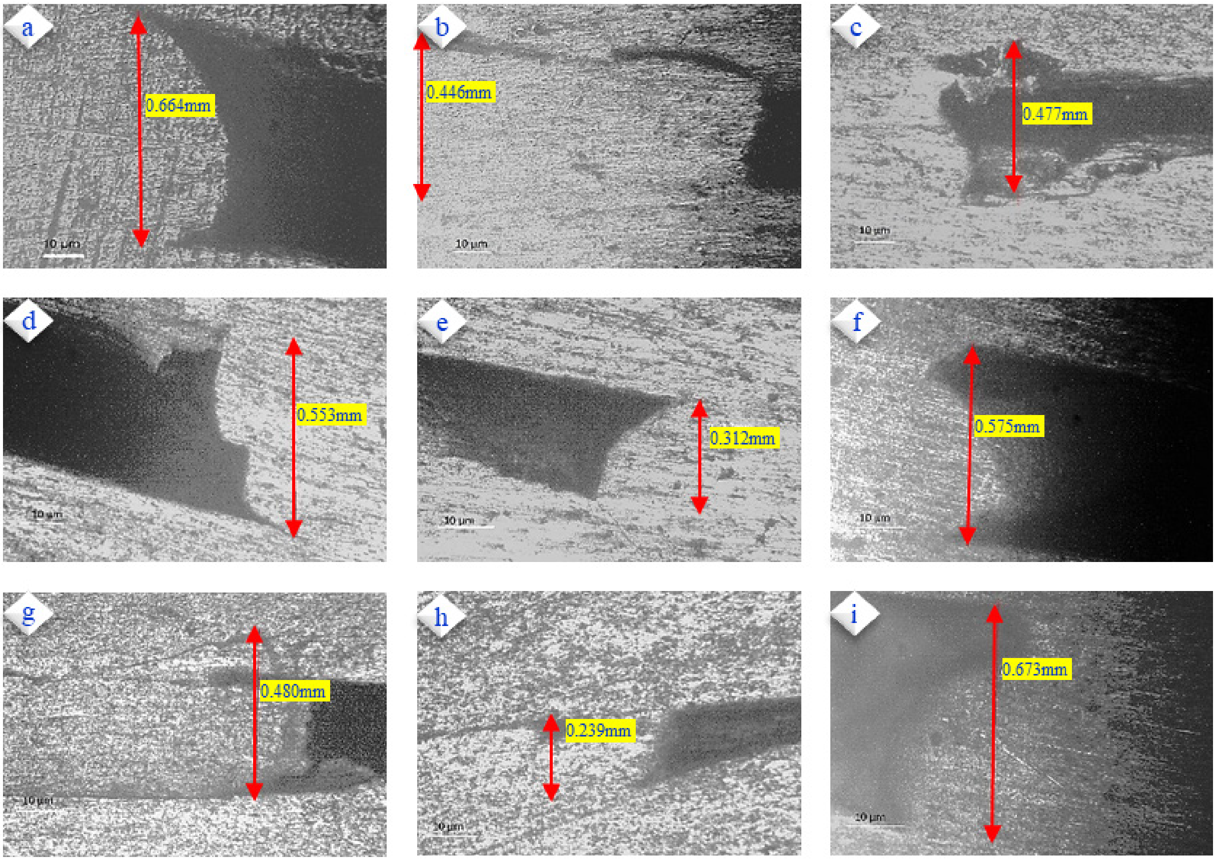

Fig. 9. *Microstructure examination of hook height*

Table 5. *Experimental results with snr for response variable*

Run	Spindle speed	Dwell time	Plunge Depth	Hook geometry		S/N ratio	
				Height	Distance	Height	Distance
1	1000	20	0.10	0.664	1.974	3.5566	5.90694
2	1000	25	0.15	0.446	1.824	7.0133	5.22050
3	1000	30	0.20	0.477	1.851	6.4296	5.34813
4	1100	20	0.15	0.553	1.210	5.1455	1.65571
5	1100	25	0.20	0.312	1.916	10.1169	5.64791
6	1100	30	0.10	0.575	1.934	4.8066	5.72913
7	1200	20	0.20	0.480	1.864	6.3752	5.40892
8	1200	25	0.10	0.239	2.061	12.4320	6.28156
9	1200	30	0.15	0.673	2.246	3.4397	7.02820

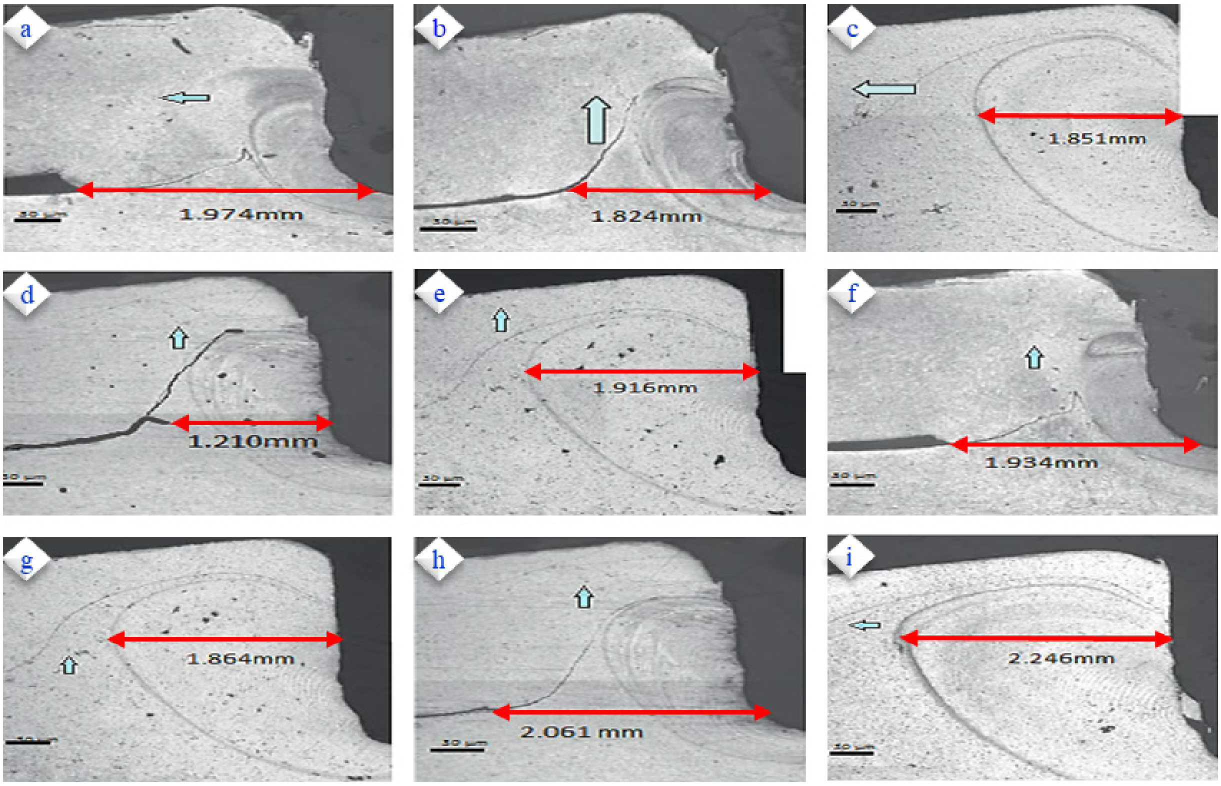

Fig. 10. *Distance from the pinhole periphery*

from experiment 9 (1200 rpm, 30 s, 0.15 mm) had the greatest hook distance from the peripheral while the welded specimen from trial 2 had the smallest hook distance, measuring 1.824 mm (1000 rpm, 25 s, 0.15 mm).

2.3 Main Effect Plot of SN Ratio

The FSSW variables are standardized throughout this research; therefore, TSS and hardness are appropriate characteristics for identifying dependents. The "Larger is Better" design was applied during the S/N ratio evaluation because the highest possible tensile shear strength and hardness are required. Table 4 shows the S/N ratios of the welded joints made from Al 6063 and Al 5083 based on the results of the testing. The highest S/N ratio in Fig. 11 indicates that the welding input settings are very effective. The ideal spindle speed is 1200 rpm since the TSS S/N ratio increases continuously from 1000 rpm to 1100 rpm and then from 1100 rpm to 1200 rpm, as illustrated in Fig. 11a. In line with this, the S/N ratio of dwell time increases from 20 s to 25 s, then progressively increases from 25 s to 30 s, with 30 s being the maximum dwell duration. A 0.20 mm ideal plunge depth is reached when the S/N ratio of the number of plunge depths improves from 0.10 mm to 0.15 mm, then increases from 0.15 mm to 0.20 mm. This analysis shows that the maximum TSS recorded from the welding situation is 1200 rpm, 30 s, and 0.15 mm. Fig. 11b shows the hardness plot with the largest influence on the S/N ratio chart. The above-mentioned method to calculate the hardness value: 1200 rpm, 20 s, and 0.20 mm, was used to estimate the maximum hardness attained under the welding conditions. The "Smaller is Better" formula was employed in the study utilizing the S/N ratio because hook height is one of the methodological flaws for the stir region. The S/N ratio of the connections leading to trials for the AA6061 and AA7075 is shown in Table 5. Fig. 12 displays the principal effect chart, which focuses mainly on the SN ratio. The optimal spindle speed is 1200 rpm, which has the maximum value, as the S/N ratio increases from 1000 rpm to 1200 rpm, as shown in Fig. 12a. Accordingly, the dwell time S/N ratio increases from 20 s to 25 s before falling from 25 s to 30 s, proving that 25 s is the ideal dwell time. Indicating that 0.20 mm is the maximum plunge depth, the S/N ratio of plunge depth then decreases from 0.10 mm to 0.15 mm, then increases from 0.15 mm to 0.20 mm above the 0.10 threshold. Similar techniques are used to evaluate the hook distance S/N ratio diagrams, and it can be deduced from Fig. 12b that the maximum hook distance that can be obtained from a variable is 1200 rpm, 30 s, and 0.10 mm.

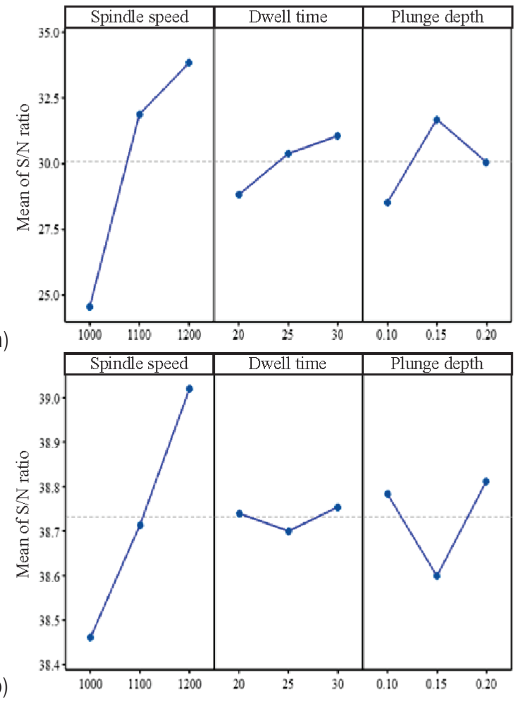

Fig. 11. *Main effect plot for S/N ratio a) TSS, b) hardness*

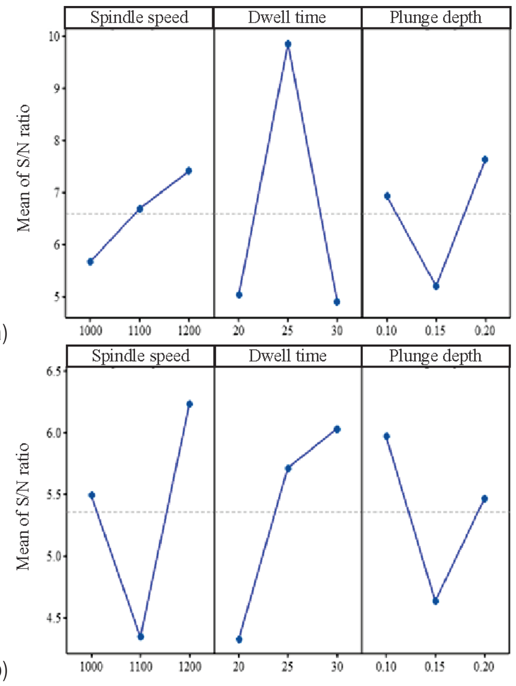

Fig. 12. *Main Effect plot for SN ratio Hook a) height, b) distance*

2.4 Analysis of Variance

ANOVA has been used to compare the effects of different welding operation conditions on TSS and hardness. To assess the severity of various operating circumstances, the ANOVA is used. The P-value displays the percentage of unexpected quantities that are classified as sound, and Tables 6 to 9 display the optimal values of customizable operational parameters to maximize hardness. The highest F value and lowest P value are therefore preferred, and any variable with a probability of less than 5 % is taken to be a significant characteristic. From Table 6, it can be inferred that the variable has a statistically significant F value of 131.64. From Table 7, it can be inferred that the variable has a statistically significant F value of 23.277.

Table 6. *ANOVA for TSS*

Source	DF	Seq SS	Adj SS	AdjMS	F	P
Spindle speed	2	1588.76	1588.76	794.38	131.64	1.008
Dwell time	2	75.83	75.83	37.91	6.28	0.137
Plunge depth	2	152.91	152.91	76.45	12.67	0.073
Error	2	12.07	12.07	6.03		
Total	8	1829.57				

Table 7. *ANOVA for hardness*

Source	DF	Seq SS	Adj SS	AdjMS	F	P
Spindle speed	2	46.554	46.554	23.277	10.51	0.087
Dwell time	2	0.405	0.405	0.202	0.09	0.916
Plunge depth	2	7.617	7.617	3.808	1.72	0.368
Error	2	4.430	4.430	2.215		
Total	8	59.006				

Table 8. *ANOVA for Hook height*

Source	DF	Seq SS	Adj SS	AdjMS	F	P
Spindle speed	2	0.00688	0.00688	0.00344	0.28	0.780
Dwell time	2	0.11342	0.11342	0.05671	4.64	0.177
Plunge depth	2	0.02708	0.02708	0.01354	1.11	0.475
Error	2	0.02446	0.02446	0.01223		
Total	8	0.17184				

When welding dissimilar aluminium alloys with FSSW, the F-test is utilized to determine the key operating element that impacts hook height and length. The F value of 0.28 and 1.20 in Tables 8 and 9 respectively represent the mean value of some well-operating conditions to reach minimum hook height, while the ‘P’ value offers the potential for disproportionate inputs. A maximum F value and an average P value are therefore needed. Similarly, dwell duration corresponds with the highest hook distance by 27.85 %, whereas spindle speed connects with the greatest hook distance by 12.51 %.

Table 9. *ANOVA for Hook length*

Source	DF	Seq SS	Adj SS	AdjMS	F	P
Spindle speed	2	0.20597	0.20597	0.10298	1.20	0.454
Dwell time	2	0.17624	0.17624	0.08812	1.03	0.493
Plunge depth	2	0.07924	0.07924	0.03956	0.46	0.684
Error	2	0.17138	0.17138	0.08569		
Total	8	0.63272				

2.5 Effect of Contribution of Operating Parameters

Calculating the percentage contribution of operating parameters involves comparing the sum of the squares of variation to the sum of the squares of variation. The percentage contribution of each shear strength and hardness parameter is shown in Fig. 13. Fig. 13a shows that the spindle speed makes up 86.3 % of the total contribution, with dwell time making up 4.14 % and dive depth accounting for 8.35 %. Fig. 13b shows that the spindle speed contributes 78.89 % of the total, followed by dwell time with 0.68 % and dive depth with 12.92 %. The TSS and hardness of the specimen are shown to be significantly influenced by spindle speed, a key process parameter. The percentage influence of each parameter on hook height and distance is depicted in Fig. 14's chart.

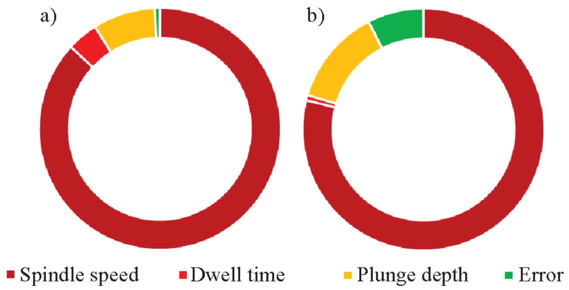

Fig. 13. *Contribution % of process parameters, a) tensile shear stress, and b) hardness*

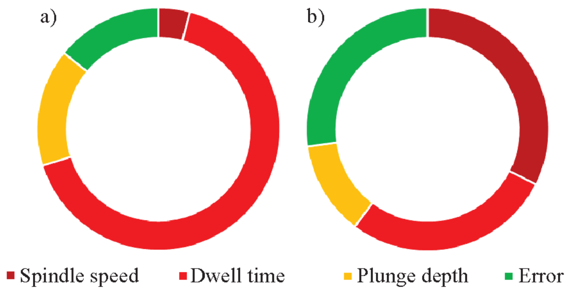

Fig. 14. *Contribution % of process parameters; a) hook height b) hook distance*

Fig. 14a shows that the spindle speed makes up 86.3 % of the total contribution, with dwell time making up 4.14 % and plunge depth making up 8.35 %. Thus, it is obvious that dwell time plays the largest role in achieving the lowest hook height. Accordingly, in FSSW, spindle speed is the most important parameter to manage the welding process's distinctive property hook height. Fig. 14b shows that the spindle speed makes up 32.55 % of the contribution, followed by dwell duration at 27.85 % and dive depth at 12.51 %. The main hook distance is shown to be influenced by spindle speed.

2.6 Multiple Regression Equations

The findings of the experiments determine the correlation coefficient between the friction spot welding operating settings and the efficiency measures. significance at a 95 % confidence level to conduct the experiment. Eqs. (1) to (4) explain the regression equations for the following variables: tensile shear strength (*TSS*), Vickers hardness (*HV*), hook height (*H*), hook distance (*L*) from the welding operating condition, spindle speed (*N*), length of dwell (*t*), and depth of plunge (*d*).

$$TSS = -161 + 0.159N + 26.7d + 0.663t, \quad (1)$$

$$HV = 55.1 + 0.0278N + 3.1d + 0.014t, \quad (2)$$

$$H = 0.930 - 0.000325N - 0.70d + 0.0009t, \quad (3)$$

$$L = 0.27 + 0.00087N - 1.13d + 0.0328t. \quad (4)$$

3 CONCLUSIONS

A successful parametric investigation on the mechanical and metallurgical properties of welded dissimilar aluminium alloys and their impact on tool geometry in the stir zone for hook production has been carried out. An overview of the research's findings is provided below.

- Spindle speed is found to be a key operating factor influencing welding strength for the Al6063-T6 and Al5083-O-H111 plates. Spindle speed (N = 86.83 %) has the biggest impact on specimen tensile strength, followed by plunge depth (D = 8.35%) and dwell time (t = 4.14%). The specimen's tensile strength varies depending on where the weld connection is strongest. The ideal parameters for high tensile strength, according to Taguchi research, are 1200 rpm, 30 s dwell duration, and 0.15 mm plunge depth.

- The most important factor influencing the hardness control is dwell time. The other factors that affect hardness are spindle speed and plunge depth, in that order of significance. The results of this investigation show that the dwell time (t = 66.00 %), plunge depth (D = 15.74 %), and spindle speed (N = 4.00 %) have the biggest effects on the hardness of the sample. The strength of the joint is inversely correlated with its hardness.
- According to the metallurgical examination, the minimum hook height will be formed by welding operating conditions such as spindle speed of 1000 rpm, dwell time of 25 s, and depth of 0.20 mm, with parameters contributing N = 4.2 %, t = 66.23 %, and D = 15.75 %, and the mean hook width will be formed by welding conditions such as 2000 rpm, 3 s, and 0.10 mm, with parameters contributing N = 32.55 %, t = 27.

4 ACKNOWLEDGEMENTS

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5 REFERENCES

[1] Ravi, K.K., Narayanan, R.G., Rana, P.K. (2019). Friction Stir Spot Welding of Al6082-T6/HDPE/Al6082-T6/HDPE/Al6082-T6 sandwich sheets: Hook formation and lap shear test performance. *Journal of Materials Science & Technology*, vol. 8, no. 1, p. 615-622, **DOI:10.1016/j.jmrt.2018.05.011**.

[2] Siddhartha, S., Senthilkumar, T. (2018) Development of friction stir spot welding windows for dissimilar Al5086/C10100 spot joints. *Materials Today Proceedings*, vol. 5, no. 2, p. 6550-6559, **DOI:10.1016/j.matpr.2017.11.310**.

[3] Rana, P.K., Narayanan, R.G., Kailas, S.V. (2018) Effect of rotational speed on friction stir spot welding of AA5052-H32/HDPE/AA5052-H32 sandwich sheets. *Journal of Material Processing Technology*, vol. 252, p. 511-523, **DOI:10.1016/j.jmatprotec.2017.10.016**.

[4] Garg, A., Bhattacharya, A. (2017). Strength and failure analysis of similar and dissimilar friction stir spot welds: Influence of different tools and pin geometries. *Materials and Design*, vol. 127, p. 272-286, **DOI:10.1016/j.matdes.2017.04.084**.

[5] Tashkandi, M.A., Al-jarrah, J., Ibrahim, M. (2017). Spot welding of 6061 aluminum alloy by friction stir spot welding process. *Engineering Technology & Applied Science Research*, vol. 7, no. 3, p. 1629-1632, **DOI:10.48084/etasr.1125**.

[6] Shubhavardhan, R.N., Rahman, M.M. (2017). Effect of FSW parameters on Hook formation, microstructure and fracture strength of Al, Mg alloys. *International Journal of Engineering Development and Research*, vol. 5, no. 2, p. 1730-1736.

[7] Satheesh, C., Sevvel, P., Senthil Kumar, R. (2020) Experimental identification of optimized process parameters for FSW of AZ91C Mg alloy using quadratic regression models. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 66, no. 12, p. 736-751, **DOI:10.5545/sv-jme.2020.6929**.

[8] Cao, J.Y., Wang, M., Kong, L., Guo, L.J. (2016). Hook formation and mechanical properties of friction spot welding in alloy 6061-T6. *Journal of Materials Processing Technology*, vol. 230, p. 254-262, **DOI:10.1016/j.jmatprotec.2015.11.026**.

[9] Piccini, J.M., Svoboda, H.G. (2015). Effect of the tool penetration depth in friction stir spot welding (FSSW) of dissimilar aluminum alloys. *Procedia Materials Science*, vol. 8, p. 868-877, **DOI:10.1016/j.mspro.2015.04.147**.

[10] Piccini, J.M., Svoboda, H.G. (2017). Tool geometry optimization in friction stir spot welding of Al-steel joints. *Journal of Manufacturing Processes*, vol. 26, p. 142-154, **DOI:10.1016/j.jmapro.2017.02.004**.

[11] Van, A.-L., Nguyen, T.-T. (2022). Optimization of friction stir welding operation using optimal taguchi-based ANFIS and genetic algorithm. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 68, no. 6, p. 424-438, **DOI:10.5545/sv-jme.2022.111**.

[12] Badarinarayan, H., Shi, Y., Li, X., Okamoto, K. (2009). Effect of tool geometry on hook formation and static strength of friction stir spot welded aluminum 5754-O sheets. *International Journal of Machine Tool Manufacture*, vol. 49, no. 11, p. 814-823, **DOI:10.1016/j.ijmachtools.2009.06.001**.