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Model development for mechanical properties and weld quality class of friction stir welding using multi-objective Taguchi method and response surface methodology†

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Abstract

This study presents the effect of the governing parameters in friction stir welding (FSW) on the mechanical properties and weld quality of a 6mm thick 6061 T651 Aluminum alloy butt joint. The main FSW parameters, the rotational and traverse speed were optimized based on multiple mechanical properties and quality features, which focus on the tensile strength, hardness and the weld quality class using the multi-objective Taguchi method (MTM). Multi signal to noise ratio (MSNR) was employed to determine the optimum welding parameters for MTM while further analysis concerning the significant level determination was accomplished via the well-established analysis of variance (ANOVA). Furthermore, the first order model for predicting the mechanical properties and weld quality class is derived by applying response surface methodology (RSM). Based on the experimental confirmation test, the proposed method can effectively estimate the mechanical properties and weld quality class which can be used to enhance the welding performance in FSW or other applications.

Keywords: Analysis of variance (ANOVA); Design of experiment (DoE); Friction stir welding (FSW); Multi-objective taguchi method (MTM); Optimization; Response surface methodology (RSM)

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1. Introduction

Since its innovation in 1991, friction stir welding (FSW) has appealed a large number of industrial applications especially lightweight high strength materials such as aluminum alloy which normally tends to have unfavorable conditions when joined using routinely used fusion welding process. In FSW, two abutting plates are joined through mechanical mixing and heat created by a rotating non-consumable tool, moved forward through specific traverse speed displacing the plastically deformed material from the anterior to the rear side of the tool.

The rapid development of FSW since its inception to the academic and industrial world is closely associated to the many advantages attributed to FSW compared to the usually used fusion welding due to its nature of not reaching the melting temperature. Among the most significant advantages which are possible to be achieved by using FSW are the finer microstructure in the stir zone, very minimal distortion and shrinkage from solidification, minimal stress concentration and weld defects. There are some main parameters to be controlled during welding namely rotation speed, travel speed and pressure. However tool geometry, pin depth, tilt angle, gaps, finishing, backing material and cooling conditions, can contribute to the FSW [1-3].

A broad development in the usage of the design of experiment (DoE) in diverse applications has been noted recently due to its capability of defining the optimal settings of any process by ascertaining the governing parameters associated to the process to further improve the performance and capability. A typical example among the many statistical techniques used to reduce the number of experiments required is the Taguchi method (TM) which enables safe identification of statistically essential parameters. Optimization in common is known as a process that enables the approximation of the most possible minimum value of machining performance at the finest point of process parameters. Numerous research involving the optimization of process parameters for FSW as well as other welding processes has been carried out previously to obtain the optimal point of governing parameters.

TM has been applied for joints with the same thickness but dissimilar material joined using the up-to-date laser welding process [4, 5]. Employing the MTM and RSM, a mathematical model was successfully developed for quality features of resistance spot welding using [6]. The prediction of the optimum tool material and tensile strength by varying process parameters for joining of a butt joint aluminum alloy using

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TM technique was investigated by several researchers [7-9]. The TM was successfully applied to optimize the process parameters of friction stir welding (FSW) of 6061 aluminum alloy in an attempt to minimize the heat affected zone (HAZ) distance to the weld line [10].

Achieving an ideal low defect FSW joint is primarily dependent on the optimization of the FSW parameters such as the revolutions per minute of the shoulder-pin assembly, travel speed, downward forging force, and pin tool design [11]. Based on the literature reviewed [12] the utmost important parameters in FSW are the tool rotation rate (ω, rpm) in clockwise or counter clockwise direction and tool traverse speed (v, mm/min) along the of joint which are ensued due to the stirring and mixing of material around the rotating pin and the translation of tool which causes the stirred material to move from the tool fore to the rear which contributes to the forging process during FSW. Higher tool rotation causing greater friction can lead to stirring and mixing of material with high temperature.

The importance of these governing parameters is ascertained by numerous research conducted previously on the effect of the rotational and traverse speed on the mechanical properties, microstructure, and weld profile as well as corrosion characteristics of FSW joints of aluminum alloys, particularly AA6061.

A mathematical model was developed by Ref. [13] combining FSW parameters in an attempt to predict the tensile strength of FSW AA6061 aluminum alloy employing statistical tools such as DoE and ANOVA. The effect of FSW parameters on the mechanical properties and microstructure of AA6016-T4 for sheets with 1mm thickness was analyzed by Ref. [14]. The effect of varying the rotational and traverse speed in a friction stir welded Al 6061-T651 butt joint with thickness of 4mm was concluded in Ref. [15]. A study revealed by Ref. [16] concurred that traverse speed tends to be the principal factor in defining the tensile properties and fracture modes of a FSW Al6061-T651 butt joint. Although many research have been conducted involving Al6061, there has been no attempt yet to relate the effect of varying the FSW governing parameters to a multi objective outcome of several desired conditions in Al6061-T651 butt joint plates.

Conversely, numerous optimization and modelling investigations focusing on the FSW process parameter optimization by forerunners employing the Taguchi method have mainly been concentrating on single quality characteristics which may deteriorate other characteristics. However, the range of industrial applications involving FSW aluminum alloy requires the overall quality for any specific joint or product hence making multi objective quality characteristics optimization a necessity. The present research attempts to optimize the governing parameters of FSW process namely the rotational and welding speed for Al6061-T651 6mm thick butt joint using a Taguchi experimental design method under simultaneous consideration of multiple weld quality characteristics (Tensile strength, hardness value and weld quality class) as defect free FSW weld joints are important in achieving good fatigue resistance properties.

2. Experimental planning method using MTM and RSM

2.1 Taguchi & multi-objective Taguchi method

A Taguchi design, or an orthogonal array, is a simple and robust method of designing experiments for optimizing the governing process parameters that usually requires only a fraction of the full factorial combinations. This technique enables each factor to be independently evaluated with randomized experiments due to the orthogonal array (OA) consisting of a balanced design with equally weighted factor levels hence eliminating the possibility of one factor effecting the estimation of another factor. The ability to narrow the range of specific study or identifying problems in manufacturing process with existing data by means of emphasizing a mean performance characteristic value close to the target value rather than a value within certain specification limits has made the Taguchi method a popular choice for improving product quality [17, 20-22].

In a typical robust parameter design, the first step is to choose the control factors effecting the process and their levels with subsequent selection of a suitable orthogonal array for the chosen control factors while simultaneously determining a set of necessary noise factors with appropriate experimental designs. The control factors comprise the inner array while the noise factors comprise the outer array. The selection of appropriate OA is based on total degree of freedom (dof) which is computed as [13]:

$$\text{dof} = \{(a - 1)\, n\} + \{(A - 1) \times (B - 1)\, n_i + 1\} \tag{1}$$

where a is the number of levels, n is the number of factors, and n_i is the number of interactions while A and B are the interacting control factors.

In general, signal to noise (S/N) ratio (η, dB) denotes quality characteristics for the obtained data in the Taguchi design of experiments (DoE) and mathematically can be computed as [13]:

$$\eta = -10 \log [\text{MSD}] \tag{2}$$

where MSD is mean square deviation from the desired value and commonly known as quality loss function. Usually, there are three categories of the quality characteristic in the analysis of the S/N ratio which are smaller-is-better, higher-is-better and nominal-is-best. In this study the higher-is-better is employed for all three objectives namely the tensile strength, nugget zone hardness profile and weld quality class classification, whereby a higher magnitude of these objectives will act favorably towards achieving higher fatigue resistance properties of the joint. The nugget zone hardness which has great influence on fatigue life cycle of aluminum alloys is directly proportional to the joint tensile strength [15]. The MSD employing the higher-is-better was calculated using the following equations:

$$\text{Higher-is-better} = \eta = -10[\log\left(\sum \frac{y^{\frac{1}{2}}}{\mathrm{n}}\right)] \tag{3}$$

where *y* is the responses for the given factor level combination and *n* is the number of responses in the factor level combination. Ensuing the estimation of the S/N ratio, the governing parameters with the ideal set of process parameters can be determined.

Successively analysis of the variance (ANOVA) will be employed to analyze the relative effect of the different parameters or factors. This statistical method quantitatively estimates the relative significance factors on quality characteristics [18, 19]. A specific factor is considered to be statistically significant should the p-value is less than the significance level (α) while the F-ratio or a percentage contribution represents the significance of factors. A higher value of the F-ratio indicates a vast change on the process performance through variation of respective process parameter while p-ratio less than 0.05 the more significant will be the factor.

In multi-objective optimization, a single overall S/N ratio for all quality characteristics is computed in place of separate S/N ratios for each of the quality characteristic. This overall S/N ratio is known as multiple S/N ratio (MSNR). The MSNR for *j*th trial $\left(\eta_j^e\right)$ is computed as [16]:

$$\eta_j^e = -10\log_{10}\left(Y_j\right) \tag{4}$$

$$Y_j = \sum\nolimits_{i=1}^{k} w_i y_{ij} \tag{5}$$

$$y_{ij} = \frac{L_{ij}}{L_{i*}} \tag{6}$$

where y_j is the total normalized quality loss in *j*th trial, w_i represents the weighting factor for the *i*th quality characteristic, *k* is the total number of quality characteristics and y_{ij} is the normalized quality loss associated with the *i*th quality characteristic at the *j*th trial condition, and it varies from a minimum of zero to a maximum of 1. L_{ij} is the quality loss or MSD for the *i*th quality characteristic at the *j*th trial, and L_{i*} is the maximum quality loss for the *i*th quality characteristic among all the experimental runs.

2.2 Response surface methodology (RSM)

Response surface methodology is used to examine the relationship between one or more response variables and a set of quantitative experimental variables or factors. The primary objective of this technique is optimization of the response surface which is influenced by various process parameters. Designs of this type are usually chosen when you suspect curvature in the response surface and it is capable of quantifying the correlation concerning the governable input parameters and the attained response surface [18]. In addition to this, this approach can be also employed to find factor settings (Operating conditions) that produce the "Best" response or satisfy operating or process specifications. With the capability of being able to model a relationship between the quantitative factors and the response, this method can often be used to identify new operating settings that produce established improvement in product quality over the quality achieved by existing conditions with negligible errors. However, a true functional relationship between independent variables and the response surface is essential to determine an apposite approximation [20].

In modelling and optimization of manufacturing processes using RSM, the sufficient data is collected through designed experimentation. In general, a first-order model or second-order regression model is developed depending on the developed lack-of-fit [11]. According to RSM, all the input process parameters are assumed to be measurable, the corresponding responses can be expressed as follows:

$$y = f\left(x_1, x_2 ..., x_p\right) \tag{7}$$

where, $x_1, x_2 ..., x_p$ are input process parameters and *y* is the response which is required to be optimized.

Here, it is assumed that the independent variables (Input process parameters) are continuous and controllable by experiments with negligible errors. It is also required to find a suitable approximation for the true functional relationship between independent variables and responses. Usually, a linear function of the factors, the first-order model, as given below is utilized in RSM [18].

$$\mathrm{y} = \mathrm{b}_0 + \mathrm{b}_1\mathrm{X}_1 + \mathrm{b}_2\mathrm{X}_2 + ... + \mathrm{b}_\mathrm{k}\mathrm{X}_\mathrm{k} + \varepsilon \tag{8}$$

where *y* is the response, *x* is the factors, b_k is the regression coefficients , and ε is the error term with a normal distribution, and standard deviation of *s*. Coefficients, b_k, are the estimates of the population regression coefficients, b_k. The estimated coefficients are used, along with the factors, to calculate the fitted value of the response. In matrix terms, the vector of coefficients in multiple regression is calculated by the formula:

$$\mathrm{b} = (\mathrm{X'X})^{-1}(\mathrm{X'Y}) \tag{9}$$

where *X* is the design matrix, including the constant and *Y* is the response vector [18].

3. Experimental design and setup

After the orthogonal array has been selected, the subsequent step in the Taguchi parameter design is running the experi-

Table 1. Chemical composition of workpiece.

	Si	Fe	Cu	Mn	Mg	Cr	Ni
Percent composition (%)	0.74	0.44	0.22	0.034	1.03	0.054	0.007

Table 2. Control factors and their levels used in OA design matrix.

Symbol	Factors	Unit	Level 1	Level 2	Level 3
A	Rotational speed	RPM	650	950	1400
B	Traverse speed	mm/s	0.78	1.42	4.55

Table 3. Experimental layout using L9 orthogonal array.

Experiment number	Levels of factors	
	A	B
1	1	1
2	1	2
3	1	3
4	2	1
5	2	2
6	2	3
7	3	1
8	3	2
9	3	3

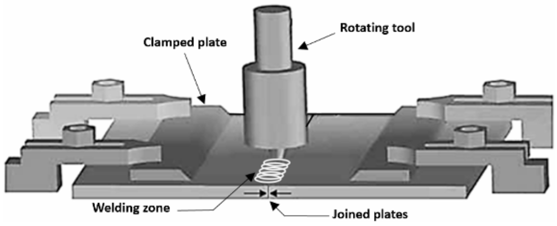
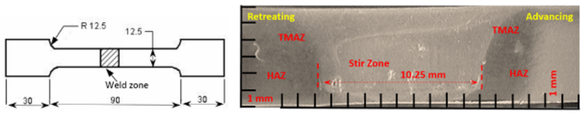


Fig. 1. The position of the clamps fixed relative to the surface of the sheet.



(a) (b)

Fig. 2. Cutting out specimens from a FS-welded AA6061-T651 joint: (a) dimensions of flat tensile specimen; (b) macrostructure of the FSW joint with a rotational speed of 650 rpm and traverse speed of 0.78 mm/s.

ment. The AA6061-T651 aluminum alloy was used in this investigation. All the welds were performed in plates rolled to 6-mm-thick pieces perpendicular to the rolling direction (RD) in a butt joint arrangement with straight edge preparation. The chemical composition of the workpiece is listed in Table 1. Two welding parameters namely the rotational speed and traverse speed were selected for experimentation with three levels of each factor. The value of the welding process parameter at the different levels is tabulated in Table 2. Experimental process was conducted using L9 orthogonal array in Taguchi Method which has nine rows corresponding to the number of experiments as shown in Table 3. Plates of 250 mm of length and 50 mm of width were cut out using a milling machine and welded along their long edge. After welding, specimens were produced, and mechanical tests were carried out.

The FSW was done on the vertical head milling machine with the position of the tool fixed relative to the surface of the sheet as shown in Fig. 1. The work piece was firmly clamped to the bed and a specially made tool was plunged into the selected area of the material sheet for sufficient time in order to plasticize around the pin. Specimens were taken from each welded plate for tensile test, hardness tests and macro profile. The tensile specimen dimension are as shown in Fig. 2(a). Before hardness tests were performed, samples for macro profiles were prepared by the usual metallurgical polishing methods and etched with Keller's reagent and the weld zone was captured using a metallurgical microscope interfaced with an image analysis system as shown in Fig. 2(b).

Three tensile specimens (SP1, SP2, and SP3) were taken from each welded plate. Tensile tests were performed under a cross head speed of 5 mm/min according to the EN-895-2002 standard. The room temperature tensile strength of the base and the friction stir processed sheet was evaluated by conducting tensile test on a 250 KN Instron universal testing machine. A high resolution extensometer was used during uniaxial tensile tests. The hardness field was established in the midthickness (Middle level) of the cross section of the weld seam according to the ISO 6507-2 standard with 3 measured points in the nugget zone with 1 kgf force using a Struers Duramin Micro-Vickers hardness test machine.

The effect of welding parameters on the joint quality was observed through defect analysis with an aim of fabricating defect-free joints. The internal defects in FSW joints were observed through macrostructures at different parameter combinations. The weld quality of the joints were then classified into three classes namely A1, A2 and A3 as per quality characteristic classification of the Class A type in AWS D17.3 based on the geometrical conditions of the defects found on each run. The weld joints from each run were then given a numerical rating according to the designated weld class. The internal defects, weld class and designated scores used are presented in Table 4.

4. Result and discussion

The values of the observed data for the three tensile specimens and the average tensile strength, Vickers hardness values and weld quality class rating are shown in the Tables 5 and 6, respectively.

Tensile tests conducted on the AA 6061-T651 base material generated results of an ultimate tensile strength of 309 MPa

Table 4. Acceptance level for weld quality classes in accordance to AWS D17.3 and the designated ratings.

Type of defects	AWS D17.3 Class A	Proposed classification accordingly to AWSD17.3 Class A		
		Class A1 (Rating = 3)	Class A2 (Rating = 2)	Class A3 (Rating = 1)
Incomplete joint penetration	None	None	None	None
Inclusion (Individual size)	1.5 mm	0-0.5 mm	0.51-1.0 mm	1.1-1.5 mm
Internal cavity or cavity open to the surface	None	None	None	None
Angular distortion	3 degrees	1 degrees	2 degrees	3 degrees
Individual defect (Maximum depth)	0.76 mm	0-0.25 mm	0.26-0.5 mm	0.5-0.76 mm
Accumulated length of underfill defect of any 3	5.1 mm	0-2.5 mm	2.6-4.0 mm	4.1-5.1 mm
Weld flash	Shall be removed	Shall be removed	Shall be removed	Shall be removed
Overlap	Shall be removed	Shall be removed	Shall be removed	Shall be removed

and a yield strength of 271 MPa. Considering the best tensile property of friction-stir-welded AA 6061-T651 plate, the ultimate tensile strengths and yield were reduced by 32.4 and 48.7 percent, respectively with respect to the parent material. At constant rotating speed with increased traverse speed, the tensile strength tended to increase in a similar pattern for all rotation speeds utilized except for rpm 1400 which showed significant changes with a sharp increments in the beginning then slightly descending before a further final increase in varied values of tensile strengths. Slower traverse speeds with various combinations of rotation speeds tended to provide a satisfactory joint strength of 50 to 60 percent of the base material tensile strength.

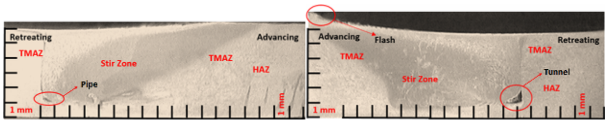
The hardness of the nugget zone were measured in center as well as in both retreating and advancing sides. It is found that the hardness of base material varies between 105 and 110 HV. Compared to the parent material, dynamic recrystallization in FSW joints plays a major role in the elimination of strain hardening which significantly softens the weld zone. This in turn causes a decrement of the hardness values in the vicinity of the weld nugget. Destructive testing was conducted to macrographically examine the weld profile of parameter variations which indicated the presence of internal defects. The worst performing rotation speed was 1400 rpm with 2 weld joints being in weld class A3 due to displaying weld defects beyond the acceptance limit. Conversely in general, higher traverse speeds between the range of (1.42 and 4.55 mm/s) displayed better overall joint quality with lesser weld defects compared to the lower traverse speeds below 1.24 mm/s. However, higher traverse speeds with 1400 rpm produced weld joints with numerous defects.

Table 5. Experimental results for tensile strength.

Experiment number	Tensile specimen 1 (MPa)	Tensile specimen 2 (MPa)	Tensile specimen 3 (MPa)	Tensile mean (MPa)
1	149.2	149.3	148.1	148
2	176	178	171	175
3	196	196	198	197
4	151	149	152	151
5	166.3	167.7	161	165
6	204.5	209.5	207	207
7	168	172	164	168
8	173	170	173	172
9	178	173	174	175

Table 6. Experimental results for nugget zone hardness values and weld quality class rating.

Experiment number	Nugget zone hardness 1 (HV)	Nugget zone hardness 2 (HV)	Nugget zone hardness 3 (HV)	Nugget zone mean hardness (HV)	Weld quality class & (Rating)
1	63.4	51.5	47.4	54.1	A3 (1)
2	52	62.8	57.4	57.4	A2 (2)
3	66.5	70.9	58.8	65.4	A1 (3)
4	52.8	65.0	46.9	54.9	A2 (2)
5	50	67.9	53.6	57.1	A2 (2)
6	66.8	77.3	71.6	71.9	A1 (3)
7	50	60.1	59.5	56.7	A3 (1)
8	54	53.9	56	59	A3 (1)
9	63.8	72.0	62.9	66.5	A1 (3)



(a) (b)

Fig. 3. Internal weld defects found in different specimens of parameter combinations: (a) pipe defect in A_1B_1 ; (b) tunnel defect and flash in A_3B_1 .

Defects such as tunnel defect, pin hole, flash and pipe defects were detected in the macrostructures. The defects area found in A_1B_1 and A_3B_1 are depicted in Figs. 3(a) and (b) respectively. The defects were formed as a result of insufficient heat input caused by higher traverse speed as well as low rotation speeds or an unsuitable combination of both. Lower traverse speeds and higher rotation speeds also influenced several weld defects such as excessive flash [15].

Table 7. Quality loss values for tensile strength, nugget zone hardness and weld quality rating.

Experiment number	A	B	Quality loss values (dB)		
			Tensile strength	Nugget zone hardness	Weld quality rating
1	1	1	0.000045	0.00036	1.00
2	1	2	0.000033	0.00031	0.25
3	1	3	0.000026	0.00024	0.11
4	2	1	0.000044	0.00035	0.25
5	2	2	0.000037	0.00032	0.25
6	2	3	0.000023	0.00020	0.11
7	3	1	0.000035	0.00032	1.00
8	3	2	0.000034	0.00029	1.00
9	3	3	0.000033	0.00023	0.11

Table 8. Normalized quality loss values.

Experiment number	A	B	Normalized quality loss values		
			Tensile strength	Nugget zone hardness	Weld quality rating
1	1	1	1	1	1.000
2	1	2	0.724226	0.865523	0.250
3	1	3	0.572988	0.666999	0.111
4	2	1	0.976411	0.980489	0.250
5	2	2	0.81473	0.902279	0.250
6	2	3	0.517325	0.547686	0.111
7	3	1	0.786052	0.888442	1.000
8	3	2	0.74922	0.807911	1.000
9	3	3	0.723932	0.641618	0.111

4.1 Multi-objective optimization results

From Tables 5 and 6, quality loss values for the quality characteristics of higher-is-better in each experimental run are calculated using Eq. (3). These quality loss values are depicted in Table 7. The normalized quality loss values for both quality characteristics in each experimental run have been calculated using Eq. (6) that is shown in Table 8. The total normalized quality loss values (TNQL) and MSNR for multiple quality characteristics for tensile strength, hardness profile and weld quality class has been calculated using Eqs. (4) and (5), respectively. These results are presented in Table 9.

In calculating total normalized quality loss values, two equal weights of w1 and w2 was assigned as 0.4 for tensile strength and hardness profile , while an unequal weight of w3 with a value of 0.2 was assigned for weld quality class. Higher weighting factor has been assigned to the mechanical properties rather than quality class as it is more important in order to achieve a good joint with multiple characteristics in friction stir welding process.

Table 9. Total normalized quality loss values (TNQL) and multiple S/N ratios (MSNR).

Experiment number	A	B	TNQL	MSNR(dB)
1	1	1	0.9990	0.0001
2	1	2	0.6859	1.637395
3	1	3	0.5182	2.855069
4	2	1	0.8328	0.794801
5	2	2	0.7368	1.326483
6	2	3	0.4482	3.485239
7	3	1	0.8698	0.605818
8	3	2	0.8229	0.846781
9	3	3	0.5684	2.453306
Mean of MSNR of all experiment runs				1.55611

Table 10. Multiple S/N response (Average factor effect at different level).

Symbol	Factors	Mean of multiple S/N ratio (dB)		
		Level 1	Level 2	Level 3
A	Rotational speed	1.4978	1.8688*	1.3020
B	Traverse speed	0.4672	1.2702	2.9312*

* Optimum level.

Table 11. ANOVA result.

Factors	Rotational speed	Traverse speed	Error	Total
DoF	2	2	4	8
Sum of square	5.582	47.182	3.73	56.49
Mean of square	2.791	23.591	1.865	
F	0.1	8.57		
P	0.909	0.036		
Contribution %	28.2	71.8		

The effect of different control factors on MSNR is shown in Table 10. The optimum levels of different control factors for tensile strength, hardness profile and weld quality class obtained are rotation speed at level 2 (950 rpm) and traverse speed at level 1 (0.78 mm/s) with constant axial load. ANOVA technique was further employed to detect significant factors in multi-objective optimization for tensile strength, hardness profile and weld quality class. The result of ANOVA for the welding outputs is presented in Table 11. The analysis conducted indicates that traverse speed was statistically significant since its p-value is less than 0.05. Furthermore, it also shows the percentage contribution which indicates the relative power of a factor to reduce variation. For a factor with a high percentage contribution, a small variation will have a great influence on the performance [13].

The percentage contribution of different control factors on multiple quality characteristics (Tensile strength, hardness profile and weld quality class) shows that traverse speed was the major factor (71.8%), followed by rotation speed (28.2%). In Friction stir welding, traverse speed have the greatest effect on the joint quality and mechanical properties [1-4].

4.2 Response surface modeling

The first order response surface model for tensile strength, hardness profile and weld quality class has been developed from the experimental response values obtained using OA experimental matrix. These equations were developed using RSM in MINITAB software.

$$\text{Tensile strength} = 162.22 + 0.036A + 12.297B - 0.0055AB \quad (10)$$

$$\text{Nugget zone hardness} = 73.57 - 0.0041A - 12.65B + 0.015AB \quad (11)$$

$$\text{Weld quality class} = 4.7 - 0.00225A - 1.7611B + 0.00206AB \quad (12)$$

where A and B are the rotational speed and traverse speed, respectively.

In conformance of a model with well fitted data, observations of the S (Standard errors of samples) and R^2 (R is correlation coefficient) is essential. Normally, a greater value of R^2 and a smaller value of S will determine the appropriateness of a regression model. The calculated values from the developed models for the S value of the regression analysis on tensile strength is 1.011, nugget hardness is 0.3049 and weld quality class is 0.05328 while the obtained R^2 values are reasonably high for tensile strength , nugget hardness and weld quality class with 87.6%, 90% and 82.5%, respectively.

4.3 Confirmation tests

The ultimate step is the validation of the optimum parameter settings suggested by the matrix through experimental verification to determine these conditions certainly produce the projected improvements. Hence, a specific combination of the factors and levels previously evaluated will be used in the confirmation experimental test. Subsequent to defining the optimal conditions, a new experiment was conducted using the determined optimum levels of governing parameters (A_2B_3). Then the predicted value of MSNR (η_{opt}) at the optimum parameter levels was calculated by using the following equation [19]:

$$\eta_{opt} = \eta_m + \sum_{i=t}^{p} \left(\eta_{mi} - \eta_m\right) \quad (13)$$

where η_m is the mean MSNR of all experimental runs, p is the number of main welding parameters that significantly affect the performance and η_{mi} is the average MSNR at the optimal level.

Table 12. Result of the confirmation experiment.

	Initial parameter setting	Optimal process parameters		Error (%)
		Prediction	Experiment	
Level	A_1B_3	A_2B_3	A_2B_3	
Tensile strength (MPa)	168	205	206.5	0.73
Nugget hardness (HV)	56.7	71.75	70.2	2.16
Weld quality class	1	$2.819 \approx 3$	3	0
Multiple S/N ratio (dB)	0.605818	3.5843	3.68543	
Improvement in multiple S/N ratio = 3.0796 dB				

The predicted value of MSNR and that confirmation experiment is shown in Table 12. This verification depicts an improvement in multiple S/N ratio of 3.0796 dB upon the alteration of the initial governing parameter setting of A_1B_3 to the optimal setting of A_2B_3. The initial parameters was chosen based on recommendations to use a low rotation speed combined with a higher traverse speed to maintain a lower heat input with minimal flash [5]. The outcomes shows reasonable improvement in all three outcomes, namely the tensile strength, nugget hardness and weld quality class with the multi-response optimization used as compared to the initial values of the tensile strength and nugget hardness values obtained.

The weld class quality shows significant changes with improvement from the initial weld quality class A3 to the optimal conditions weld quality class A1. The results obtained from the verification experiments was further compared with Eqs. (10)-(12). The percentage error of the acquired values using the developed model for the tensile strength, nugget hardness values and the weld quality class is also presented in Table 10. The percentage error for tensile strength and nugget hardness is 0.7% and 2.16% while the weld quality shows the exact quality class without any errors at all. This indications good agreement between the model equations with the experimental result.

5. Conclusions

A multi-objective optimization has been applied with simultaneous consideration of multiple response (Tensile strength, hardness profile and weld quality class) using Taguchi Method to optimize the multiple quality characteristics in FSW process. Based on the optimization and modelling results, the following conclusions can be drawn:

(1) The multiple characteristic such as tensile strength, hardness profile and weld quality class can be simultaneously con-

sidered using multi-objective Taguchi method.

(2) The role of different control factors is traverse speed (71.8%) and rotation speed (28.2%). The traverse speed plays a major role in determining good mechanical properties and weld quality in FSW joint.

(3) The optimum parameters for a higher tensile strength and hardness with good weld quality is: rotation speed at level 2 (950 rpm) and traverse speed at level 3 (4.55 mm/s).

(4) The linear response surface model established for the prediction of tensile strength, nugget hardness and weld class quality has been found to be well fitted.

(5) The confirmation test validated the use of multi objective TM for enhancing the welding performance and optimizing the welding parameters in FSW process.

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