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Optimization of Friction Stir Spot Welding Process Parameters for AA6061-T4 Aluminium Alloy Plates

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Abstract

In the present investigation, friction stir spot welding (FSSW) on AA6061-T4 aluminium alloy plates was performed. The influences of the tool rotational speed, dwell time, plunge depth and plunge rate on tensile-shear load of welds were evaluated. The process parameters were optimized by Taguchi technique based on Taguchi's L9 orthogonal array. The optimum FSSW process parameters were predicted, and their percentage of contribution was estimated by applying the signal-to-noise ratio and analysis of variance. The experimental results showed that the optimal levels of the rotational speed, plunge depth, plunge rate and dwell time were found to be 2000 rpm, 0.9 mm,10 mm/min and 8 seconds, respectively. The analysis of variance (ANOVA) results showed that the plunge depth is the most influential FSSW process parameter on the tensile-shear load with a percentage of contribution of 55 % of the overall response. The rotational speed, plunge rate and dwell time FSSW process parameters showed percentage of contribution of 17%, 5% and 23%, respectively, of the overall response.

Keywords: Friction Stir Spot Welding; tensile-shear test; Optimization; Aluminium.

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1. Introduction

The heat treatable aluminum 6xxx alloys have moderately high strength levels, better corrosion resistance than the 2xxx and 7xxx alloys, good weldability and superior extrudabiltiy [1]. With yield strength comparable to that of mild steel, AA6061 is one of the most widely used aluminum alloys. The highest strengths are obtained when artificial aging is started immediately after quenching.

Friction stir spot welding (FSSW) has been developed and implemented in automotive industry as a replacement of resistance spot welding (RSW) for aluminum alloys [2-4]. *Mazda Motor Co.*, for instance, uses the FSSW technique for production of new *RX-8* sports car [2]. This welding technology involves a process similar to friction stir welding (FSW), except that, instead of moving the tool along the weld seam, the tool only indents the parts, which are placed on tap of each other [4]. The FSSW process can be done remarkably quickly since cycle times are within a few seconds, for example, cycle time for friction spot wield of 1mm thickness AA6061-T6 aluminum alloy is about 2 seconds [5]. It has been reported that that the investment of spot FSW system was approximately 50% less than the equivalent RSW system, because several pieces of equipment, including a large electric power supply, a cooling unit, an electrode dresser, and others, were not necessary [2]. The cost per single spot estimation showed that the cost of spot FSW system is 85% less than that of the RSW system [2, 6].

The Taguchi method is one of the most frequently employed design of experiments (DOE) methods [7]. Essentially, this category of DOE methods can be considered as a special category of fractional factorial designs. Although Taguchi methods derive from factorial designs, their development introduced several new concepts on the design and evaluation of experiments, which provide valuable help both to scientific and industrial applications [7, 8]. The most important difference between a classical experimental design and a Taguchi method-based robust design technique is that the former tends to focus solely on the mean of the quality characteristic, while the later considers the minimization of the variance of the characteristic of interest. Taguchi enables a comprehensive understanding of the individual and combined from a minimum number of experiments [8].

There is no much work undertaken with the application of Taguchi method for FSSW [9-12]. Hence, the main aim of the present investigation is to study the significance of the influence of the process parameters, mainly, the tool rotational speed, plunge depth, plunge rate and dwell time on the tensile-shear load on AA6061-T4 plates joined using FSSW.

The Taguchi method was applied to find out the optimum settings for each FSSW process parameters to achieve the maximum tensile-shear load for the welded AA6061-T4 plates.

2. Experimental Procedures

2.1. Materials

In the present investigation, aluminum AA6061-T4 plates were joined using FSSW. The AA6061-T4 plates have 3 mm thick. The chemical composition of the AA6061 is given in the Table 1.

Table 1: The chemical composition of the AA6061 aluminum alloy.

Element	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	Other
Min. (wt. %)	95.8	0.04	0.15	-	0.8	-	0.4	-	-	0.05
Max. (wt. %)	98.6	0.35	0.4	0.7	1.2	0.15	0.8	0.15	0.25	0.15

2.2. FSSW Process

The FSSW of AA6061-T4 plates were performed using CNC milling machine. Before welding, the sheets were cleaned with acetone to remove the oil and dirt impurities from the surface. Figure 1 illustrates the FSSW process carried out in the present study.

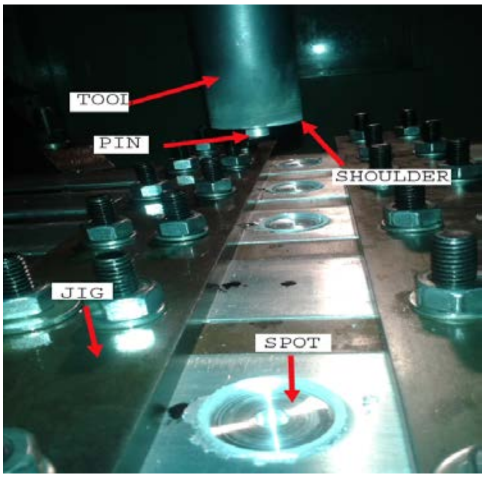

Figure 1: The FSSW setup used in the present work.

The FSSW was carried out using a hardened H13 steel tool with a nominal chemical composition (in wt. %) 0.39% C, 0.40% Mn, 5.2% Cr, 0.95% V, 1.4% Mo, 1.10% Si, and 90.56% Fe. The tool has a straight cylindrical pin with 6 mm diameter and 4.5 mm length, and a shoulder of 24 mm.

2.3. Tensile-Shear Tests

Tensile-shear tests were carried out to evaluate the performance of the welds. Lap-shear specimens according to DIN EN-ISO 14273 were made using two 50×170 mm coupons with 3-mm thickness and a 50×50 mm overlap area, at which the FSSW was performed at its centre. Tensile-shear tests were carried out at ambient temperature using a universal testing machine with a constant crosshead speed of 1 mm/min. From each condition, three tensile samples were tested.

2.4. Design of Experiments (DOE)

It has been reported that FSSW process parameters such as tool geometry, tool material, title angle, tool rotation speed, dwell time, plunge rate and plunge depth significantly influence the process and play a major role in deciding the quality of the weld [2,4,6,9-13]. In the present study, four FSSW process parameters were studied. These parameters are the tool rotation speed, dwell time, plunge rate and plunge depth which are mostly contribute to heat input and subsequently influence the mechanical properties of the welded joints [2,6,9]. These FSSW process parameters were selected in three different levels. Table 2 shows the FSSW process parameters and their levels.

Table 2: The FSSW process parameters and their levels.

FSSW Process Parameter	Unit	Level 1	Level 2	Level 3
Rotational speed	(rpm)	1000	1500	2000
Plunge depth	(mm)	0.5	0.7	0.9
Plunge rate	(mm/min)	10	20	30
Dwell time	(s)	4	6	8

Before selection of the orthogonal array (OA) particular, the number of factors and interactions of interest and the number of levels and interactions of interest must be considered. As three levels and four factors are taken into consideration, L9 OA is used in this investigation.

Table3: The matrix of L9 orthogonal array.

RUN#	Rotational Speed (rpm)	Plunge Depth (mm)	Plunge Rate (mm/min)	Dwell time (s)
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Only the main factor effects are taken into consideration and not the interactions. The degrees of freedom (DOF) for each factor is 2 (number of levels − 1, i.e. 3 − 1 = 2) and therefore, the total DOF will be 8(= 4 × (3-1)). As per Taguchi method, the total DOF of selected OA must be greater than or equal to the total DOF required for the experiment. So, an L9 OA having 8 (=9-1) degrees of freedom are selected for the present analysis. Table 3 shows the matrix of L9 orthogonal array.

The signal to noise S/N ratio was calculated based on the quality of characteristics intended. The main objective function described in this investigation is maximization of the tensile shear strength, so the larger the best S/N ratio was calculated. The formula for S/N ratio is given below.

$$\eta = -10 \log 10 \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \quad \ldots (1)$$

Where n is number of experiments and y is observed response value.

Analysis of variance (ANOVA) test was performed to determine the influence and relative importance of the different factors. The purpose of the ANOVA test is to investigate the significance of the process parameters which affect the tensile shear strength of FSSW joints. In the present study, the tensile shear strength value of the FSSW joints was analysed to study the effects of the FSSW process parameters. The experimental results are then transformed into means and signal-to-noise (S/N) ratio. The design of experiments, S/N and ANOVA calculations were performed using Minitab commercial statistical software.

3. Results and Discussion

In the present work, 9 means and 9 S/N ratios were calculated and the estimated tensile shear loads, means and signal-to-noise (S/N) ratio are given in Table 4. The main effects of average mean and S/N ratio values of all levels are calculated and listed in Table 5 and 6 respectively. It is clear that a larger S/N ratio corresponds to better quality characteristics. Therefore, the optimal level of process parameter is the level of highest S/N ratio. Based on both mean and S/N ratio, the optimal levels of tensile shear strength at rotational speed, plunge depth, plunge rate and dwell times are level 3, 3, 1 and 3 (2000 rpm, 0.9 mm, 10 mm/min and 8 sec), respectively, as shown in graph and Figures 3 and 4.

Table 4: The means and signal-to-noise (S/N) ratio of tensile-shear load.

Run #	Factors				Trails			Mean (KN)	S/N ratio
	Rotational speed (rpm)	Plunge depth (mm)	Plunge rate (mm/min)	Dwell time (sec)	T1 (KN)	T2 (KN)	T3 (KN)		
1	1000	0.5	10	4	5.88	5.81	6.35	6.01333	15.5623
2	1000	0.7	20	6	5.82	6.2	5.26	5.76000	15.1484
3	1000	0.9	30	8	8.13	8.5	7.43	8.02000	18.0424
4	1500	0.5	20	8	6.25	5.45	5.35	5.68333	15.0305
5	1500	0.7	30	4	6.34	5.52	6.43	6.09667	15.6392
6	1500	0.9	10	6	6.68	6.65	7.08	6.80333	16.6439
7	2000	0.5	30	6	5.26	5.18	5.79	5.41000	14.6327
8	2000	0.7	10	8	8.16	8.72	8.21	8.36333	18.4360
9	2000	0.9	20	4	9.21	9	7.79	8.66667	18.6845

Table 5: The main effects of S/N ratio values of all levels of tensile shear load.

Level	Rotational speed(rpm)	Plunge depth (mm)	Plunge rate (mm/min)	Dwell time (sec)
1	16.25	15.08	16.88	16.63
2	15.77	16.41	16.29	15.48
3	17.25	17.79	16.10	17.17
Delta	1.48	2.72	0.78	1.69

Table 6: The main effects of average mean and of all levels of tensile shear strength.

Level	Rotational speed(rpm)	Plunge depth(mm)	Plunge rate (mm/min)	Dwell time (sec)
1	6.598	5.702	7.060	6.926
2	6.194	6.740	6.703	5.991
3	7.480	7.830	6.509	7.356
Delta	1.286	2.128	0.551	1.364

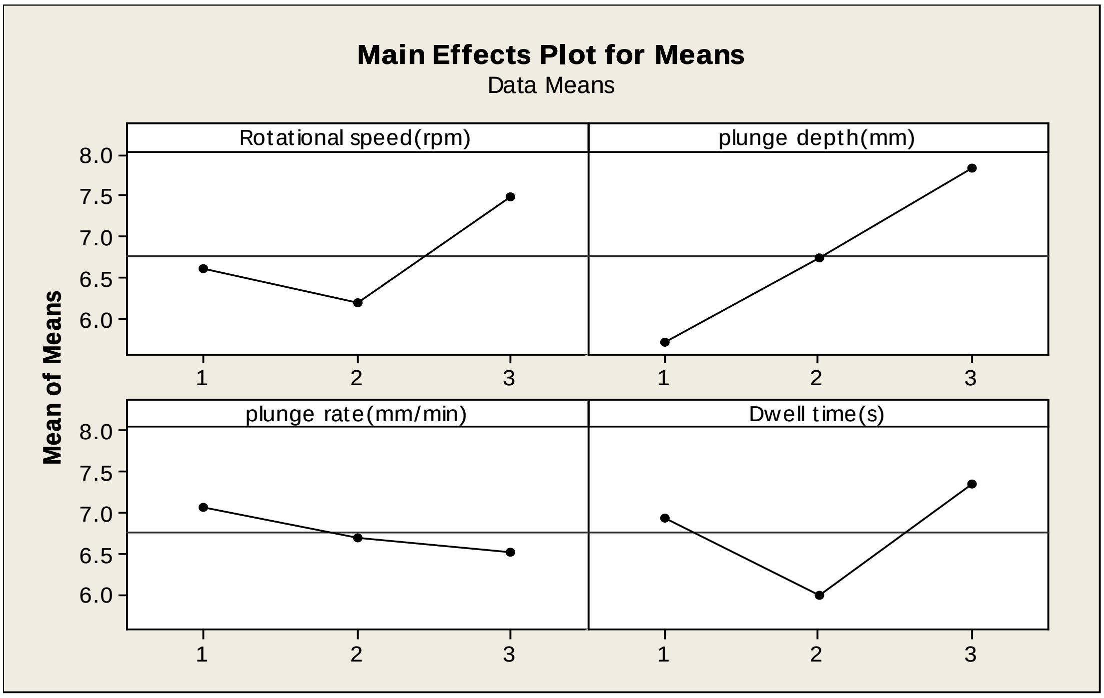

Figure 2: Main effects of S/N ratios of tensile-shear load.

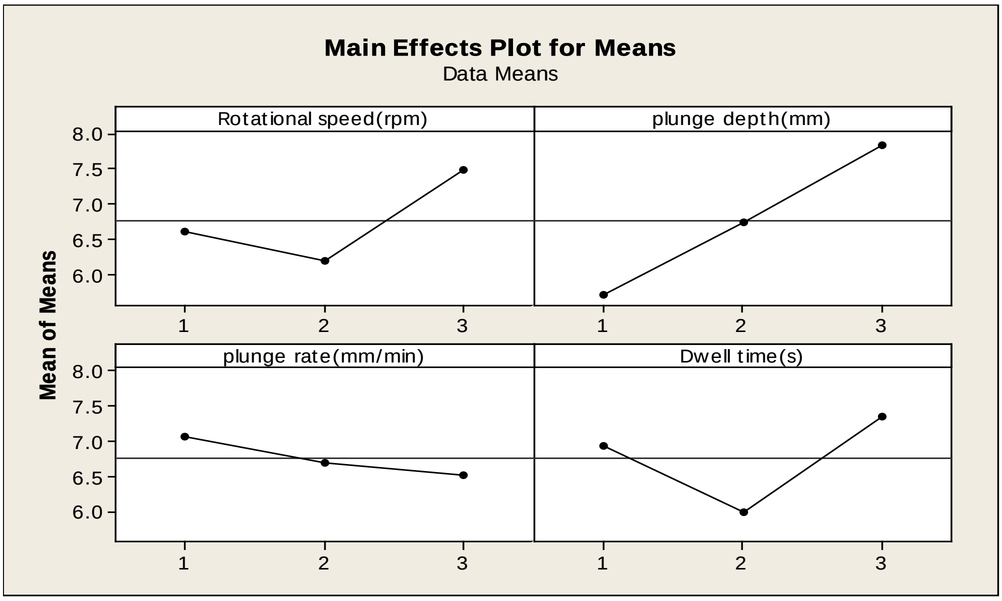

Figure 3: Main effects of means of tensile-shear load.

The ANOVA results for tensile-shear loads of S/N ratio and mean are given in Tables 7 and 8, respectively. The percentage of contribution is the portion of the total variation observed in the experiment attributed to each significant factors and/or interaction which is reflected.

The percentage of contribution is a function of the sum of squares for each significant item; it indicates the relative power of a factor to reduce the variation. If the factor levels are controlled precisely, then the total variation could be reduced by the amount indicated by the percentage of contribution. The percentage of contribution of the rotational speed, welding speed, plunge depth, plunge rate and dwell time is shown in Figure 4. It is clear the plunge depth is the most FSSW process parameter that affect the tensile-shear characteristics of AA6061-T4 joints. The plunge depth showed a contribution of 55 % of the overall response.

Mumin et al [11] reported that the order of importance of the FSSW parameters and it was as follows: plunge depth, dwell time, and tool rotational speed. As in the present work, the most significant parameter was the plunge depth. In their work it showed a contribution of 69.26 %. With increasing plunge depth, the tensile shear load of the FSSW joints increased.

Table 7: ANOVA for S/N, using Adjusted SS for tensile-shear tests

Source	DF	Seq. SS	Adj. SS	Adj. MS	Contribution (P, %)
rotational speed	2	3.4202	3.4202	1.7101	17.13372542
plunge depth	2	11.0591	11.0591	5.5295	55.40131651
plunge rate	2	0.9871	0.9871	0.4936	4.944944845
dwell time	2	4.4953	4.4953	2.2477	22.51951227
Error	0	*	*	*	
Total	8	19.9618			100

Where: DF=Degrees of freedom, Seq SS=Sequencial sum of squares, Adj SS=Adjusted sum of square, Adj MS=Adjusted mean square.

Table 8: ANOVA for mean, using Adjusted SS for tensile-shear tests.

source	DF	Seq. SS	Adj. SS	Adj. MS	Contribution (P, %)
rotational speed	2	2.5936	2.5936	1.2968	20.30262942
plunge depth	2	6.7925	6.7925	3.3963	53.17150305
plunge rate	2	0.4687	0.4687	0.2344	3.6689707
dwell time	2	2.9198	2.9198	1.4599	22.85611404
error	0	*	*	*	
Total	8	12.7747			100

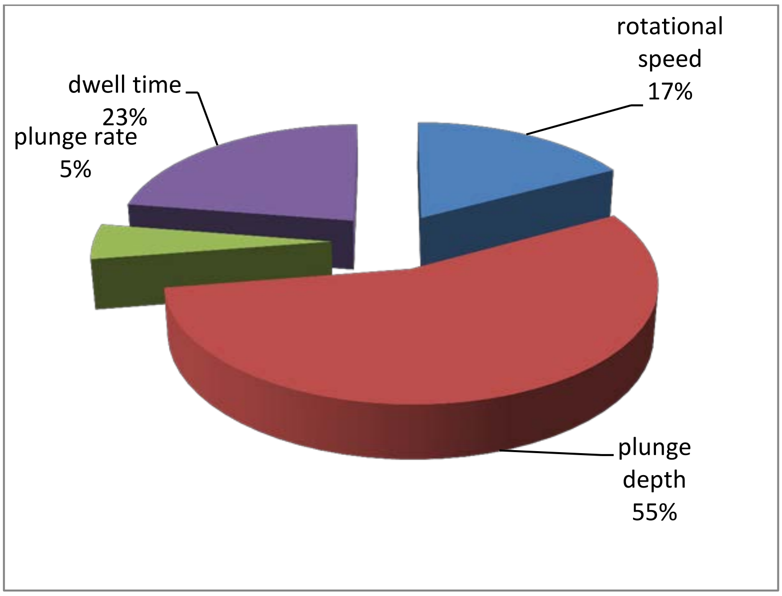

Figure 4: Contribution of each factor on the performance statistics (Influential effects based on percentage distributions).

Once the optimal level of design parameters has been selected, the final step is to predict and verify the improvement of the quality characteristic using the optimal level of design parameters. The estimated tensile shear load using the optimal level of the design parameters can be calculated as

$$\eta = \ddot{\eta} + \sum_{i=1}^{n}(\eta_i - \ddot{\eta}) \qquad \ldots (2)$$

Where:

$\ddot{\eta}$ is total mean of responses, η_i is the mean of responses at the optimal level, and n is the number of main welding parameters that significantly affect the performance. The results showed that the predicted average tensile-shear load is 9.455 kN. The confirmation experiments are carried out by setting the process parameters at optimum levels. The rotational speed, plunge depth, plunge rate and dwell time are set at 2000 rpm, 0.9 mm, 10 mm/min and 8 sec respectively. Three tensile shear specimens are subjected to tensile-shear test and the average tensile-shear load value was about 9.57 kN. The error % between the experimental and predicted value is about 1%.

4. Conclusions

Based the aforementioned results, the following conclusions can be concluded:

1. The FSSW process parameters are optimized to maximize the tensile-shear load of joint. The optimum levels of the rotational speed, plunge depth, plunge rate and dwell time are found to be 2000 rpm, 0.9 mm,10 mm/min and 8 seconds, respectively.
2. The plunge depth can be considered the most influential FSSW process parameter on the tensile-shear load. It showed a percentage of contribution of 55 % of the overall response.
3. The rotational speed, plunge rate and dwell time FSSW process parameters showed percentage of contribution of 17%, 5% and 23%, respectively, of the overall response.

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References

[1] Joseph R. Davis. (1993). Aluminum and Aluminum Alloys. ASM International. [On-line].Available:Aluminum and Aluminum Alloys.

[2] R.S. Mishra and Z.Y. Ma. “Friction Stir Welding and Processing” .*Mater. Sci. Eng. R*, 50, pp. 1–78 .2005.

[3] P.L. Threadgill, A.J. Leonard, H.R. Shercliff, and P.J. Withers.“*Friction Stir Welding of Aluminium Alloys”* Int. Mater. Rev, 54. (2), pp. 49–93. 2009.

[4] H. Badarinarayan, F. Hunt, and K. Okamoto. “Friction Stir Spot Welding” in *Friction Stir Welding and Processing*. R.S. Mishra and M.W. Mahoney, Ed. ASM International, Materials Park, OH, 2007, pp. 235–272.

[5] M. Awing. (2007) .*Simulation of Friction stir spot welding*. ProQuest, [On-line].Available: Simulation of Friction Stir Spot Welding (FSSW) Process: Study of ...

[6] T.S. Mahmoud, T.A. Khalifa. “Microstructural and Mechanical Characteristics of Aluminium Alloy AA5754 Friction Stir Spot Welds”. *Journal of Materials Engineering and* Performance, 23. (3), pp.

898-905, 2014.

[7] J. Paulo Davim, Aveiro, Portugal. (2016). *Design of Experiments in Production Engineering*. Springer International Publishing, Switzerland, [On-line].Available: Design of Experiments in Production Engineering - Page iv

[8] S. Deepak kumara, Pandu R. Vundavillia, Sisir Mantryb, A. Mandalc, M. Chakrabortyc, "A Taguchi optimization of cooling slope casting process parameters for production of semi-solid A356 alloy and A356-5TiB2 in-situ composite feedstock". *Procedia Materials Science*, 5, pp. 232 – 241,2014 .

[9] Yahya Bozkurt, Mustafa Kemal Bilici. "Taguchi Optimization of Process Parameters in Friction Stir Spot Welding of AA5754 and AA2024 Alloys". *Advanced Materials Research*, vol. 1016, pp. 161-166, 2014.

[10] R. Karthikeyan, V. Balasubramanian. "Optimization and sensitivity analysis of friction stir spot-welding process parameters for joining AA6061 aluminum alloy". *Int. J. Manufacturing Research*, 7. (3), pp.257–272, 2012.

[11] Mumin Tutar, Hakan Aydin, Celalettin Yuce, Nurettin Yavuz, Ali Bayram. "The optimization of process parameters for friction stir spot-welded AA3003-H12 aluminum alloy using a Taguchi orthogonal array". *Materials and Design*, 63, pp.789–797,2014.

[12] G. Pieta, J. dos Santos, T. R. Strohaecker, T. Clarke. "Optimization of Friction Spot Welding Process Parameters for AA2198-T8 Sheets". *Materials and Manufacturing Processes*, 29. (8), pp. 37-41, 2014.

[13] R.M. Afify, T.S. Mahmoud, S.M. Abd-Rabbo, T.A.Khalifa. "On the microstructural and mechanical characteristics of friction stir spot welded AA1050-O aluminum alloys". *MSAIJ*, 13. (7), pp. 226-236, 2015.