Optimizing Friction Stir Welding Process for Enhancing Strength and Hardness using Taguchi Multi-Objective Function Method

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Abstract: As a solid-state welding method, friction stir welding is widely employed for welding aluminium alloys. An important subject in this regard is the optimal adjustment of the parameters to maximize the ultimate tensile strength and the surface hardness. Four parameters have been selected for the multi-objective optimization of the 6061-T6 aluminium alloy, namely the rotational and the linear speed of the tool, the variation of the shoulder diameter with respect to the pin diameter (D/d ratio), and the shoulder base angle. The Taguchi's L9 Orthogonal Array has been employed for designing experiments. The experimental results have been examined using the Taguchi signal-to-noise (S/N) method, the analysis of variance, and regression. Optimization using the multi-objective Taguchi function revealed that a rotational speed of 800 rpm, a D/d ratio of 18/6, a shoulder base angle of 7°, and a linear speed of 80 mm/min yield both maximum strength and surface hardness. The results of the S/N analysis suggested the rotational speed of the tool and the linear tool speed have the most significant impact on the tensile strength with the average of 44.07 dB. On the other hand, the linear speed and the ratio of the diameters have the most significant impact on the surface hardness (around 36.91 dB). The results showed that using this optimization method, simultaneous improvement of tensile strength and surface hardness occurs. In fact, the tensile strength and hardness of the sheet surface were improved by 17.3% and 6.2%, respectively.

Keywords: Aluminium Alloy, Friction Stir Welding, Hardness, Taguchi Technique, Strength

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1 INTRODUCTION

The Friction Stir Welding (FSW) process was introduced by The Welding Institute (TWI) in 1991 [1]. In this method, a non-consumable spinning tool with a convenient inclination is inserted at the contact of two sheets. The heat generated as a result of the friction between the tool and the work-piece deforms the materials, joining the two metal sheets. Figure 1 shows a schematic view of the FSW process. In comparison with the fusion welding processes, the FSW method offers numerous advantages including high welding speed, and desirable mechanical and metallurgical properties [2]. Moreover, this process requires a moderate level of skill and inflicts negligible distortion upon the work-piece. Today, the FSW is extensively applied in the aerospace, shipbuilding, automotive, and arms industries as a result of the unique advantages offered by this process [3-4]. The process can be controlled by adjusting parameters such as the rotational speed of the tool, the linear speed, and the tool geometry. This allows for repeatability and optimization of the joint [5-6].

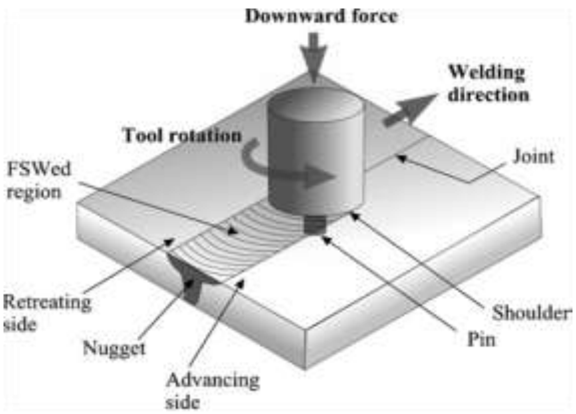

Fig. 1 The friction stir welding process [2].

Zhang et al. [7] studied the effect of the shoulder diameter in FSW using a thermo-mechanical model. Their results showed that the maximum temperature rises with the increasing of the shoulder diameter. Also he announced that the variation of temperature is the main factor for controlling the grain growth near the weld line. However, when the strain and strain rate are low, material deformation is dominant in the controlling of grain growth instead of increasing temperature. Venkateswarlu et al. [8] optimized the parameters of the Mg AZ31B alloy in the process of FSW. The aim of this study was to attain the maximum tensile strength. The researchers conclude that the rotational speed, the linear speed and the shoulder base angle are respectively the most effective parameters on the tensile strength. Zhang et al. [9] numerically studied the impact of the geometry and the size of the tool on the FSW of AA2024-T3 alloy, stating that the level of contact between the bottom of the shoulder and the work-piece is in direct relation with heat generation and the input forces.

Moreover, they concluded that the impact of the variation of shoulder diameter on the temperature is more important than the variation of the pin diameter. Meena et al. [10] investigated the impact of the linear speed, the rotational speed of the tool, and the number of passes on the FSW of the Brass 60/40 alloy using the Taguchi optimization and the analysis of variance. Their results suggest that the number of passes, the linear speed, and the rotational speed are the parameters of the highest impact regarding the hardness of brass sheets, in the same order of significance.

Saravanan et al. [11] studied the impact of the ratio of the shoulder diameter to the pin diameter on the microstructure and the mechanical properties of a friction-stir-welded joint of two different aluminium alloys (AA7075-T6 and AA2024-T6). They stated that the tensile strength and the hardness are changed by changing the diameters of the shoulder and the plunger pin with the highest tensile strength (356 MPa) being associated with a specimen that was welded at a rotational speed of 1200 rpm, a linear speed of 12 mm/min, and a downward load of 8 KN, with a D/d ratio of 3. Moreover, the minimum hardness in the Heat Affected Zone (HAZ) was observed on the advancing side, while the maximum hardness in the Stir Zone (SZ) was found to be 151 HV.

In this study, the parameters of the FSW process of the 6061-T6 aluminium alloy were optimized aiming to increase the ultimate tensile strength (UTS) and the surface hardness using the Taguchi multi-objective function technique. In this regard, four parameters were selected namely the rotational (ω) and linear speed (υ) of the tool, the shoulder diameter with respect to the pin diameter $(\delta = D/d)$, and the shoulder base angle (θ). According to review of the literature, the Taguchi multi-objective function technique has a very high capability to optimize this process. On the other hand, while there are experimental studies on analysis of FSW, the use of these parameters especially the shoulder diameter with respect to the pin diameter to optimize the process has not been reported so far. Also, there is no model to evaluate the effect of input parameters on the final properties of processed material during the FSW process.

2 EXPERIMENTAL PROCEDURE

The 6061-T6 aluminium alloy was used in this study. Sheets were cut in $150 \times 50 \times 5$ mm dimensions to be welded in a butt-joint configuration using the FSW process. The chemical composition and the mechanical properties of the 6061-T6 aluminium alloy are presented in “Tables 1 and 2”, respectively.

Table 1 Chemical composition (wt.%) of AA6061-T6

Al	97.4	Mn	0.0443
Cr	0.163	Si	0.592
Cu	0.259	Ti	0.0225
Fe	0.345	Zn	0.0423
Mg	1.01		

Table 2 Mechanical properties of AA6061-T6

Young’s modulus (GPa)	68.9
Yield Strength (MPa)	276
UTS (MPa)	319
(%)Elongation	16.3
Vickers Hardness (0.5 kg)	107

A jig and a fixture were fabricated to hold the sheets side-by-side (Fig. 2). Figure 3 shows the plan of the tool designed in this study.

Fig. 2 Experimental setup of the FSW process.

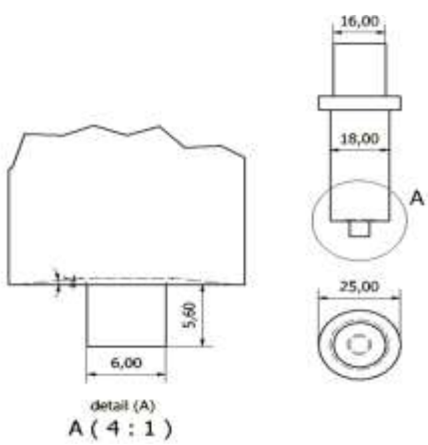

Fig. 3 Tool design.

Many Design of Experiment (DOE) techniques have been presented by researchers previously [12]. Examples include the full-factorial design, the fractional factorial design, the mixture design, and the Taguchi method [2]. One principle is very important in the Taguchi technique, and that is the evaluation of the impacts of the factors on the output by changing the factors. Design of experiment discusses how many times and how much a factor should be changed. DOE techniques allow for obtaining the maximum amount of information required for the subsequent analysis while conducting the fewest number of experiments [13].

In this study, the Taguchi method was employed using the standard L9 orthogonal array. This array consists of four factors, each containing three levels [14]. In standard arrays, the number of rows shows the number of runs while the number of columns indicates the number of factors and interactions. “Table 3” shows the number of factors and their levels. The four factors considered in this study are the rotational speed of the tool, the linear speed of the tool, the shoulder-diameter-to-pin-diameter ratio, and the shoulder base angle.

In order to provide various heat inputs and various plastic deformations, different ratios of shoulder diameter to pin diameter were considered. The idea of addressing the concave angle at the bottom of the tool was to provide more space below the shoulder for the mixture of the materials and more plastic deformation by various shoulder angles. Moreover, it is expected that by combining the shoulder-diameter-to-pin-diameter ratio with the shoulder base angle, the space at the base of the shoulder is changed in both perpendicular and radial directions, leading to various results.

Table 3 FSW process parameters and their levels

Parameter	Level 1	Level 2	Level 3
Tool Rotation speed, ω , (rpm)	800	1000	1250
Tool Travel speed, υ , (mm/min)	40	63	80
ratio D/d	16/4=4	18/6=3	21/6=3.5
Shoulder base angle, θ , (degree)	3	5	7

Accordingly, nine high-carbon H13 steel tools were designed and fabricated. Three shoulder diameters (16, 18, and 21 mm), three pin diameters (4, 6, and 6 mm), and three shoulder base angles (3, 5, and 7°) were considered. After performing the experiments, standard tensile test specimens were prepared to examine and obtain the tensile strength data. Moreover, the Vickers micro-hardness test was carried out with a 200 gf force and a loading time of 10 s. The micro-hardness test was performed on nine points along the weld line (including three points from the advancing side, three points on the centreline of the weld, and three other points from the retreating side). Finally, their average was presented as the surface hardness output. In fact, a hardness profile was assumed for investigating the surface hardness. Aiming to optimize the parameters of the FSW process, the multi-objective Taguchi function (with UTS and hardness objective functions) was employed in this study. Furthermore, the obtained experimental data were analysed using the Taguchi Signal-to-Noise method (S/N).

3 RESULTS AND DISCUSSION

3.1. Signals-To-Noise Ratio

The Signal-to-Noise (S/N) ratio shows the sensitivity of the output data to the effective external factors and uncontrollable factors in a series of controlled experiments [15]. A high S/N indicates that the impact of controllable factors is greater than that of the uncontrollable ones. In other words, it is safe to say that optimal conditions are achieved in an experiment when the output is predominantly affected by the variation of the controlled signal values instead of the noise values. Therefore, the S/N analysis shows the optimal conditions taking place when the Signal-to-Noise ratio is maximum [16]. Generally, there are three quality indicators in an S/N analysis: Smaller is Better, Larger is Better and Nominal is Best. When discussing hardness and strength, it is obvious that the higher these parameters are, the better is the quality. Therefore, the "*Larger is Better*" model was adopted. Transforming a collection of data and observations to a number (the S/N ratio) is carried out in two steps. First, the dissipation function, which equals the Mean Squared Deviation (MSD), is calculated. Then, the S/N ratio of the MSD is calculated using the equation below [17]:

$$S/N=-\log (MSD) \quad (1)$$

In case the quality indicator is "*Larger is Better*", the MSD is calculated as follows:

$$MSD=\frac{\sum_{i=1}^{n}(\frac{1}{y_i^2})}{n} \quad (2)$$

Where y_i represents the response value for the ith experiment of the design, and n shows the number of times the experiment was repeated. Thus S/N can be calculated for each experiment related to the adjustment of a series of factors. The highest S/N value shows the optimal conditions.

In this study, nine values were obtained for the UTS and the hardness. Moreover, nine values were calculated for the S/N ratio. The experiments were all carried out randomly. This was to reduce the noises for each factor. Figure 4 illustrates the nine welded sheets. The experimental results of UTS, surface hardness, and the S/N ratio based on Taguchi method with the L9 orthogonal array are presented in "Table 4".

Fig. 4 Photograph of sheets after welding.

Table 4 L9 orthogonal array, measured responses, and S/N ratio

No	Parameter				Response		ratio S/N	
	υ (mm/min)	ω (rpm)	$\delta = D/d$	θ (degree)	UTS	Hardness	UTS	Hardness
1	40	800	16/4=4	3	167	66.73	44.45	36.48
2	40	1000	18/6=3	5	167	68.07	44.45	36.65
3	40	1250	21/6=3.5	7	167	66.60	44.45	36.46
4	63	800	18/6=3	7	171	73.10	44.65	37.27
5	63	1000	21/6=3.5	3	143	67.47	43.12	36.58
6	63	1250	16/4=4	5	147	70.47	43.34	36.96
7	80	800	21/6=3.5	5	172	71.83	44.71	37.12
8	80	1000	16/4=4	7	152	72.23	43.63	37.17
9	80	1250	18/6=3	3	155	73.10	43.80	37.52

In order to investigate the impact of the parameters of the FSW process on the UTS and the hardness, the mean S/N ratio was calculated for every parameter level. The results for UTS and the hardness are presented in "Tables 5 and 6", respectively. The impact of the FSW parameters on the mean S/N ratio for the UTS and the hardness are illustrated in "Figs. 5 and 6", respectively. The design of experiments and the calculation of the S/N ratio were all carried out by Minitab software. Considering "Table 5 and Fig. 5", it is evident that the ω, υ, δ and θ parameters with values of 800 rpm, 40 mm/min, 18/6=3, and 7° respectively are optimal for achieving the maximum UTS. Moreover, considering Table 6 and "Fig. 6", it is deduced that v, δ, θ, and ω, at 80 mm/min, 18/6=3, 7°, and 800 rpm levels have the largest impact on the surface hardness in that order of significance. Considering the fact that the hardness of metals is reduced by heating, increasing the linear speed exposes the weld surface to less thermal energy, thus preserving its hardness [18]. It should be mentioned that the mean S/N for the nine experiments was 44.07 dB for tensile strength and 36.91 dB for surface hardness.

Table 5 Mean S/N ratio for each level of factors for UTS

Parameter	(dB) Mean S/N ratio			Delta	Rank
	Level 1	Level 2	Level 3		
υ	44.45	43.70	44.05	0.75	2
ω	44.61	43.73	43.87	0.88	1
δ	44.31	44.09	43.81	0.49	3
θ	43.79	44.17	44.25	0.46	4

Table 6 Mean S/N ratio for each level of factors for hardness

Parameter	(dB) Mean S/N ratio			Delta	Rank
	Level 1	Level 2	Level 3		
υ	36.54	36.94	37.19	0.65	1
ω	36.96	36.81	36.90	0.16	4
δ	37.07	36.73	36.87	0.35	2
θ	36.78	36.92	36.97	0.19	3

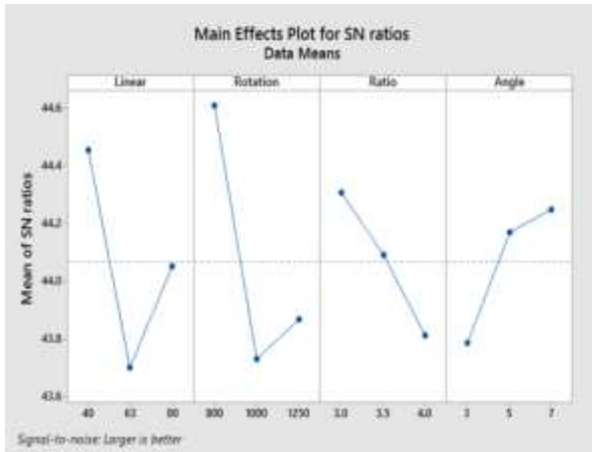

Fig. 5 Main effects plot for UTS.

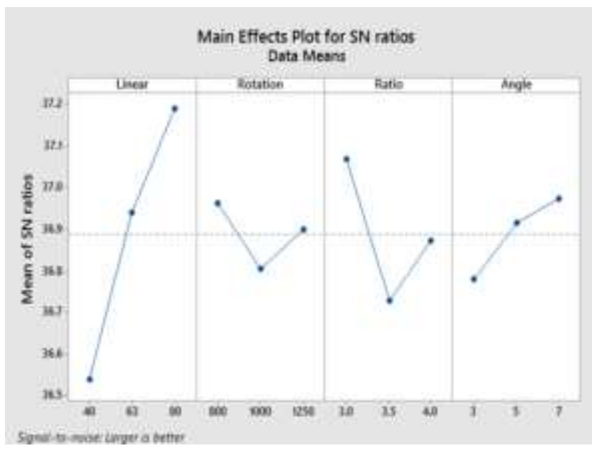

Fig. 6 Main effects plot for surface hardness.

3.2. Weighted Multi-Objective Function

The results presented in the previous section are relevant to the cases where only one output is sought to be optimized. However, if the optimization is to cover the other output too (hardness in addition to the strength), the multi-objective Taguchi function should be employed. Given the fact that no such feature is supported by Minitab and also for the sake of simplicity in weighting the outputs, every relation and formula were re-written in Excel. First, the normalized dissipation function (C_{ij}) $(C_{ij})$is to be calculated for each output in every experiment. In this regard, the dissipation function in each experiment (L_{ij}) $(L_{ij})$is divided by the maximum dissipation function (L_i^*) among all experiments for each response.

$$C_{ij} = \frac{L_{ij}}{L_i^*} \quad and \quad L_i^* = \{L_{i1}, L_{i2}, \ldots, L_{ij}\} \tag{3}$$

Where $L_{ij}L_{ij}$ is the dissipation function for the ith output of the jth experiment. In the "Larger is Better" model, the dissipation function of the outputs is calculated using the equation below [19]:

$$L_{ij} = \frac{1}{n_i}\sum_{k=1}^{n_i}\left(\frac{1}{y_{ijk}}\right)^2 \tag{4}$$

Where n_i shows the number of iterations of the ith output, and $y_{ijk}y_{ijk}$ shows the value recorded for the ith output in the kth iteration of the jth experiment. An appropriate weight (W_i)(w_i) is allocated to every response, showing their significance with respect to the others. Considering the weight of each solution, the general normalized dissipation function ($TNQL_j$) can be calculated using the equation below [20]:

$$TNQL_j = \sum_{i=1}^{m} w_i C_{ij} \tag{5}$$

Where m shows the number of outputs or the objective functions. The multi-objective S/N coefficient ($MRSN_j$) can be obtained using the general normalized dissipation function:

$$MRSN_j = -10\,log(TNQL_j) \tag{6}$$

In order to optimize the parameters of the FSW process aiming to achieve maximum UTS and maximum hardness simultaneously, the above-mentioned formulas were coded in Excel. In this code, the sum of the weights allocated to the outputs must be 1, so the equation is validated, and the calculation can proceed. Accordingly, the program was executed in five cases with different weights allocated to each output response. The program results are presented in "Table 7". In this table, the effectiveness of each factor is presented along with its optimal level for each weighting case.

Considering the calculations for the case where the UTS and hardness are weighted similarly, the rotational speed of the tool $(\omega = 800\,rpm)$, the shoulder-diameter-to-pin-diameter ratio $(\delta = D/d = 3)$, the shoulder base angle$(\theta = 7\text{degree})$, and the linear speed of the tool $(v = 80\text{ mm/min})$ are respectively the most effective variables. The results suggest that the more concave the shoulder base is, the better the materials are mixed, therefore, yielding a higher hardness and UTS. Figure 7 shows the sheet welded with optimal parameters.

Fig. 7 Sheet welded with optimum conditions.

A non-welded specimen of the 6061-T6 aluminium alloy sheet was tested for its UTS. It was found that the UTS of this alloy is 319 MPa while the average UTS of the nine welded specimens is 162 MPa. This reduction in the strength is in line with the results reported in [21]. The tensile strength of the sheet welded under optimal conditions was 190 MPa. The results show that the UTS value is enhanced by 28 MPa as a result of the optimization. Moreover, the average hardness of the nine specimens was 70 HV while the surface hardness under the optimized conditions was 74.3 HV. The results suggest the enhancement of the hardness by 4.3 HV as a result of the optimization.

Table 7 Effectiveness of each factor in five different weighting cases

Weight of each output		Parameter 1	Parameter 2	Parameter 3	Parameter 3
UTS	Hardness				
1	0	$\omega = 800rpm$	$\upsilon = 40mm/min$	$\delta = 3$	$\theta = 7^o$
0.75	0.25	$\omega = 800rpm$	$\upsilon = 40mm/min$	$\delta = 3$	$\theta = 7^o$
0.5	0.5	$\omega = 800rpm$	$\delta = 3$	$\theta = 7^o$	$\upsilon = 80mm/min$
0.25	0.75	$\upsilon = 80mm/min$	$\delta = 3$	$\omega = 800rpm$	$\theta = 7^o$
0	1	$\upsilon = 80mm/min$	$\delta = 3$	$\theta = 7^o$	$\omega = 800rpm$

3.3. Interaction between the Factors

Interaction is the relationship between two factors in which the impact of one factor on the output response depends on the other factor. Figure 8 illustrates the interactions of the UTS output. When different interactions exist for output, the level of other factors must be taken into account in order to make the variation of one factor more effective.

As it is evident in "Fig. 8", the lines representing the interactions of the D/d $\mathrm{D/d}$ratio – the shoulder base angle, and the $\mathrm{D/d}$ ratio – the linear speed are steep and cross each other more than the other interactions. This shows that these interactions are more effective in variations of strength. By examining the interactions between the rotational speed of the tool and the shoulder base angle closely, it becomes clear that the impact of the shoulder base angle on the UTS depends on the rotational speed of the tool. If the tool rotates at 1250 rpm, the strength is minimized at 5°, however, at 1000 rpm the shoulder base angle yields the maximum strength at 5°. The same applies to other interactions and can be justified similarly.

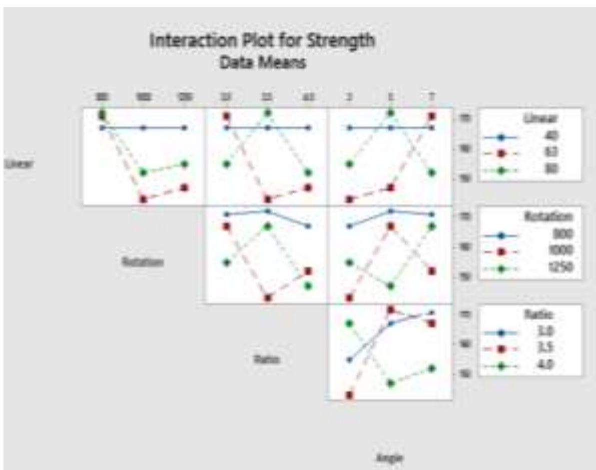

Fig. 8 Interaction Plot for UTS Sheet.

The interactions between factors regarding the surface hardness are presented in "Fig. 9". As it is evident in the figure, the interactions of the D/d ratio - the shoulder base angle, the D/d ratio - the rotational speed, and the shoulder base angle - the rotational speed have a more significant impact on the surface hardness compared to other interactions. By examining the interactions between the D/d ratio and the shoulder base angle, it is revealed that the impact of the shoulder base angle on the hardness depends on the ratio of the shoulder diameter to the pin diameter. For $D/d = 3$, the surface hardness is minimized at 5°, meanwhile, at$\mathrm{D/d} = 3.5$, a shoulder base angle of 5° yields the maximum hardness.

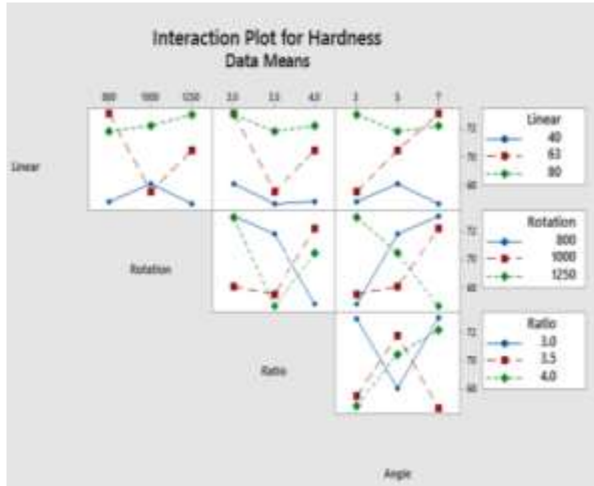

Fig. 9 Interaction Plot for surface hardness.

4 CONCLUSION

The optimization of the Friction Stir Welding (FSW) process of 6-mm-thick 6061-T6 aluminium alloy sheets was experimentally addressed in this study. The following results were obtained through optimization using the multi-objective Taguchi function and other analytical approaches.

- The S/N analysis revealed that the maximum Ultimate tensile strength (UTS) could be achieved when ω, υ, δ, and θ are respectively adjusted at 800 rpm, 40 mm/min, 18/6=3, and 7°.
- Moreover, for surface hardness, the S/N analysis showed that υ, δ, θ, and ω at 80 mm/min, 18/6=3, 7°, and 800 rpm are respectively the most effective parameters on surface hardness.
- The average S/N for the nine experiments was calculated to be 44.07 dB for UTS and 36.91 dB for surface hardness.
- Process optimization allowed for the enhancement of the tensile strength by 28 MPa and the surface hardness of the welded sheet by 4.3 HV.
- Optimization using the multi-objective Taguchi function revealed that a rotational speed of 800 rpm, a shoulder-diameter-to-pin-diameter ratio of 18/6, a shoulder base angle of 7°, and a linear speed of 80 mm/min yield both maximum strength and maximum surface hardness.

5 APPENDIX OR NOMENCLATURE

C : Normalized dissipation function

d	: Diameter of pin
D	: Diameter of shoulder
L	: Dissipation function
m	: Number of objective functions
n	: Number of iterations
y	: Response value
w	: Weight of objective functions
δ	: Shoulder-diameter-to-pin-diameter ratio
θ	: Shoulder base angle
υ	: Linear speed of tool
ω	: Rotational speed of tool

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