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Springback Optimization of Dissimilar Thickness AA6061-T6 Blank Joint with Double Butt-Lap (DBL) Using Taguchi Method and ANOVA

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Abstract

This study focuses on investigating the effect of welding parameters, specifically spindle speed, feed rate, and tool tilt angle, on the springback of double-butt lap joints blank. To optimize springback of friction stir welded AA6061-T6 blanks with different thicknesses, a Taguchi L9 orthogonal design experiment was utilized. The responses of springback from lines perpendicular and parallel to the welding line were observed, and the optimal parameter combination for each type of springback was determined. Analysis of Variance (ANOVA) revealed that the tilt angle contributed the most to springback (parallel to the weld line) with 50.4%, while the spindle speed contributed the most to springback (perpendicular to the weld line) with 52.5%. Through confirmation testing, the optimal FSW parameters were validated.

1. Introduction

Friction stir welding (FSW), developed in 1991 at The Welding Institute (TWI) in the United Kingdom [1], is an environmentally friendly and energy-efficient solid-state welding process that provides a viable alternative to fusion welding for producing joints with desirable combinations of microstructure and properties [2]. Ongoing investigations of FSW aim to explore its potential for joining difficult-to-weld materials, to deepen the understanding of the thermo-mechanical phenomena that occur during welding, and to evaluate its potential for synthesising and transforming metallic materials of engineering interest [3]. Aluminium, which is lightweight and has high strength, has found wide application in automobiles and aircraft [4] and is known for its low cost, durability, corrosion resistance, and suitability for rigorous service conditions, making it an attractive material for use in the shipbuilding and aerospace industries [5]. Tailor welded blanks (TWBs) made from AA6xxx series aluminium alloys are highly versatile and can be utilised in numerous industries, including sheet metal, automobiles, and aircraft, where they serve as stamped parts for exterior body panels [6].

Friction stir welding (FSW) of aluminium 6061 can be performed using various joint designs, including square butt (SB) joints, edge butt joints, T butt joints, lap joints, multiple lap joints, T lap joints, and fillet joints [7]. In addition to these joint designs, researchers have investigated other joint designs such as scarf joints [8] and staggered joints [9]. Acharya et al., [10] have recently proposed a novel joint design called the “double butt lap” (DBL) joint, which increases the welding surface contact area between the two materials. The DBL joint combines the features of both butt and lap joints, resulting in an interlock between the materials that reduces vibration and mismatch during machining and improves FSW quality.

The quality of aluminium TWB in FSW is dependent on the process parameters, which can be optimised to achieve the desired outcome. Gite et al., (2019) identified several process parameters, such as tool geometry, tool and workpiece material, tool speed of rotation, and traverse speed. Among these, feed rate, spindle speed, and tool tilt angle are the most commonly studied due to their significant impact on joint quality. Asmare et al., [11] successfully performed FSW of AA 6061 plates using different welding parameters and found that rotating speed and traverse speed became significant parameters at a 99% confidence interval with a joint efficiency of 91.3%. Additionally, Andrade et al., [12] found that tool dimension and rotational speed are the main parameters governing torque and temperature, followed by traverse speed and the base material thickness. Material flow during welding is caused by variations in temperature, stresses, and torque due to various tool tilt angles, which can cause welding defects [13]. A tool tilt angle of 2.5^0 is ideal for good weld surface morphology, as the shoulder can restrict and forge the plasticized material well. Yuvaraj et al., [4] found that the tool tilt angle was the most influential factor, contributing to 45.8% of the friction stir welded dissimilar joint tensile strength, followed by the tool pin shape (40.3%) and tool offset (12.4%).

The strength of friction stir welded joints is affected not only by parameter selection but also by variations in rolling direction and thickness. This has been corroborated by recent studies, such as those by Kalashnikova et al., [14] who found that the ultimate tensile strength of joints in the transverse direction exceeded that in the rolling direction. Accordingly, optimal welding parameters should be tailored to the specific workpiece configuration. Additionally, Zhang et al., [15] demonstrated that proper alignment of aluminium workpieces according to rolling and transverse directions resulted in joints with superior tensile strength due to favourable material flow and heat generation. Joining different thicknesses via FSW presents a challenge for researchers and machinists, as different parameter combinations must be optimized to achieve good joint quality. Despite this challenge, the structural advantages of FSW-produced TWBs make them attractive for automotive engineering applications, as they can reduce vehicle weight and, consequently, oil consumption. However, the difference in TWB thickness affects the springback value of the joint. Adnan et al., [16] demonstrated that springback (%) varied with changes in thickness ratio while Martinez et al., [17] found that tool dimensions and parameter selection influenced weld dissolution and re-precipitation, with little dependence on plate thickness. Consequently, investigating the effect of thickness, rolling angle, and DBL joint on springback output could yield valuable insights.

The study conducted by Ma et al. [18] investigates the effect of gap variation on joint quality and thermomechanical behaviour in 2A14-T6 aluminum alloy friction stir butt welding and identifies that defects arise at gap widths of 1.6 and 2 mm, joint efficiency decreases significantly when the gap exceeds 1.6 mm, and the thermomechanical model shows incomplete filling of the cavity created by the tool's forward motion when the gap exceeds 0.8 mm. The DBL joint offers the advantage of interlocking the movement of two plates, in addition to reducing the gap between them, which helps to keep the plate in position. Li et al., [19] examined the influence of initial gap size on welding distortion and residual stress in a thin-plate partial-length butt-welded joint, finding that contact behaviour can increase out-of-plane deformation, which intensifies as the initial gap size decreases, and does not occur when the initial gap size exceeds transverse shrinkage. Singh et al,. [20] demonstrated that utilizing a pin profile design with a larger contact area between plates can effectively address the gap issue and lead to increased material stirring and filling of the cavity behind the tool pin. Investigating the joint configuration in which a DBL joint mechanism is utilized is believed to be a viable solution for addressing the gap issue between two plates in FSW by minimizing movement through effective interlocking, although its effectiveness needs to be demonstrated.

Conventional experimental procedures to evaluate the effects of FSW process parameters are time-consuming because they involve changing one parameter at a time while keeping other values constant. To address this issue, the Taguchi statistical design is an effective method that can identify significant factors from a large range of variables with minimal experiments [21]. Previous studies have shown that rotating speed, welding speed, and plunge depth are significant control factors that contribute to joint tensile strength, with approximately 53%, 26%, and 17% overall contributions, respectively [22]. Similarly, Sunmugasundaram et al., [23] found that tool rotating speed has the greatest influence on tensile strength, followed by tool tilt angle and welding speed. Despite some variations in the percentage contribution value, spindle speed remains the most dominant parameter compared to others. While the Taguchi method is frequently used to optimize FSW process parameters, there has been very limited research on using this approach on the AA6061 DBL joint for dissimilar thicknesses. This study employs the Taguchi approach to optimize the process parameters for DBL joints and investigate the correlations between parameters and properties. The experimental results are analyzed using S/N and ANOVA to systematically examine the relationships between process parameters and mechanical properties. The findings of this study will assist researchers in identifying the best combination of FSW parameters for producing high-quality AA6061 TWB and provide alternative joint configurations.

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2. Methodology

The FSW process was performed on the 6061-T6 aluminium alloy with a double butt lap joint configuration (Figure 1). The advancing side was composed of 200 x 90 x 2.0 mm plates, while the retreating side had 200 x 90 x 1.5 mm plates, and the rolling directions used in the fabrication of the TWB were $90^0/0^0$. A rolling direction of $90^0/0^0$ and a thickness difference of 2 mm and 1.5 mm were selected based on their superior joint strength in comparison to rolling directions of $0^0/0^0$ or $90^0/90^0$ when joining materials of dissimilar thickness [24]. A displacement-controlled milling machine was used to perform the FSW method, and the number of experiments was determined using Taguchi's L9 orthogonal array, as presented in Table 1. The FSW tool, designed from D2 tool steel and heat-treated to 62 HRC, had a shoulder diameter of 10 mm, a pin diameter of 5 mm, and a pin length of 1 mm, as illustrated in Figure 2. A custom-made fixture was used to secure the DBL joint configuration, with each aluminium sheet clamped to a steel backing plate and secured by a pair of clamps on both sides. Prior to commencing the FSW process, spindle speed, feed rate, and tilt angle were set.

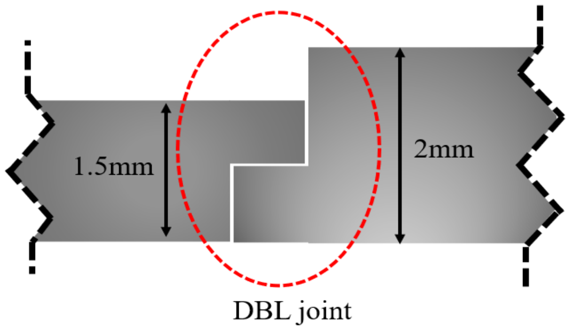

Fig. 1 *Double butt lap (DBL) joint configuration*

Table 1 *Taguchi L933 orthogonal array parameters setup*

Experiment Number	Spindle Speed (RPM)	Feed Rate (mm/min)	Tilt Angle (^{0})
1	410	65	1
2	410	90	2
3	410	127	3
4	865	65	2
5	865	90	3
6	865	127	1
7	1140	65	3
8	1140	90	1
9	1140	127	2

In order to determine the maximum tensile strength of each experimental sample with varying parameters, a tensile test was conducted on an INSTRON 3367 universal testing machine (UTM), and the tensile specimens were cut in accordance with ASTM E8 using an EDM wire cut. The TWB is also cut using an EDM wire cut to a specific dimension (Figure 3), and to evaluate the springback of the TWB, a V-bending test will be performed using dies set on a hydraulic press machine (TMC 30T) by setting a constant speed of 5 mm/s of crosshead speed. Both parallel and perpendicular bending to the weld line will be tested to determine the spring back value, with experiments conducted using 6mm stroke depths and a dial indicator employed to monitor the stroke depth for each bend. The springback value is calculated by subtracting the loading angle (θ_1) and unloading angles (θ_2), as demonstrated in Figure 4. To reduce the springback, a higher bending angle of 90° (θ_1) was used for all specimens [25]. All springback measurements were performed using a profile projector.

3. Results and Discussion

This discussion will concentrate on the springback pattern of the welded blank bend at the parallel and perpendicular weld line, and optimization was performed using MINITAB 17. Figure 5 illustrates how the specimens were mounted on a hydraulic press machine, with the same tooling angles and radius utilised to bend the specimens at 90°. Once the load was released, the specimens were removed from the die, and springback was measured for each specimen. To evaluate the process performance characteristics and minimise the percentage of springback within the optimal values of machining parameters, the smaller-the-better signal-to-noise (S/N) ratio was applied.

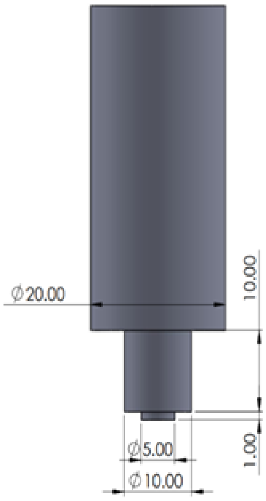

Fig. 2 *Tool profile and dimension (mm)*

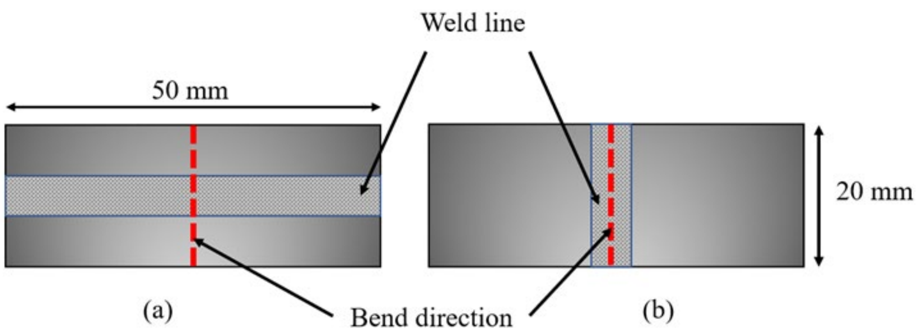

Fig. 3 *Bending direction (a) Perpendicular; (b) Parallel*

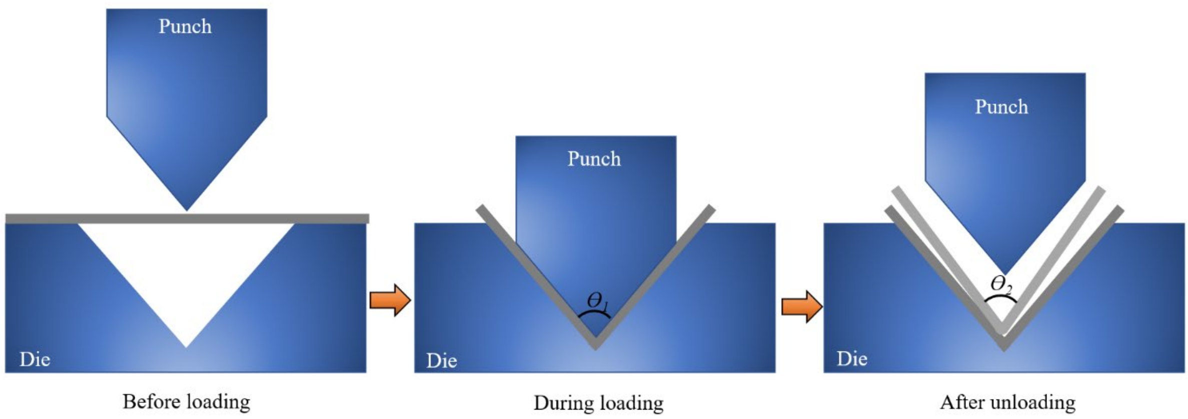

Fig. 4 *Formation of V-bending of the TWB before loading, during loading, and after unloading*

3.1 Parallel to Weld Line

Table 2 presents the experimental $L_9 3^3$ orthogonal design for springback results and signal-to-noise ratios (where lower values are preferred) of springback values for the parallel weld line. From Table 2, it is observed that the highest springback values are obtained for experiment number 6, while the lowest springback values are obtained for experiment number 9. The S/N ratio response tables for springback parallel to the weld line are presented in Table 3. The ranking of factors that have the greatest influence on the springback value is based on the S/N delta value (subtraction of maximum and minimum value) and the highest individual S/N ratio value for each factor represents the best parameter level for springback. The response Table 3 reveals that the springback values for different weld lines produce different results, with spindle speed having the most significant influence on the springback value parallel to the weld line, followed by tilt angle and feed rate. Figure 6 shows that the best parameters for springback parallel to the weld line are determined to be 1140 rpm for the spindle speed (level 3), 90 mm/min for the feed rate (level 2), and a 2^0 tilt angle (level 2). ANOVA is performed to ascertain the significance level of the control parameters on the springback performance characteristics. The R-Sq values in Table 4 summarise the result percentage. The results indicate that the tilt angle and spindle speed parameters have a significant influence on the springback value parallel to the weld line, with the tilt angle having a 50.4% influence and the spindle speed having a 45.0% influence. The feed rate parameter has the smallest influence value of 3.6%.

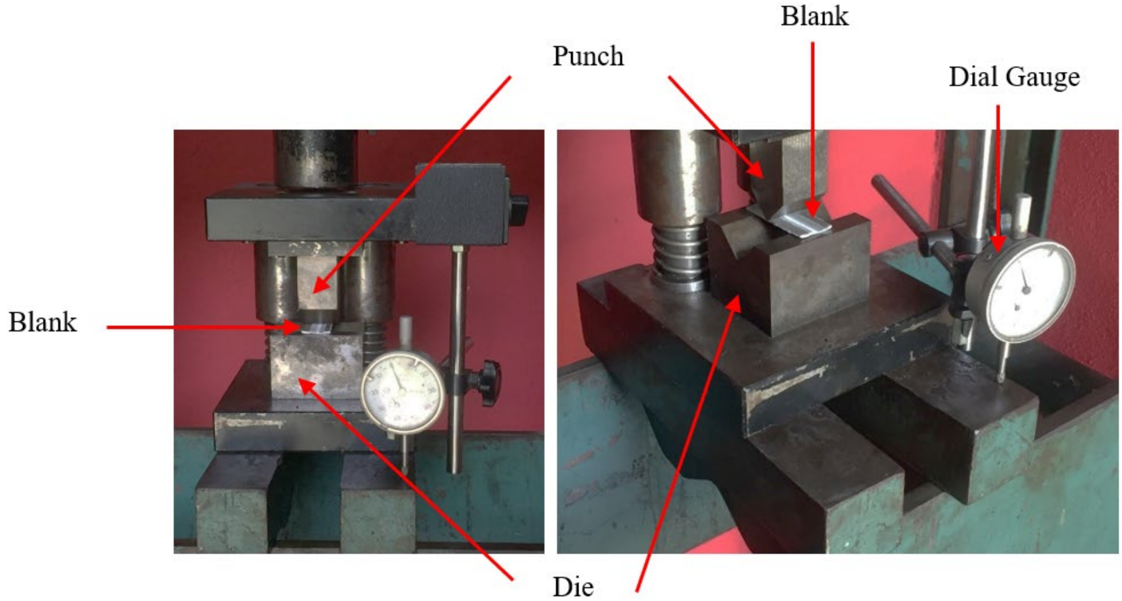

Fig. 5 *Hydraulic press machine setup*

Table 2 *Springback results parallel to weld line and signal to noise ratios (smaller is better)*

Experiment Number	Springback Parallel to Weld Line (^{0})	S/N Ratio (dB)
1	2.992	-9.519231784
2	1.523	-3.653998067
3	2.097	-6.431968609
4	2.343	-7.395445772
5	2.362	-7.465597866
6	3.206	-10.11927036
7	1.48	-3.405234308
8	2.083	-6.373785399
9	1.277	-2.123817945

Table 3 *Response table signal-to-noise ratios for springback parallel to the weld line (smaller is better)*

Level	Spindle Speed (rpm)	Feed Rate (mm/min)	Tilt (^{0})
1	-6.535	-6.773	-8.671
2	-8.327	-5.831	-4.391
3	-3.968	-6.225	-5.768
Delta	4.359	0.942	4.28
Rank	1	3	2

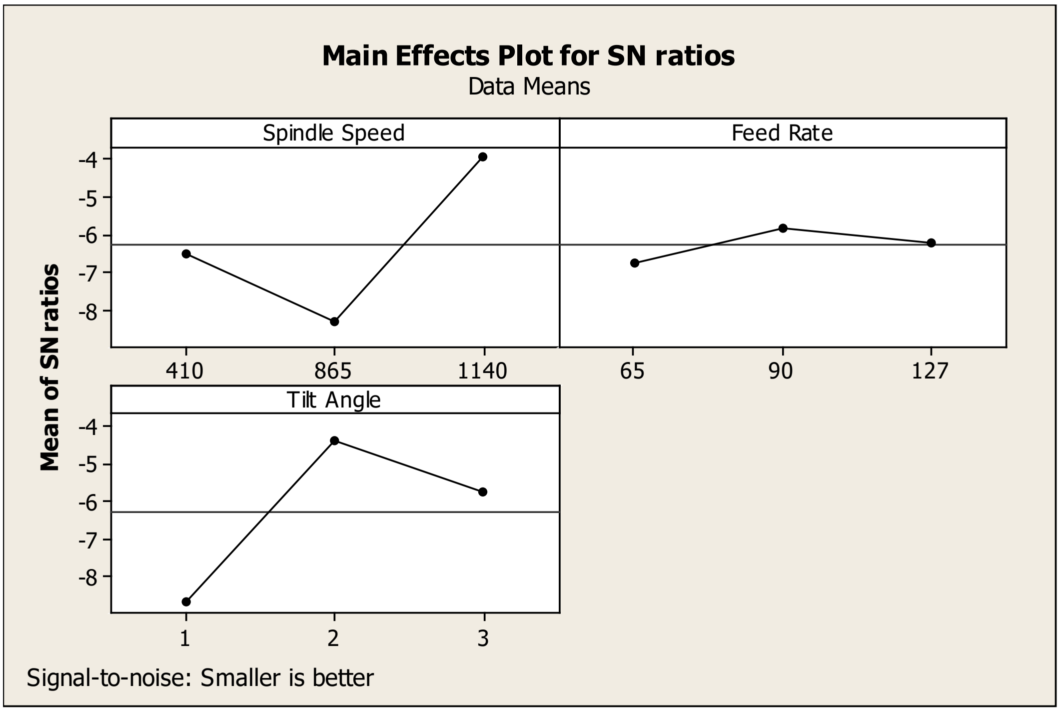

Fig. 6 *Effect of spindle speed, feed rate and tilt angle to springback parallel to weld line*

Table 4 *One-way ANOVA for springback*

Parameter	Springback (Parallel to weld line)	Springback (Perpendicular to weld line)
	R-Rq (%)	R-Rq (%)
Spindle Speed	45.0	52.5
Feed Rate	3.6	19.4
Tilt Angle	50.4	7.0

3.2 Perpendicular to Weld Line

Table 5 presents the results of the L_93^3 orthogonal design experiment for springback values perpendicular to the weld line, including signal-to-noise ratios (where lower values are preferable). The outcomes indicate that the highest and lowest springback values were achieved in experiments 1 and 5, respectively. Table 6 demonstrates the S/N ratio response tables for springback perpendicular to the weld line, revealing that the spindle speed has the most significant influence on springback, followed by feed rate and tilt angle. The optimal settings for achieving the best springback value perpendicular to the weld line are 865 rpm for the spindle speed (level 2), 127 mm/min for the feed rate (level 3), and a tilt angle of 2^0 (level 2), as depicted in Figure 7. The ANOVA analysis in Table 4 confirms that springback has a significant impact, with a substantial difference observed between the two types of springback. The spindle speed, feed rate, and tilt angle have significant influences of 52.5%, 19.4%, and 7.0%, respectively, on the springback value perpendicular to the weld line.

3.3 Confirmations Test

The confirmation test was utilized to assess the consistency of experimental outcomes with predicted results. The predicted results are calculated from the equation (1) [26]. The total mean, T, and significant factor of optimized value, Ti, for both springback are as shown in Table 7.

$$\eta = T + \sum_{i=1}^{q} T_i - T \quad (1)$$

Where;
η = predicted value, T = total mean, T_i = significant factor of optimise value

Table 5 *Springback results perpendicular to weld line and signal to noise ratios (smaller is better)*

Experiment Number	Springback Perpendicular to Weld Line (^{0})	S/N Ratio: (dB)
1	8.965	-19.05100588
2	7.986	-18.04658612
3	8.578	-18.66772084
4	6.141	-15.76478195
5	3.399	-10.62702329
6	4.881	-13.77017615
7	8.575	-18.66468257
8	7.81	-17.85302068
9	3.604	-11.13569565

Table 6 *Response table signal-to-noise ratios for springback perpendicular to the weld line (smaller is better)*

Level	Spindle Speed (rpm)	Feed Rate (mm/min)	Tilt (^{0})
1	-18.59	-17.83	-16.89
2	-13.39	-15.51	-14.98
3	-15.88	-14.52	-15.99
Delta	5.2	3.3	1.91
Rank	1	2	3

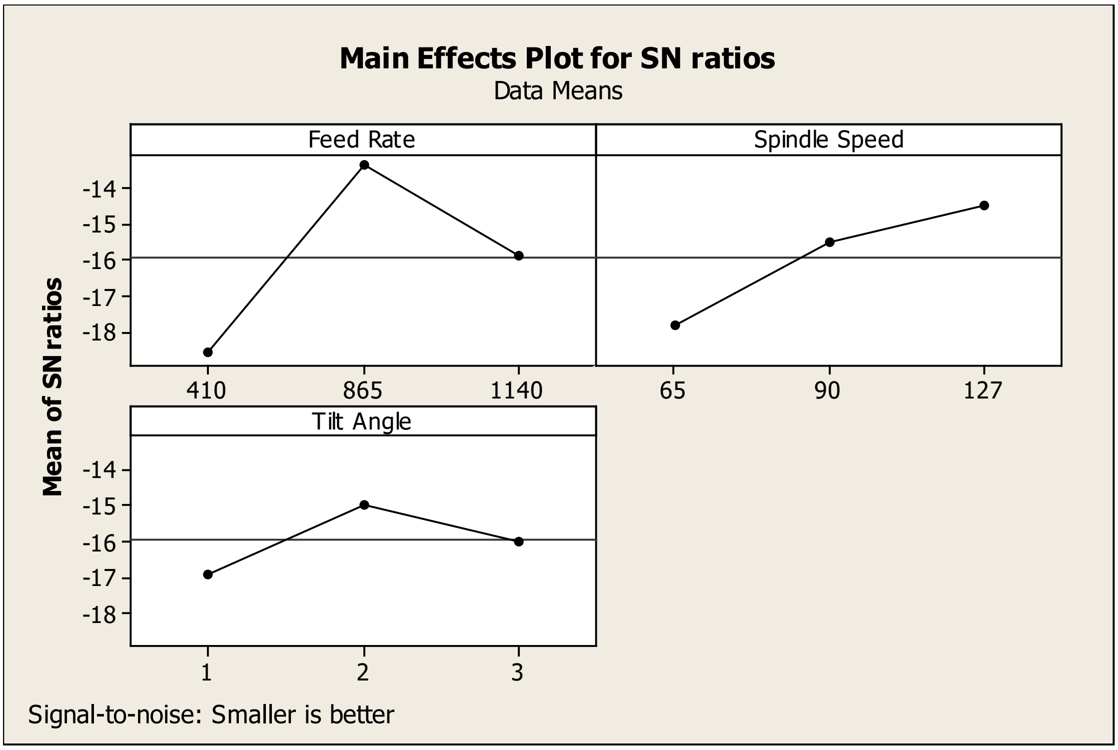

Fig. 7 *Effect of spindle speed, feed rate and tilt angle to springback perpendicular to weld line*

Table 7 *Total mean value and significant factor of optimised value for springback (parallel and perpendicular to the weld line)*

Springback	T	T_i, i=1	T_i, i=2	T_i, i=3
Parallel to weld line	2.151	1.613	1.989	1.714
Perpendicular to weld line	6.66	4.807	5.688	5.91

Table 8 presents the error margins between the predicted and experimental springback values, both parallel and perpendicular to the weld line, respectively. It is observed that the differences between the predicted and actual values are minimal for both types of springback. These small margin values indicate the high reliability of the data obtained from the experiments, affirming its suitability for determining springback values in other combinations of FSW parameters. Additionally, it is noteworthy that the springback (parallel to the weld line) is comparatively smaller than the springback value (perpendicular to the weld line). Therefore, the orientation of the joint parallel to the weld line is deemed superior and more applicable in various engineering fields, particularly in metal sheet forming.

Table 8 *Comparison of the experimental result with the predicted value*

Response	Optimum Parameter		Predict (mean)	Actual	Error (%)
Springback (Parallel to weld line)	Spindle Speed	1140	1.013	1.086	**6.6**
	Feed Rate	90			
	Tilt Angle	2			
Springback (Perpendicular to weld line)	Spindle Speed	850	3.085	3.192	**3.4**
	Feed Rate	127			
	Tilt Angle	2			

4. Conclusions

In this study, the impact of three FSW machine parameters on the springback of a double butt lap joint made of AA6061-T6 alloy was investigated using the Taguchi method. Based on the investigation, it was determined that the optimal parameter settings for springback parallel to the weld line were 1140 rpm spindle speed (level 3), 90 mm/min feed rate (level 2), and 2^0 tilt angle (level 2), according to the signal-to-noise (S/N) ratio response. Similarly, for springback perpendicular to the weld line, the optimal parameters were 865 rpm spindle speed (level 2), 127 mm/min feed rate (level 3), and 2^0 degrees tilt angle (level 2). The results also indicate that the springback (parallel to the weld line) is superior to the springback (perpendicular to the weld line), with respective values of 1.086 and 3.192. Furthermore, a comparison between the predicted values and the confirmation tests revealed that both responses had a small error margin, with 6.6% for springback parallel to the weld line and 3.4% for springback perpendicular to the weld line.

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