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ORIGINAL PAPER

Enhancement of friction stir welding characteristics of alloy AA6061 by design of experiment methodology

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Abstract

The advent of material technology witnessed an enormous application of aluminium alloys in day-to-day life. The Aluminum Alloy 6061 is one such alloy that finds immense application in engineering field. However, joining process of such aluminium alloys is difficult task through conventional techniques due to occurrence of high thermal conductivity. Friction stir welding (FSW) turns out to be an innovative welding technique used for joining such alloys and comparatively less hazard. The FSW process required to controlled several working parameters for strengthen the mechanical properties. It becomes very important to optimize these process parameters to obtain a good weld with enhanced mechanical properties. The current article describes the experimental procedure for welding AA6061 alloy at different operating parameters. Taguchi method and regression analysis which is widely acceptable methodology implemented to optimize different FSW parameters using L16 orthogonal array. The present study implemented the ANOVA table to examine the influence of tool geometry, rotational speed and welding speed on tensile strength, percentage elongation and harness respectively. The percent contributions of factors i.e., tool geometry, rotation speed and welding speed to the tensile strength is found to be of 33.4%, 4.69% and 58.39% respectively. It is observed that welding speed (58.39%) plays significant role influencing the tensile strength. Similarly, the percentage contributions of tool geometry, rotation speed and welding speed on percentage elongation is found to be 35.08%, 14.29% and 38.28% respectively. The observation concluded that welding speed is the most influential factor for percentage elongation. In addition, the percent contributions of the tool geometry, rotation speed and welding speed on hardness reported as 50.1%, 19.36% and 20.49% respectively. This concluded that tool geometry is the most effective factor for hardness. The predicted results are validated with experimental data's depicted a good convergence with optimization techniques for controlled operating parameters.

Keywords Friction stir welding · Aluminum alloy 6061 · Taguchi method · ANOVA · Regression analysis

1 Introduction

The heat treatable Al–Mg–Si alloys conforming to aluminum alloy 6061 has adequate strength along with its welding properties as compared to high strength aluminum alloys. The AA6061 is very difficult to join using butt or lap joints through conventional arc welding techniques due to high thermal conductivity. As the result, such designated welding procedure would become difficult to incorporate high-quality defect-free welding under favorable process parameters. The mechanical properties such as machinability, weldability, etc. of AA6061 have wide applications in the aerospace industry and ship building resulting the corrosion resistance over other aluminum alloys [1, 2].

Friction Stir Welding (FSW) involves the adequate solid-state joining technique resulting the melting point below of the order of 80% of the liquidus temperature of the parent metal [3]. This technique incorporates rotating non-consumable tool resulting heat generation without filler or fusion material. FSW is performed by butt joining of two plates and traversing the rotating tool at the interface of the plates. Welding controlled through a combined action of stirring process of rotating tool and frictional heating. The welding process widely applicable in numerous fields of engineering involving automotive industries, aerospace, ship-building, railways etc. due its low construction cost

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reduced welding distortion and enhanced mechanical properties as compared to other solid state welding processes [4].

Owing to numerous investigations carried out for FSW process over the last three-decade focusing on the mechanical-metallurgical properties of welding. These processes largely depend on the operating parameter such as tool profile and tool movement. Sun and Fujji [5] experimentally verified the role of tool pin profile in improving the weld quality and reducing weld defects. Lui et al. [6] considered the parametric effect on weld geometry and localized heating. Elangovan et al. [7] investigated the influence of pin profile and fabricated the butt joints at different welding operating parameters. Palanivel et al. [8] conducted FSW on dissimilar aluminum alloy (AA5083H111-AA6351T6) and proposed a mathematical relationship for the processes parameter and wear resistant. Patil and Soman[9] carried friction stir welding on AA6082-O aluminum alloys to analysis the tool pin profiles and welding speed on butt weld. They confirmed the relationship between welding speedwith ultimate tensile stress and tool pin profile with elongation. The visual appearance of the weld was found satisfactory with no defect. Taper screw thread pin produced joints exhibit superior tensile properties. Cabibbo et al. [10] evaluated micro-structuraland mechanical behavior of AA6056-T6 friction stir welded aluminum alloy. They observed that the weld depicted lower ultimate tensile and yield strength, leading to the weld region having lower ductility in comparison to the parent material.

Chen [11] implemented Taguchi technique to determine the working speed and rotation speed to obtain optimum tensile strength for friction stir welded AA6061.Jayaraman et al. [12] conducted a FSW experimentation work for A319 to optimize tensile strength for different variables like rotational speed, axial force, and linear velocity. The Taguchi techniques has adopted by various researchers to obtain the optimum working condition [13–15].

As per the above discussion, it is evident that FSW can be used advantageously to weld aluminium alloys. It is clearly observed that the properties greatly depend on the operating parameters. Therefore, FSW involves several variable process parameters which affect the mechanical properties. Therefore, it becomes necessary to analyze and predict an appropriate value of the process parameter to obtain an optimal mechanical property. Owing to referred article, the researchers did not investigate material characteristic and process parameters of FSW butt joint. The present investigation deals with the controlled parameters with tensile strength, hardness and temperature distribution for FSW butt joint of AA6061. The developed regression analysis with experimental values is validated with optimized process parameters obtained from Taguchi method.

Fig. 1 Experimental setup of the FSW process

Table 1 Chemical analysis of workpiece (AA6061-T6)

Parent material	Si	Mn	Mg	Zn	Cr	Al
Content %	0.62	0.06	0.9	0.02	0.17	Bal

2 Experimentation

2.1 Weld setup, tool and process parameters

The FSW experimental investigation was conducted with modified heavy duty milling machine, having a capacity of 7.5HP motor. Suitable collate was used to mount the tool in vertical arbor of the milling machine. The space between horizontal bed and plates to be joined was set to zero root gaps resulting no slip of the plates during tool movement. The workpiece is allowed to have movement along the interface and tool remains just above the interface. The spindle speed and transverse speed of the bed was set prior to welding. The rotating tool was plunged into the workpiece at one end of the interface. The contact between plate surface and tool shoulder was verified then bed movement in translation direction is provided. The annealed aluminum alloy AA6061-T6 plates of 5 mm thickness was cut to rectangular plate of dimension 120 mm × 75mm with the help of electron discharge machining. The experimental setup and chemical composition of AA6061-T6 aluminum alloys are depicted in Fig. 1 and Table 1 respectively. For welding of the two similar plates, four different tool geometries namely straight cylindrical, straight square pin, straight triangular pin, and tapered pin have been used and geometry of tool pin profile is depicted in Fig. 2. The welding has been done at different rotation speed and transverse speed of the tool, the rotational speed varying from 400 to 1600 rpm and traverse speed varying from 10 to 63 mm/min.

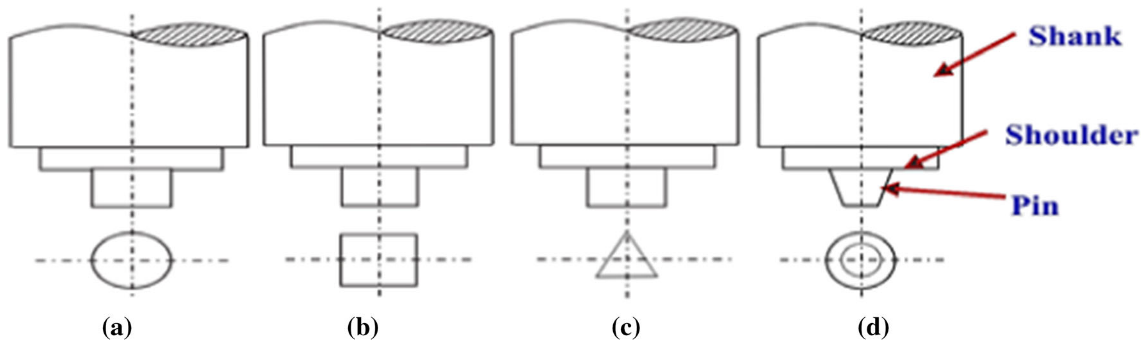

Fig. 2 FSW tool pin profiles **a** Cylindrical **b** Square **c** Triangular and **d** Tapered

The tool used for welding aluminium alloy is made of tool steel (AISI H13) with constituent element provided in Table 2. The oil quenching of tool resulted to increase its hardness (55HRC). The tool consisting 18 mm shoulder diameter and 4.7 mm pin length used FSW.

2.2 Orthogonal array

The L16 orthogonal Taguchi design consisting of 4 levels and 3 factors depicted in Table 3 is implemented for obtaining an optimized value of the FSW parameter. The controlled parameters of FSW for the analysis of welding are tool rotational speed, traverse speed, and tool geometry. The S/N analysis is performed for individual level of process parameter based on the obtained results by Taguchi method. The highest value of the S/N ratio corresponds to the optimized value of the experiment achieved for regardless of the category for the quality characteristic [16].

2.3 Tensile strength test

The welded specimen AA6061-T6 used in CNC Milling machine has been prepared as per instruction of ASTM E8M-04 standards [17] to evaluate tensile properties of the welded portion. The dimensions of the prepared welded specimen for the tensile test aredepicted in Figs. 3 and 4 respectively. The prepared specimenis tested inUniversal Testing Machine with load capacity of 100kN for the tensile strength and percentage elongation with constant crosshead displacement of 0.5 mm/min.

2.4 Measurement of micro-hardness

The micro hardness of the welded joints was determined with help of a micro-hardness machine (Fig. 5), with 0.2 kg of test load for 15 s of loading time. The indentation was performed at mid-section of the welded region of the plates across the joint.

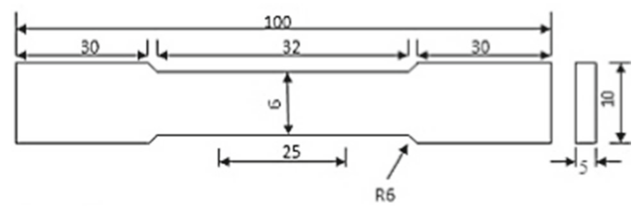

Fig. 3 ASTM E8 sub size specimen; Tensile specimen

3 Optimization methodology

Today, world is witnessing customer driven market which leads to manufacturing and unique product. The product should be more and more reliable, robust, compact and processes should be progressively matured. The optimization of operating parameters and composition of materials has become essential for product features [18–20]. The simplest and systematic approach for FS welding optimization techniques is Taguchi's method which is used to obtain high quality, low cost and excellent design for performance with acceptable results.

The controlled parameters like percentage elongation, tensile strength, and hardness were analyzed and optimized for FSW process. The signal to noise (S/N) ratios for each control factor performance is calculated and served as the objective functions for optimization. The predicated optimum results were evaluated for the criterion of the "larger-the-better" which chosen for S/N ratio to maximize the response from Eq. 1.

$$S/N = -10\log_{10}\frac{1}{N}\sum_{i=1}^{n}\frac{1}{X_i^2} \tag{1}$$

where, X_i is the function of tensile strength, percentage elongation and hardness for the ith test, N is the total number of data points, and n is the number of tests.

Fig. 4 Specimens for welded plates

Fig. 5 Micro-hardness machine

4 Result and discussion

4.1 Analysis of S/N ratio

By means of the experimental design through Taguchi techniques, tensile strength (TS), percentage elongation (PE) and hardness (H) were calculated for individual combination of control factors and S/N ratios were optimized for calculated control factors with the "larger-the-better" condition. The significant values tool geometry (TG), welding speed (WS) and rotating speed(RS) emphasized to tensile strength, percentage elongation and hardness resulting product quality improvement and lower cost production.

The S/N ratio graphs in Figs. 6, 7 and 8 depicted optimal welding parameters for minimizing the TS, PE and H. The optimal levels for each control factor were computed as per the S/N ratio highest value. The tool geometry (Level 1, S/N = 44.32), rotation speed (Level 4, S/ N = 43.69) and rotation speed (Level 4, S/N = 45.07) were achieved for optimum value for tensile strength. Similarly, for square pin profile, the optimum Tensile Strength value was obtained at a rotation speed (RS4) of 1600 rpm and at a feed rate (WS4) of 63 mm/min (Fig. 6), Corresponding to the tool geometry (Level 1, S/N = 18.22), rotation speed factor (Level 4, S/N = 17.68) and rotation speed factor (Level 4, S/N = 18.79) and optimal percentage elongation achieved for S/N ratios12.59%.

The optimum levels and S/N ratios were determined for the optimal result of hardness corresponding to tapered pin profile factor (Level 4, S/N = 40.94), RS factor (Level 1, S/N = 40.72) and WS factor (Level 3, S/N = 40.58). The optimum hardness value was achieved at rotation speed of 400 rpm and at a feed rate of 40 mm/min for tapered pin profile as depicted in Fig. 8. The S/N response for optimal values of TS, PE and H are depicted in Table 4. The S/N ratio values for tensile strength, percentage elongation and hardness are represented in Table 5.The average S/N ratio was determined as 43.31 dB, 16.3 dB and 40.17 dB for 148.53 MPa of tensile strength, 6.95% percentage elongation and 102.44HV hardness respectively, at the end of the welding experiments.

P_{TS} (Tensile strength total mean value) = 148.53 MPa

$P_{TS-S/N}$(Tensile strength S/N ratio total mean value) = 43.31 dB

P_{PE} (Percentage elongation total mean value) = 6.95%

$P_{PE-S/N}$(Percentage elongation S/N ratio total mean value) = 16.3 dB

P_H (Hardness total mean value) = 102.44HV

$P_{H-S/N}$(Hardness S/N ratio total mean value) = 40.17 dB

4.2 Analysis of variance method

ANOVA is a statistical approach that is used in the experimental design to control the access of individual interactions within the vicinity domain of working parameters. The physical significance of ANOVA analysis deprecates the

Table 2 Constituent element of toolsteel

Tool material	S	V	Mo	Mn	Cr	Si	Ni
Content (%)	0.03	0.8- 1.2	1.10–0.75	0.2–0.5	4.75–5.50	0.8–1.2	0.3

Table 3 Control variables and their levels

Sl. No	Factor	Level			
		1	2	3	4
1	Tool geometry	Square	Cylindrical	Triangular	Tapered
2	Rotational speed	400	630	1000	1600
3	Transverse speed	10	25	40	63

Fig. 6 Effect of process parameters on average S/N ratio for TS

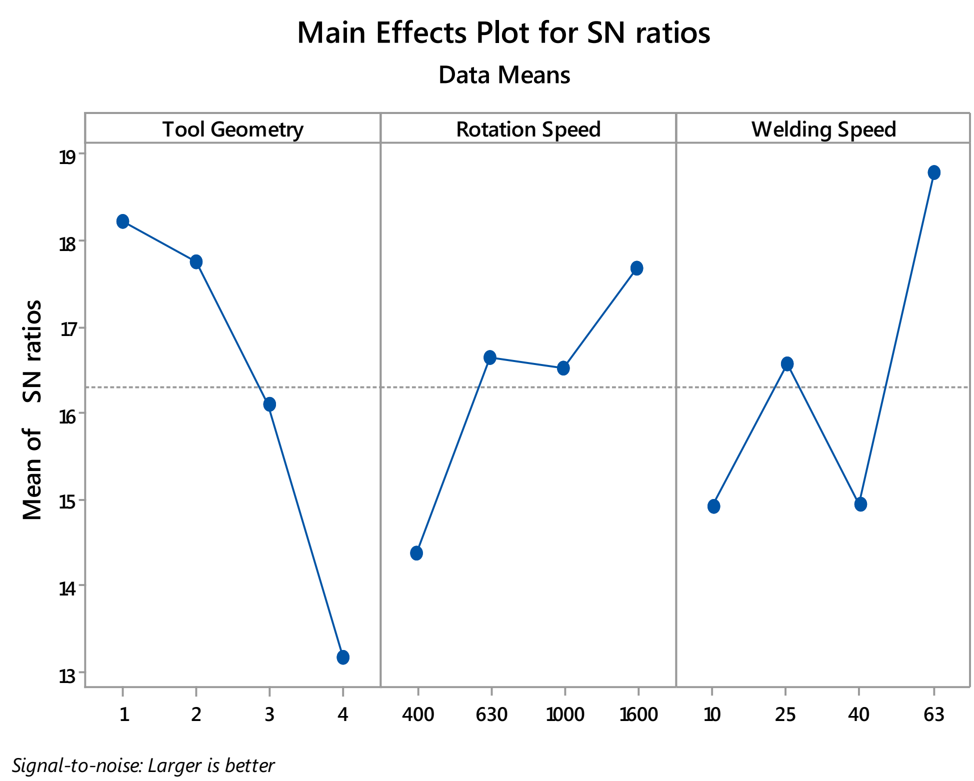

Fig. 7 Effect of process parameters on average S/N ratio for PE

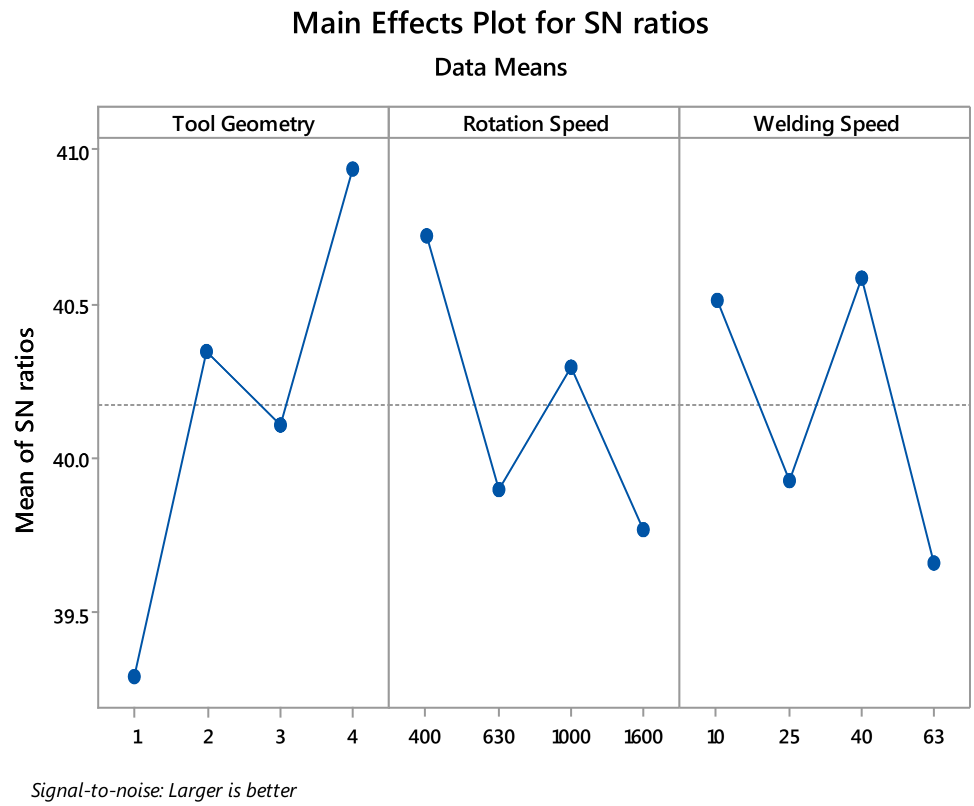

Fig. 8 Effect of process parameters on average S/N ratio for H

Table 4 S/N ratio for TS, PE and H factor

Levels	Control Factors		
	Tool Geometry	Rotation Speed	Welding Speed
Tensile strength (TS)			
1	44.32	42.89	42.20
2	**44.06**	43.57	43.43
3	42.29	43.08	42.53
4	42.57	**43.69**	**45.07**
Delta	2.03	0.80	2.87
Percentage elongation (PE)			
1	**18.22**	14.37	14.91
2	17.75	16.65	16.57
3	16.09	16.52	14.95
4	13.16	**17.68**	**18.79**
Delta	5.06	3.31	3.88
Hardness (H)			
1	39.29	**40.72**	40.51
2	40.35	39.90	39.93
3	40.10	40.29	39.66
4	**40.94**	39.77	**40.58**
Delta	1.65	0.96	0.93

Bold values show optimum value of the tensile strength, percentage elongation and hardness

experimental inaccuracy units to a great extent. The ANOVA techniques used for executing the optimum decisions for homogeneous set of experimental units [24, 25].

The present study implemented the ANOVA table to examine the influence of tool geometry, rotational speed and welding speed on TS, PE and H respectively. The experimental observations for TS, PE and H for identical metal alloys are shown in Table 6.

The percent contributions of factors i.e., tool geometry, rotation speed and welding speed to the tensile strength is found to be of 33.4%, 4.69% and 58.39% respectively. The results depict that taper tool geometry contributes to the maximum amount of heat distribution to the intermetallic compounds during FSW as compare other tool geometries.

The rotational speed play's significant role in the generation and crystallization of intermetallic compounds due to friction between tool and workpiece causing consequently high temperatures. Additionally, welding speed drives the time spent by the tool per unit area: at low welding speed, friction between tool and workpiece lasts a longer time in a certain region results to increasing temperature [26].

It is observed that welding speed (58.39%) plays significant role influencing the tensile strength. Similarly, the percentage contributions of tool geometry, rotation speed and welding speed on percentage elongation is found to be 35.08%, 14.29% and 38.28% respectively. The observation concluded that welding speed is the most influential factor

Table 5 The similar friction stir welding results of experimental and S/N ratios values

Exp. No	Control parameters			TS (MPa)	S/N ratio for TS	PE (%)	S/N ratio for PE	H (HV)	S/N ratio for H
	TG	RS	WS						
1	1	400	10	138.94	42.8565	5.34	14.5508	102.2	40.1890
2	1	630	25	173.80	44.8010	9.13	19.2094	84.4	38.5268
3	1	1000	40	156.88	43.9114	7.19	17.1346	104.5	40.3823
4	1	1600	63	192.58	45.6922	12.59	22.0005	79.9	38.0509
5	2	400	25	152.75	43.6796	7.56	17.5704	106.8	40.5714
6	2	630	10	143.53	43.1389	5.73	15.1631	108.9	40.7406
7	2	1000	63	188.03	45.4845	11.45	21.1761	99.9	39.9913
8	2	1600	40	157.30	43.9346	7.14	17.0740	101.0	40.0864
9	3	400	40	108.39	40.6998	4.77	13.5704	111.6	40.9533
10	3	630	63	173.47	44.7845	10.23	20.1975	93.4	39.4069
11	3	1000	10	108.01	40.6693	5.27	14.4362	101.4	40.1208
12	3	1600	25	141.12	42.9918	6.43	16.1642	99.3	39.9390
13	4	400	63	164.21	44.3080	3.89	11.7990	114.5	41.1761
14	4	630	40	119.83	41.5713	3.99	12.0195	111.1	40.9143
15	4	1000	25	129.59	42.2514	4.64	13.3304	108.1	40.6765
16	4	1600	10	128.00	42.1442	5.95	15.4903	112.1	40.9921

1 (Square pin), 2 (Cylindrical pin), 3 (Triangular pin) and 4 (Tapered pin)
TG1, TG2, TG3 and TG4

for percentage elongation. In addition, the percent contributions of the tool geometry, rotation speed and welding speed on hardness reported as 50.1%, 19.36% and 20.49%respectively. This concluded that tool geometry is the most effective factor for hardness.

4.3 Estimation of optimum tensile strength, hardness and percentage elongation

The optimum levels of control factors were determined with the help of S/ N ratio and mean response features. The expected average of quality characteristics, i.e., tensile strength, percentage elongation and hardness, is therefore calculated using the Eq. 2 to Eq. 4 [19]. The authors also put efforts to enhance the characteristic to of welding and other process by using the design of experiment methodology [20–23].

$$TS_{opt} = P_{TS} + (TG_1 - P_{TS}) + (RS_4 - P_{TS}) + (WS_4 - P_{TS}) \quad (2)$$

$$PE_{opt} = P_{PE} + (TG_1 - P_{PE}) + (RS_4 - P_{PE}) + (WS_4 - P_{PE}) \quad (3)$$

$$H_{opt} = P_H + (TG_4 - P_H) + (RS_1 - P_H) + (WS_4 - P_H) \quad (4)$$

where P_{TS}, P_{PE} *and* P_H is mean value for performance characteristics corresponding to TS, PE and H respectively. P_{TS}, P_{PE} and P_H represents the predicted mean of the tensile strength, percentage elongation and hardness at optimum conditions. The optimum average values for tensile strength, percentage elongation and hardness, i.e.,(TG_1, RS_4, WS_4), (TG_1, RS_4, WS_4) and (TG_4, RS_1, WS_4) respectively shown in Table 7. Substituting these values in Eq. (2) to (4), the mean optimum value of the tensile strength, percentage elongation and hardness was achieved as $TS_{opt} = 202.94MPa$, $PE_{opt} = 12.23\%$ and $H_{opt} = 115.1HV$ respectively.

The Taguchi optimization technique validated with optimized condition with confidence interval of 95% and predicted result is obtained with the help of Eq. 5 and Eq. 6.

$$CI = \sqrt{F(\alpha, 1, f_e) \times V_C \left| \frac{1}{n_{eff.}} + \frac{1}{R} \right|} \quad (5)$$

$$n_{eff.} = \frac{N}{(1 + T_{dof})} \quad (6)$$

where $F(\alpha, 1, f_e)$ is the F-ratio required for $100(1 - \alpha)$ percent confidence interval,

Degree of freedom (DOF) for error, $f_e = 6$,

The error variance, $V_c = 357.5$,

The number of replications for confirmation experiments, R = 3,

Table 6 ANOVA analysis for TS, PE and H

Variance source	Degree of freedom (DOF)	Sum of square (SS)	Mean square (MS)	F ratio	P value	Contribution rate (%)
Tensile strength (TS)						
Tool Geometry	3	3407.7	1135.90	19.06	0.002	33.4
Rotation speed	3	479.1	159.68	2.68	0.141	4.69
Welding speed	3	**5956.1**	**1985.37**	**33.32**	**0.000**	**58.39**
Error	6	357.5	59.59			3.5
Percentage elongation (PE)						
Tool Geometry	3	36.63	12.209	5.68	0.035	35.08
Rotation speed	3	14.93	4.976	2.31	0.176	14.29
Welding speed	3	**39.97**	**13.323**	**6.20**	**0.029**	**38.28**
Error	6	12.90	2.150			12.35
Hardness (H)						
Tool Geometry	3	**716.1**	**238.71**	**9.97**	**0.010**	**50.1**
Rotation speed	3	276.8	92.26	3.85	0.075	19.36
Welding speed	3	292.9	97.62	4.08	0.068	20.49
Error	6	143.6	23.94			10.05

Bold values show maximum contribution rate (%)

Effective number of replications, n_{eff}.

Total number of experiments, N = 48 (16 × 3)

The total degrees of freedom associated with the mean optimum, $T_{dof} = 9$ (3 × 3),

Ross et al. [19] recommended F-ratio for $\alpha = 0.05$ as $F(0.05, 1, 6) = 5.99$ from standard statistical table. Substituting these values in Eqs. (4) and (5), we reported $n_{eff} = 4.8$ and $CI = 34.05$ for Tensile strength, $CI = 6.47$ for percentage elongation and $CI = 21.58$ for hardness.

The predicted average optimal tensile strength at 95% confidence interval is expressed as;

$$\left[TS_{opt} - CI_{TS}\right] < TS\left[TS_{opt} + CI_{TS}\right]_{exp.}$$
$$[202.94 - 34.05] < 192.58 < [[202.94 + 34.05]]$$
$$168.89 < 192.58 < 236.99$$

$$\left[PE_{opt} - CI_{PE}\right] < PE\left[PE_{opt} + CI_{PE}\right]_{exp.}$$
$$[12.23 - 4.75] < 12.59 < [[12.23 + 4.75]]$$
$$7.48 < 12.59 < 16.98$$

$$\left[H_{opt} - CI_{H}\right] < H\left[H_{opt} + CI_{H}\right]_{exp.}$$
$$[115.1 - 21.58] < 114.5 < [[115.1 + 21.58]]$$
$$93.52 < 114.5 < 136.68$$

It is concluded from the above discussion that the experimental values obtained for TS_{exp}, PE_{exp} and H_{exp} lies within domain of the confidence interval limits and the system optimization for tensile strength is achieved at 0.05of significance level.

4.4 Empirical relationship

The present study involved second order response surface central composite design with the help of Minitab 17software package. The response function i.e., tensile strength (TS), percentage elongation (PE)and hardness (H) are expressed as the functions of tool geometry (TG), rotation speed (RS) and welding speed (WS) respectively and expressed as:

$$TS = f(TG, RS, WS) \tag{7}$$

$$PE = f(TG, RS, WS) \tag{8}$$

Table 7 Mean response for TS, PE, H and WR factor

Levels	Control factors		
	Tool Geometry (TG)	Rotation Speed (RS)	Welding Speed (WS)
Tensile strength (TS)			
1	**165.6**	141.6	129.6
2	160.4	152.7	149.3
3	132.7	145.6	135.6
4	135.4	**154.8**	**179.6**
Delta	32.8	13.7	50.0
Percentage elongation (PE)			
1	**8.563**	5.390	5.572
2	7.970	7.270	6.940
3	6.675	7.138	5.773
4	4.617	**8.027**	**9.540**
Delta	3.945	2.638	3.967
Hardness (H)			
1	92.75	**108.78**	106.15
2	104.15	99.45	99.65
3	101.43	103.47	96.93
4	**111.45**	98.07	**107.05**
Delta	18.70	10.70	10.13

Bold values show optimum value of the tensile strength (TS), percentage elongation (PE) and hardness (H)

Table 8 confirmation tests by the Taguchi and regression model empirical relationship

Level	Taguchi model			linear regression			quadratic regression		
	Exp	Pred	Error %	Exp	Pred	Error %	Exp	Pred	Error %
Tensile strength (TS)									
TG1RS4WS4	192.58	202.94	5.38	192.58	194.45	0.97	192.58	187.2	2.79
Percentage elongation (PE)									
TG1RS4WS4	12.59	12.23	2.8	12.59	12.04	4.4	12.59	12.22	2.96
Hardness (H)									
TG4RS1WS4	114.5	115.1	0.52	114.5	113.0	1.27	114.5	114.46	0.03

$$H = f(TG, RS, WS) \tag{9}$$

The second order polynomial equation that represents the response surface $'Y'$ is:

$$Y = b_0 + \sum b_i x_i + \sum b_{ii} x_i^2 + \sum b_{ij} x_i x_j \tag{10}$$

Further, the individual responses are expressed in linear and interaction regression functions as:

$$TS = b_0 + b_1(TG) + b_2(RS) + b_3(WS) + b_{11}(TG^2) + b_{22}(RS^2) + b_{33}(WS^2) + b_{12}(TG \times RS) + b_{13}(TG \times WS) + b_{23}(RS \times WS) \tag{11}$$

$$PE = b_0^{'} + b_1^{'}(TG) + b_2^{'}(RS) + b_3^{'}(WS) + b_{11}^{'}(TG^2) + b_{22}^{'}(RS^2) + b_{33}^{'}(WS^2) + b_{12}^{'}(TG \times RS) + b_{13}^{'}(TG \times WS) + b_{23}^{'}(RS \times WS) \tag{12}$$

$$H = b_0^{''} + b_1^{''}(TG) + b_2^{''}(RS) + b_3^{''}(WS) + b_{11}^{''}(TG^2) + b_{22}^{''}(RS^2) + b_{33}^{''}(WS^2) + b_{12}^{''}(TG \times RS) + b_{13}^{''}(TG \times WS) + b_{23}^{''}(RS \times WS) \tag{13}$$

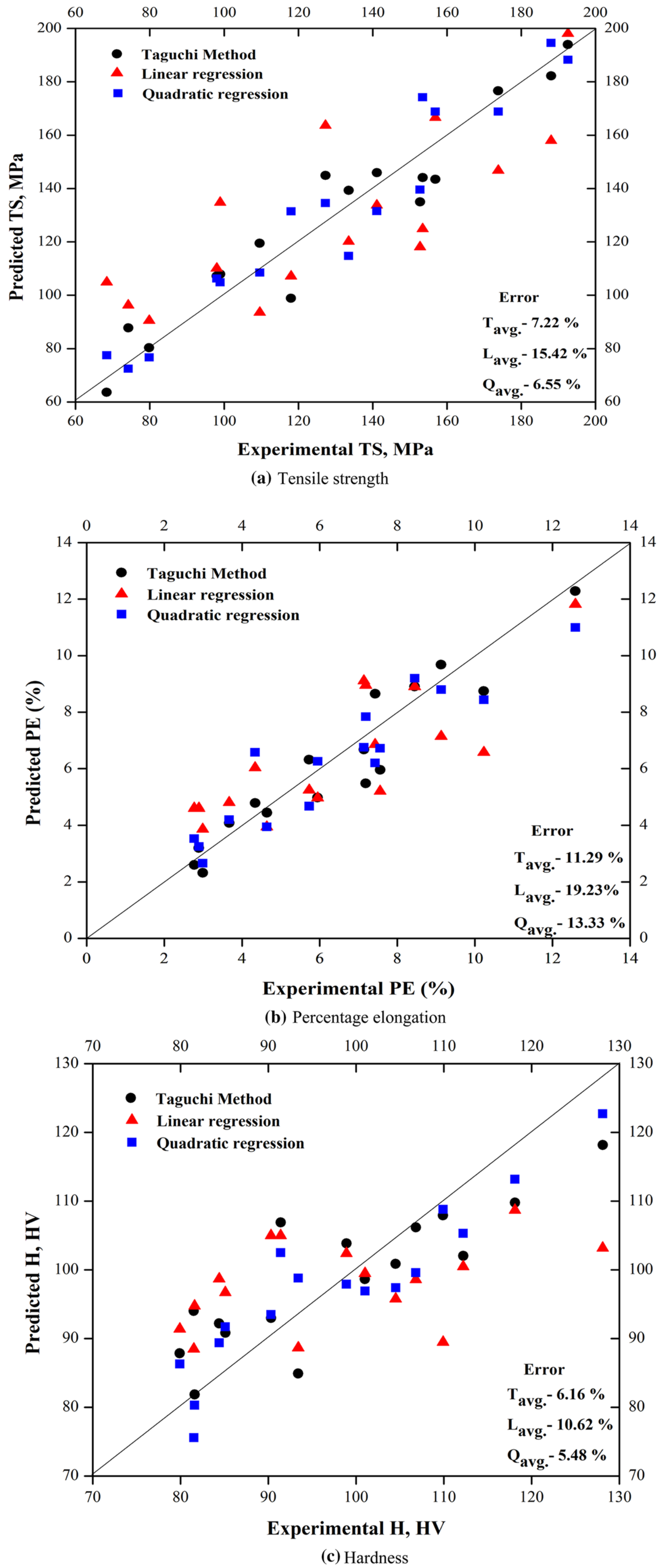

Fig. 9 Comparison for Taguchi method, linear regression and quadratic regression of similar welding with experimental results for TS, PE and H

where, b_0, $b_0^{'}$ *and* $b_0^{''}$ are responses averages. b_i, $b_i^{'}$ *and* $b_i^{''}$ and b_{ij}, $b_{ij}^{'}$ *and* $b_{ij}^{''}$ are the coefficients that depend on the respective main and interaction effects of the parameters. The final relationships were established based on the determined coefficients.

The empirical relationship to predict tensile strength, percentage elongation and hardness of friction stir welded AA6061-T6 is obtained from Eq. 14 to Eq. 19.

$$\begin{aligned} TS = & 204.2 - 37.1TG - 0.0362RS - 0.70WS \\ & + 0.0117WS^2 + 0.0180(TG \times RS) \\ & + 0.314(TG \times WS) + 0.000269(RS \times WS) \end{aligned} \quad (14)$$

R-sq = 85.16% and R-sq (adj) = 68.19%

$$\begin{aligned} PE = & 10.92 - 2.58\,TG - 0.00576RS + 0.001WS \\ & - 0.000001RS^2 + 0.00156\,WS^2 + 0.00267(TG \times RS) \\ & - 0.0226(TG \times WS) + 0.000065(RS \times WS) \end{aligned} \quad (15)$$

R-sq = 84.83% and R-sq (adj) = 67.49%

$$\begin{aligned} H = & 87.5 + 6.92TG + 0.0084RS + 0.279WS \\ & - 0.00281WS^2 - 0.00294(TG \times RS) \\ & - 0.013(TG \times WS) - 0.000248(RS \times WS) \end{aligned} \quad (16)$$

R-sq = 59.30% and R-sq (adj) = 12.78%

The quadratic regression models highlighted in Eq. 14 to Eq. 16, the resultant R^2 values for tensile strength, percentage elongation and hardness as 85.16%, 84.83% and 59.30% respectively. Similarly, R^2 values for linear regression model in Eq. 17 to Eq. 19 were obtained for tensile strength, percentage elongation and hardness as 70.69%, 68.61% and 56.49% respectively. Hence, the quadratic regression model is more intensive and reliable as compared to that of linear regression model through obtained predicted values.

$$TS = 142.1 - 11.81TG + 0.00812RS + 0.828WS \quad (17)$$

R-sq = 70.69% and R-sq (adj) = 63.36%

$$PE = 6.34 - 1.313TG + 0.001782RS + 0.0660WS \quad (18)$$

R-sq = 68.61% and R-sq (adj) = 60.77%

$$H = 99.38 + 5.34TG - 0.00646RS - 0.1280WS \quad (19)$$

R-sq = 56.49% and R-sq (adj) = 45.61%

4.5 Confirmation tests

For Taguchi and regression model equations at optimum values are considered by the confirmation tests of the operating parameters [27, 28]. Table 8 shows the comparison of the experimental results and predicted results carried out by the Taguchi and developed empirical relationship through regression model. The experimental results validated with predicted results showing good convergence.

4.6 The comparison between Taguchi method and regression equations

The experimental results and predicted values obtained by Taguchi method and linear & quadratic regression model are shown in Fig. 9 for AA6061-T6. The data points are evaluated through 45° line with scatter point, corresponding to perfect fit of the developed three empirical models. The variation of the predicted and experimental results lies within the limit of 20% indicating good predictive results and adhere to the statistical analysis obtained from literature i.e., error should less than 20% [29–33].

5 Conclusion

The Taguchi technique implemented to evaluate an optimal welding condition for Friction stir welding of AA6061-T6 aluminum alloy. Experimental results were optimized for a set of control factor i.e., tensile strength, percentage elongation and hardness with the help of ANOVA analysis. The following conclusions were carried out with present investigation are:

- The square pin profile provides the maximum tensile strength of 192.58 MPa and percentage elongation of 12.59%at optimum operating condition of 1600 rpm and 63 mm/min for tool rotation speed and welding speed respectively.
- The tapered pin profile provides the maximum hardness of 114.5HV at optimum welding condition of welding speed of 63 mm/min and tool rotation speed of 400 rpm.
- The developed quadratic regression model predicted coefficient of determination (R^2) value for tensile strength, percentage elongation and hardness as 85.16%, 84.83% and 59.30% respectively corresponding to 95% confidence level with performed experimentation.
- The comparison of three method i.e., Taguchi method, linear regression and quadratic regression reveals that the quadratic regression is more suitable amongst other methods because of minimum percentage error between experimental and predicted values for friction stir welded metals.

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