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Effect of Single Point Incremental Forming (SPIF) Process Parameters on Surface Roughness of Dissimilar Tailor Welded Blanks using the Taguchi Method

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ABSTRACT

In the present paper, the Taguchi method is implemented to figure out which set of process parameters is optimal for forming dissimilar aluminum alloy blank joints together using friction stir welding. In single-point incremental forming (SPIF), four process parameters were taken into consideration: rotational speed, feed rate, step size, and wall angle. Measurements were made on both sides, inner and outer of each surface of the formed part due to dissimilar material of tailor welded blanks (TWBs) to see the pattern and relationship. The results show that step size is the most important parameter, then the wall angle. The rotating speed and feed rate had the least impact on surface roughness. The optimal parameters are a 0.2 mm step size, a 55-degree wall angle, a 1500 rpm rotational speed, and a 1000 mm/min feed rate for the inner and outer surfaces of AA5052. While the AA6061 gives the optimum values of 0.2 mm step size, a 55-degree wall angle, and a 1000 mm/min feed rate on the inner and outer of the measured surface, the slightly different optimum values on the rotational speed are 1250 rpm and 1750 rpm for the inner and outer surfaces, respectively. On Analysis of Variance (ANOVA) showed the step size has a greater percentage contribution effect on the surface roughness of formed TWBs than any other parameter. Furthermore, confirmation test results using optimal conditions showed good agreement wit experimental findings.

Keywords: Surface roughness; single point incremental forming; tailor welded blanks; Taguchi method

INTRODUCTION

Single-point incremental sheet forming (SPIF) is a new technology used for rapid prototyping of sheet parts. (Trzepieciński et al. 2022). The process involves forming a blank sheet locally and progressively utilizing a hemispherical tool while adhering to a 3-axis CNC machine-controlled tool path. This technology is utilised in numerous disciplines to produce complex parts for small batches and prototypes (Dakhli et al. 2019). Due to its numerous advantages, friction stir welding (FSW) is a solid-state welding technique that shows great promise (Glaissa et al. 2020; Mamgain, Singh, et al. 2023). Mainly on the capability of joining dissimilar material (Shah et al. 2020;Shubham et al. 2022).

In order to produce lighter parts that contribute to the overall weight reduction of the car, these technologies are applied in various application (Oleksik et al. 2021). Door panels, pillars, and rear long members for luxury or race cars are a few of the example of products which are produced in small batches and units by combining the two processes (Mamgain, Pratap Singh, et al. 2023; Mohan et al. 2024; Nasir et al. 2020). More application can be seen on high-speed train components and the aeronautics industry's customization of luxury airplanes, and recently, in architecture, where materials with varying colors and textures can be used to produce unique design (Andrade-Campos et al. 2020; Thuillier et al. 2019).

Due to the nature of the process, frequently incremental forming may produce a rough surface on one side of the formed sheet, which is typically known as the "orange peel pattern" (Liao et al. 2020). Part quality, dimensional accuracy and time of processing become the main constraints of the process (Gandla et al. 2020). This is because, to produce prototypes with good surface quality, it is important to control the surface roughness (Echrif & Hrairi, 2014). The issue worsens when two different materials are joined together, which both have their own behaviour towards forming and properties (Martinsen et al. 2015).

In the single-point incremental forming, there are many material and process parameters, including wall forming angle, tool size and shape, step size, friction and lubricant, and sheet thickness that must be controlled to achieve a better surface roughness. The investigations were summarized in Table 1, which shows that the most frequently identified parameters that are significant to the surface roughness are step size and wall angle, while feed rate is among the insignificant ones.

TABLE 1. Significant parameter on previous study

References	Parameters Studied	Material	Most Significant Parameter
Dabwan et al. (2020)	Sheet thickness, Tool diameter, Step depth and Feed Rate	AA1050-H4	Tool diameter
Mohanty et al. (2019)	Wall angle, Step depth and Feed rate	AA1100-H14	Wall angle and Step depth
Mulay et al. (2017)	Tool diameter, Sheet thickness, Step depth and Feed Rate	AA5052-H32	Tool diameter and Step depth
Kumar et al. (2021)	Wall angle and Step size	AA2024-T3	Wall angle and Step size
Kumar et al. (2019)	Step depth, Spindle speed, Tool diameter and Wall angle	AA1200-H14	Step depth
Azpen et al. (2018)	Tool rotational speed, feed rate, step size and tool diameter	AA6061-T6	Tool diameter
Murugesan et al. (2022)	Tool radius, Spindle speed, Step size and Feed rate	AA3003-H18	Step size

Mulay et al. (2017) investigated the impact of process variables on surface roughness, including tool diameter, sheet thickness, step down, and feed rate using AA5052-H32 Al alloy sheets. The two most significant variables influencing surface roughness have been determined to be tool diameter and step size. Mohanty et al. (2019) researched into how various process variables affected the surface roughness of sheets made of the Al-1100 alloy. It can be concluded that forming angle has the greatest impact on surface roughness, followed by step depth and the least amount of feed rate affects surface quality. Oraon et al. (2020) investigated the analysis of the Al-Mg alloy to determine how SPIF process parameters affected the average surface roughness. and according to the outcome, the only input parameter that significantly influences surface roughness is the step depth.

In the literature, there are several research studies on the impacts of various parameters like wall angle and step size, on surface roughness. However, all of them only involve a single material. Therefore, the main objective of research is to investigate the effects of the SPIF parameters on the average surface roughness of tailor-welded blank made from two dissimilar aluminum alloys.

METHODOLOGY

MATERIALS

The dissimilar blank is fabricated by friction stir welding (FSW) process is consist of AA 5052-H32 and AA 6061-T6 sheets with a thickness of 1.6 mm. Table 2 shows the chemical composition for both materials (Aziz et al. 2024; Cinar et al. 2021). The plates utilised for the FSW butt-joint operation had dimensions of 85 mm x 200 mm, resulting in the production of TWBs with dimensions of 170 mm x 200 mm. Figure 1 (a) illustrates the process setup, (b) schematically show the tool use and (c) the fabricated blanks.

TABLE 2. Chemical composition of AA6061 and AA5052 in weight % (Sindhuja et al. 2021).

Base Materials	Al	Cu	Fe	Mg	Si	Cr	Zn	Mn
AA 6061	95.8-98.6	0.15-0.4	<0.7	0.8-1.2	<0.4	0.04-0.35	<0.25	<0.15
AA 5052	95.7-97.7	<0.1	<0.4	2.2-2.8	<0.25	0.15-0.35	<0.1	<0.1

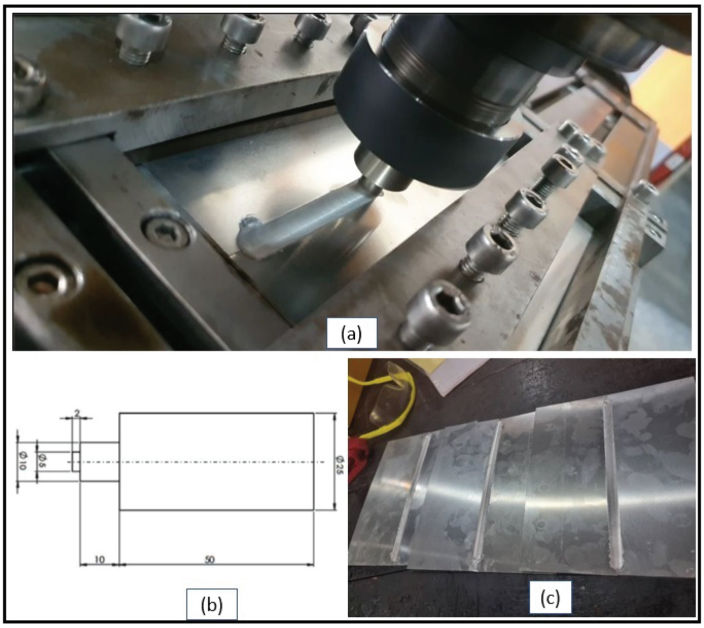

FIGURE 1. FSW (a) Process (b) Tool dimensions and (c) Welded blanks.

After FSWed blanks are produced, the SPIF process is carried out by forming the blanks into a conical shape. The Fusion 360 CAM programmed produced the incremental forming path. The tool swept a spiral helix path, gradually moving downwards and towards the center according to the SPIF parameters and three levels of experiments indicated in Table 3.

TABLE 3. SPIF parameters and levels

Factors	Units	Levels		
		1	2	3
Rotational Speed	RPM	1250	1500	1750
Feed Rate	mm/min	1000	1100	1200
Step Size	mm	0.2	0.3	0.4
Wall Angle	°	55	57.5	60

The forming of TWB into the conical shape with an opening diameter of 100 mm and a forming depth of 30 mm is made using a DMU40 monoblock 5-axis CNC milling machine with a Heidenhain controller. The experiment configuration is shown in Figure 2a. Additionally, Figures 2b illustrates the SPIF process parameters which is rotational speed, feed rate, step size and wall angle. Rotational speed describes the forming tool's rotational speed. It is usually given as rotations per minute (RPM). The distance the forming tool travels in a single spindle revolution is used to define feed rate. In general, it refers to the speed at which the machine drives the router bit through the material when it is forming. Step size, step depth, step down, or pitch size is a distance that the forming tool moves vertically between successive passes or steps during the deformation process, and wall angle refers to the angle between the vertical axis (perpendicular to the forming plane) and the formed wall of the sheet metal workpiece. Figure 2c shows a 3D model of the conical shape. In this research, a SPIF forming tool with a 12 mm nose diameter and a hemispherical tip made of high-speed steel is used.

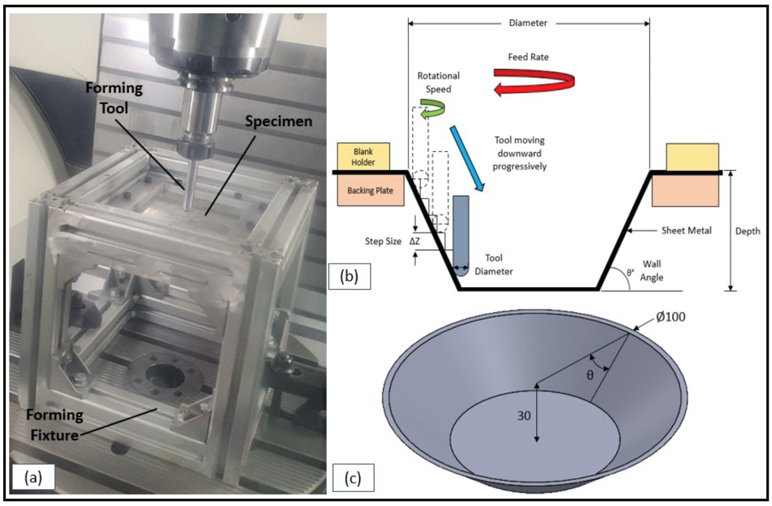

FIGURE 2. SPIF (a) setup (b) SPIF process parameters and (c) 3D model of the conical shape

The average surface roughness (Ra) was measured using Mitutoyo SJ-400 while the formed parts was fixed to the measuring arrangement with a magnetic V-block and the conical frustum's inner and outer surfaces allowed the stylus to freely travel, as seen in Figure 3.

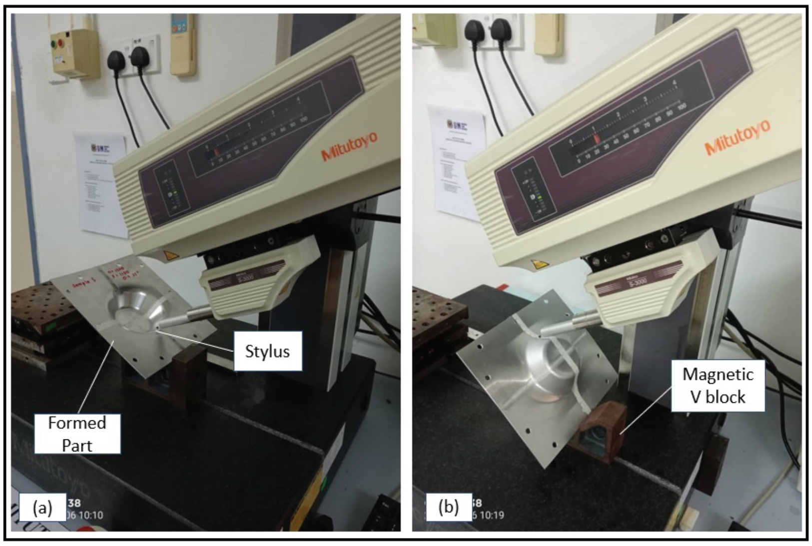

FIGURE 3. Surface roughness measurement setup (a) inner surface (b) outer surface

EXPERIMENT DESIGN AND PROCEDURE

The Taguchi method is utilized for process variable optimization due to its ease of use and simplicity. The method is commonly referred to as the factorial design of experiments. This approach makes use of a subset of arrays known as orthogonal arrays. Selecting the level combinations of the input design variables for every trial is the foundation of the orthogonal arrays approach. The L9 orthogonal array is to analyse four independent variables, each with three factor level values. Table 4 shows the Taguchi method's proposed experiment design based on the combination of all four parameters and three levels. In order to increase the formed frustums' statistical correctness, each formed part was measured five times.

TABLE 4. Taguchi orthogonal array L9

No of samples	Factors			
	Rotational Speed (RPM)	Feed Rate (mm/min)	Step Size (mm)	Wall Angle (°)
1	1250	1000	0.2	55
2	1250	1100	0.3	57.5
3	1250	1200	0.4	60
4	1500	1000	0.3	60
5	1500	1100	0.4	55
6	1500	1200	0.2	57.5
7	1750	1000	0.4	57.5
8	1750	1100	0.2	60
9	1750	1200	0.3	55

The term "noise" in the Taguchi method denotes the undesirable value for the output sign, whereas the term "signal" implies the desired value (mean) for the output sign. Taguchi identified the quality feature that differs from the target value using the S/N ratio. Several S/N ratios are available depending on the type of characteristics: target is best, smaller is better, and larger is better. In this analysis, the criteria of smaller is better is chosen due to low surface roughness. The following equation (1) calculates the quality characteristic of smaller is better.

$$S/N=-10\log(\sum(Y^2)/n) \quad (1)$$

Where Y indicates the number of responses for the given factor level combination and n indicates the number of responses in the factor level combination. S/N ratio represent the optimum values for each parameter and identified most significant parameter that influenced the response.

RESULTS AND DISCUSSION

S/N RATIO ANALYSIS

Table 5 displays the experimental results of average surface roughness (Ra) of all measured sides on formed parts using the Taguchi orthogonal array L9 design of the experiment. Ra and Rb refer to surface roughness values on the AA5052 and AA6061 sides, respectively. The indications *i* and *o* refer to the inner and outer surfaces of the formed parts.

TABLE 5. S/N ratio values for surface roughness (Ra)

No of samples	Factors				Surface Roughness (μm)			
					AA5052		AA6061	
	Rotational Speed (RPM)	Feed rate (mm/min)	Step Size (mm)	Wall Angle (°)	ΔRai	ΔRao	ΔRbi	ΔRbo
1	1250	1000	0.2	55	0.905	0.691	0.812	0.698
2	1250	1100	0.3	57.5	1.269	0.948	0.983	0.875
3	1250	1200	0.4	60	1.587	1.118	1.064	1.102
4	1500	1000	0.3	60	1.271	0.966	1.004	0.896
5	1500	1100	0.4	55	1.277	0.975	1.044	0.93
6	1500	1200	0.2	57.5	0.991	0.778	0.831	0.778
7	1750	1000	0.4	57.5	1.356	1.083	1.046	0.921
8	1750	1100	0.2	60	1.088	0.851	0.932	0.79
9	1750	1200	0.3	55	1.244	0.912	0.974	0.87

Table 4 shows that increasing step size and wall angle significantly raises the Ra value of formed components. This is because greater wall angles allow more of the tool tip's lateral surface to contact the sheet material during the forming process, creating a steeper surface on the intended part. Besides, the results showed that the values of Ra on the outer side are lower than those on the inner side of the measured surfaces. It can be summarized that the contact surface affects the surface finish compared with the uncontact surface with the forming tool.

At a lower step size and wall angle of 0.2 mm and 55°, respectively, the Ra value was found to be at its minimum of 0.691 µm. In contrast, the Ra value reached its maximum of 1.587 µm when the wall angle and step size were maintained at higher levels, 60° and 0.4 mm, respectively. As a result, the surface waviness is increased to produce a larger wall angle and step size.

Additionally, it was found that generally the Ra value increased for wall angles of 55°, 57.5°, and 60°, respectively, when the step size was increased from a lower level of 0.2 mm to a higher level of 0.4 mm. Similarly, it was observed that increasing the step size from 0.2 mm to 0.4 mm increased the Ra value at wall angles of 55°, 57.5°, and 60°, respectively. By means, the Ra value is proportional to the value of step size and wall angle.

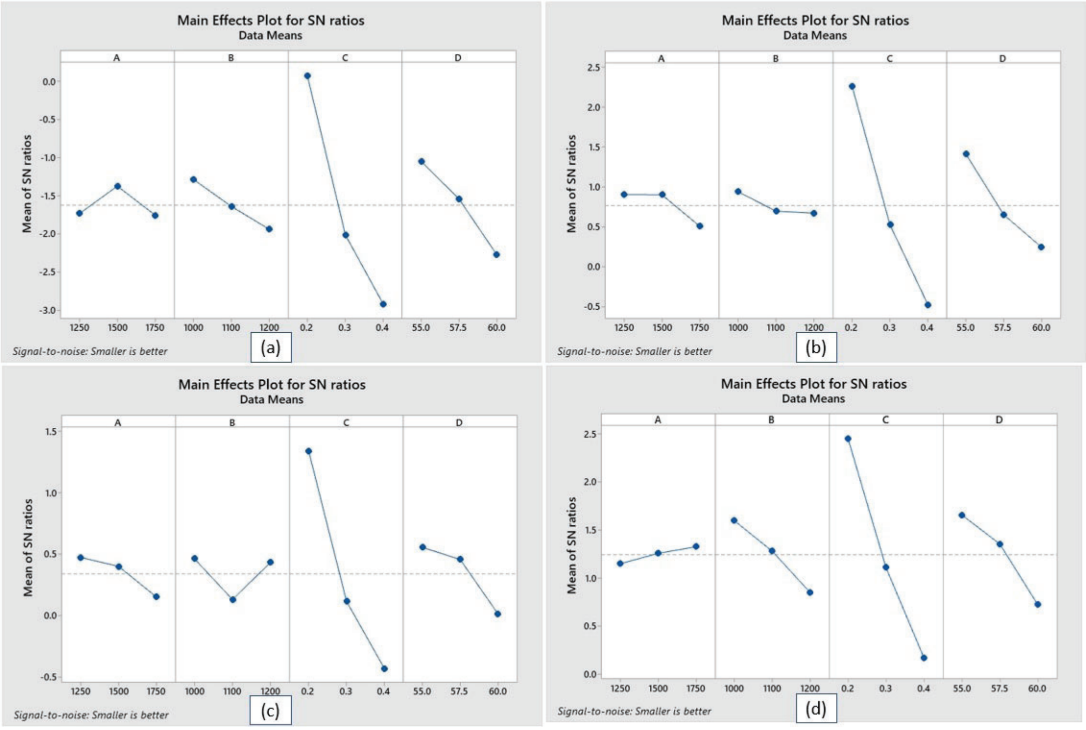

FIGURE 4. Respond graph for S/N ratio of (a) ΔRai (b) ΔRao (c) ΔRbi and (d) ΔRbo

In Figure 4, as can be seen, all four figures show the highest number on the graph for each parameter at its optimum value. On respond graphs Figure 4(a) and Figure 4(b), the S/N ratio for ΔRai and ΔRao shows the same optimal values for rotational speed, feed rate, step size, and wall angle: 1500 RPM, 1000 mm/min, 0.2 mm, and 55°, respectively, to obtain a higher quality of surface finish. The response graph S/N ratio for both the inner and outer sides of the AA5052 gives the same result. On Figs. 4(c) and 4(d), the results on the optimum value for inner and outer AA6061 are different. The inner surface in Figure 4(c) is set to an optimal 1250 RPM for rotational speed, whereas the outer surface in Figure 4(d) is set to an optimal 1750 RPM for rotational speed. However, both have the same optimal values for feed rate, step size, and wall angle, which are 1000 mm/min, 0.2 mm, and 55°, respectively.

ANALYSIS OF VARIANCE (ANOVA)

The important factors influencing the surface finish of dissimilar TWBs were assessed using ANOVA. Table 6 summarizes the ANOVA results for surface roughness, and in this investigation, the level of significance was 5% and the level of confidence was 95%. The C (%) in Table 6 refers to the percentage contribution of the SPIF parameter effect on the surface roughness.

TABLE 6. ANOVA results on surface roughness

Measured side	Rotational Speed		Feed Rate		Step Size		Wall Angle	
	P-Value	C (%)	P-Value	C (%)	P-Value	C (%)	P-Value	C (%)
ΔRai	0.925	2.57	0.875	4.35	0.009	79.13	0.637	13.95
ΔRao	0.944	1.88	0.985	0.54	0.005	82.9	0.621	14.71
ΔRbi	0.93	2.39	0.915	2.99	0.012	86.5	0.774	8.21
ΔRbo	0.955	1.52	0.752	9.06	0.007	75.07	0.628	14.34

Table 6 shows that the P values are lower than 0.05 (or 5%), which indicates that the factor of step size is too significant compared to other parameters. Which means that P values contribute a higher percentage of step size factor on all measured sides of 79.13%, 82.9%, 86.5%, and 75.07%, respectively. According to the ANOVA results, step size has a significant impact, making it a crucial parameter for surface finish. Surface finish depends on the contact area and time between both the tool and the sheet. Therefore, specifying the contact parameters is critical. As a result of the previous research, we can prove that the step size has a significant impact on surface finish. Dodiya et al. (2021) reported that step size is found to be the second most significant factor influencing surface roughness after tool diameter. Lasunon (2013) found that a small step size and a high wall angle are advantageous for achieving a smooth surface finish. According to Darmanshu & Dutt, (2022), step size and tool size also significantly affect the aluminum alloy AA1050's surface roughness. Jagtap et al. (2015) investigated the effect of tool path, tool diameter, and step size on surface roughness (Ra). The Ra value decreases with decreasing step size and increasing tool diameter. Sisodia & Kumar, (2018) reported that a small step size should be applied in order to achieve a good surface finish on the formed part.

REGRESSION MODELS

Only significant parameters are considered when predicting the optimal values of SPIF parameters. Significant parameters are those that have significant effects on the surface roughness. These significant parameters were identified using ANOVA on S/N ratio data on SPIF parameters. Linear regression is one of the options to determine the optimum value for surface roughness. A statistical method known as "linear regression" models the connection between a dependent variable and one or more independent variables by fitting a linear equation to observed data. Linear regression seeks the best-fitting line that represents the relationship between the variables. In this study, Minitab 19 software was used to generate the regression analysis of optimum surface roughness.

$$\Delta R_{ai}=-1.849-0.000049A+0.000483B+2.06C+0.0347D \quad (2)$$

$$\Delta R_{ao}=-1.086-0.000059A+0.000113B+1.427C+0.0238D \quad (3)$$

$$\Delta R_{bi}=-0.081-0.000062A+0.00012B+0.965C+0.01133D \quad (4)$$

$$\Delta R_{bo}=-1.316-0.00016A+0.000438B+1.355C+0.02727D \quad (5)$$

TABLE 7. Linear regression prediction for optimum surface roughness

Response	Optimum Parameters				Linear Regression Predictions (μm)
	A	B	C	D	
ΔRai	1500	1000	0.2	55	0.831
ΔRao	1500	1000	0.2	55	0.678
ΔRbi	1250	1000	0.2	55	0.812
ΔRbo	1750	1100	0.2	55	0.743

Based on the regression equations (2) to (5), the SPIF parameters have been labeled as rotational speed (A), feed rate (B), step size (C), and wall angle (D) of each measured side. The value of the regression results is shown in Table 7, where linear regression gives prediction values of optimum surface roughness of 0.880μm, 0.711μm, 0.824μm, and 0.657μm for ΔRai, ΔRao, ΔRbi, and ΔRbo, respectively.

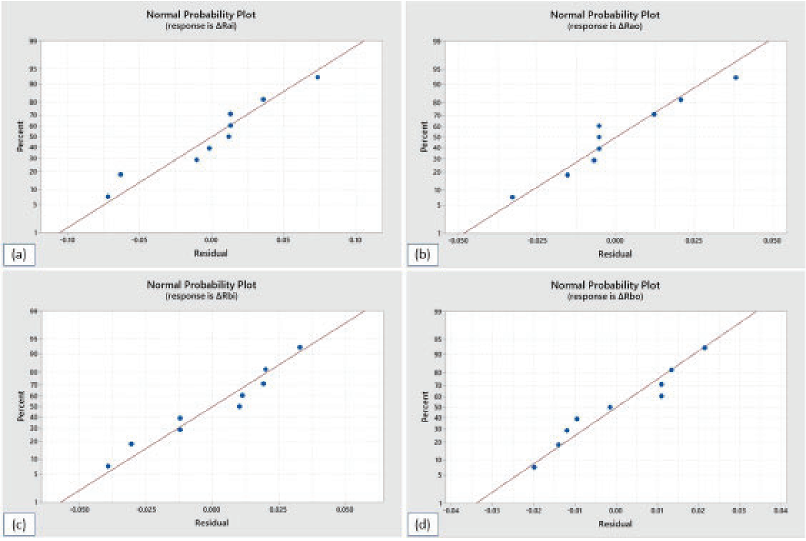

FIGURE 5. Linear regression graph of (a) ΔRai (b) ΔRao (c) ΔRbi and (d) ΔRbo

Figure 5 shows the normal probability plot with surface roughness as a response. It is used to identify deviations from normality. It plots the cumulative percentage against the residuals of a dataset. In this plot, there is a red reference line indicating where the data points would lie if they followed a perfect normal distribution. The blue dots represent actual data points. If these points fall along the reference line, it suggests that the data is normally distributed; deviations indicate non-normality. "Residual" values are shown by the x-axis, and "percent" values are represented by the y-axis. There are nine blue dots scattered on the plot, representing individual data points. A red straight line runs diagonally across the plot, serving as a reference for normal distribution. Based on the graph, Figure 5(a), (c), and (d) show the numbers of blue dots are slightly balanced at the upper and lower red lines. The positions of the blue dots are close to the red line, which suggests that the data is normally distributed. However, Figure 5(b) shows the numbers of blue dots are not balanced at the upper and lower ends of the red line. The positions of the several blue dots are slightly away from the red line, which indicates that the data may not be normally distributed. This result may be due to the effect of the measuring method on the flatness of the conical surface, which may influence the result on the roughness of the surface.

CONFIRMATION TEST

The validity of the analysis's projected optimum surface roughness value was determined by a validation test. Validating whether the predicted value is within the permitted range requires comparing the test result with the predicted value. The comparison of the actual result and the predicted value is shown in Table 8. It was found that the percentage error difference between the actual value and the prediction optimal value was 2.853%, 2.827%, 1.456%, and 6.402% for ΔRai, ΔRao, ΔRbi, and ΔRbo, respectively.

TABLE 8. Comparison between predicted value and actual value

Response	Predicted Optimal Value	Actual Value	Error (%)
ΔRai	0.880	0.905	2.853
ΔRao	0.711	0.691	2.827
ΔRbi	0.824	0.812	1.456
ΔRbo	0.656	0.698	6.402

CONCLUSIONS

The study has been successfully conducted to determine the significant SPIF parameters that influence the surface roughness of dissimilar materials in TWBs. The following findings can be drawn from the study:

1. The S/N ratio results based on the Taguchi method indicate the step size is the most significant parameter, with all at the first rank that influence the surface roughness on formed parts when compared to other parameters at both measured sides.
2. According to the ANOVA results, the step size has a greater percentage contribution effect on the surface roughness of formed TWBs than any other parameter.
3. The optimal parameters are a 0.2 mm step size, a

55-degree wall angle, a 1500 rpm rotational speed, and a 1000 mm/min feed rate for inner and outer surfaces of AA5052.

4. The optimal parameters are a 0.2 mm step size, a 55-degree wall angle, a 1000 mm/min feed rate but slightly different on rotational speed which are 1250 rpm and 1750 rpm for inner and outer surfaces of AA6061.
5. Even though the result on the AA6061 side has a slightly different optimum value of rotational speed on the inner and outer measured surfaces, the parameter has the least effect on the surface roughness compared to the step size.
6. The confirmation test revealed that the optimal settings indicated good agreement with the experimental observation, with a deviation of error less than 10%.

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DECLARATION OF COMPETING INTEREST

None.

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