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PARAMETERS OPTIMIZATION ON FRICTION SPOT WELDING OF AA5754 ALUMINIUM ALLOY[1]

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Abstract

The solid-state joining technique, Friction Spot Welding (FSpW), is able to produce spot-like joints in distinct sort of materials, especially in lightweight alloys, being an important solution to reduce the structural weight in the transport sector, and thus, minimize the fuel consumption. Some characteristics that make the FSpW advantageous are defect-free joints produced with high strength, high energy efficiency, reduction in the number of process steps, no post processing required due to high surface quality, high welding speeds and high environmental compatibility. The study of FSpW parameters and their influence on lap shear strength of AA5754 aluminium alloy welds were described in the present work. The optimization of welded parameters was developed using Design of Experiments (DOE) applied through Taguchi method. Analysis of variance was applied to determine the individual importance of each parameter. In order to indicate the best levels for improve lap shear strength values, larger-the better quality's category was used. The Taguchi analysis predicted the optimized welding condition and results showed that dwell time acquired the highest effect on the weld strength, followed by rotational speed and plunge depth.

Key words: Friction spot welding; AA5754 aluminium alloy; Taguchi method.

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1 INTRODUCTION

The utilization of light alloys, especially the aluminium alloys, has increased a lot in the last decades due to the world-wide concern in reduce the weight of vehicles such as automobiles and aircrafts, reducing the fuel consumption, and thus, causing less pollution and environmental impact. Moreover, it provides a decrease in costs for both the industry and the final consumer.(1)

The aluminium alloys not only show the advantage of being lighter than other metals, but also show a high resistance, good usinability and recycling capacity.(2) The disadvantage of these alloys is the difficulty of being joined together through conventional welding techniques. Aiming to overcome these welding problems and achieve a weld with high quality, new joining techniques have been developed in the last years.(3-5)

Friction Spot Welding process (FSpW), a spot-like joining technique, comes as an alternative to overcome these issues, being capable of replacing mechanical fastening and fusion spot welding processes in some applications. The FSpW was developed and patented by Helmholtz-Zetrum Geesthacht in Germany and it uses a tool with three parts that move independently: clamping ring, pin and sleeve.(6)

Depending on which part is plunged into the plates, pin or sleeve, two different variants of the FSpW process are possible, the pin plunge or the sleeve plunge. In both variants the process is performed in four stages. In the sleeve plunge variant, on the first stage, the plates are clamped together by the clamping ring and both pin and sleeve start to rotate together in the surface of the upper plate. On the second stage, the sleeve plunges into the plates, while the pin retracts creating a cavity to accommodate the flash generated during the process. On the third stage, when a certain plunge depth is reached, both parts are retracted back to the surface of the upper plate refilling the hole left by the plunge part. On the fourth and last stage, the whole toll is removed back, indicating that the process is over. A schematic illustration of the FSpW/sleeve plunge process is presented in Figure 1.(4,5,7)

The sleeve plunge has an advantage over the pin plunge variant that is the bigger size of the joint area than in the pin variant, which leads to higher joint strength; whereas the pin plunge is easier to perform since demands less torque by the welding machine.(7)

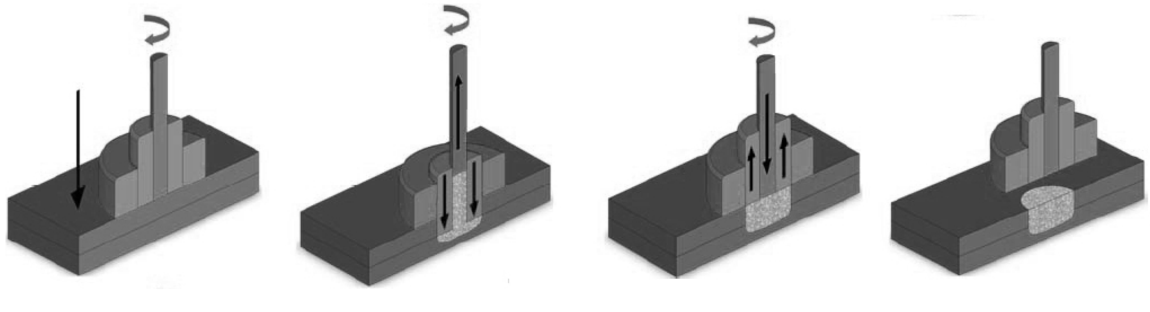
(a) (b) (c) (d)

Figure 1. Illustration of the FSpW/sleeve plunge process: a) clamping and tool rotation, b) sleeve plunges into the sheets while pin retracts, c) tool back to surface and d) tool removal.(4)

The correct choice of the process parameters such as rotational speed (RS), plunge depth (PD) and dwell time (DT) are very important to develop a good FSpW joint. Taguchi method is a great tool of Design of Experiments (DOE) that provides optimization of the process parameters, reducing the experimental costs and time [4].

Normally in the industry, the processes or products have a relatively large number of factors influencing it. Therefore the number of possible combinations increases with the increase of process parameters, leading to the necessity of design of experiments.(8,9)

Taguchi method uses a special design of orthogonal array to study the entire process parameter space with a small number of experiments, which is very flexible and can be modified according to personal needs. L9 is a popular example of Orthogonal Array. Using L9, one can handle 4 factors at 3 levels each. The objective is to find the best of the 81 (=3^4) possible combinations, although using only 9 experimental runs. This possibility exists because the L9 array has the property of orthogonality, which means that all possible combinations between pairs of columns occur, and each combination occurs an equal number of times.(8,9)

The Signal-to-Noise (S/N) ratio analysis outcomes three categories of quality characteristics: lower-the-better, larger-the-better and nominal-the-best. For each process parameter, the S/N ratio is calculated based on the analysis of S/N function. Generally, a larger S/N ratio is related with better quality characteristics regardless of the category. So, the level owing the larger S/N ratio is the optimal process parameter.(10,11) Aiming to investigate which parameters have an important effect on the quality aspects is carried out the analysis of variance (Anova).

So at first, the experiments are planned according to the optimized problems and the Orthogonal Array test and data analysis methods are written. In the second stage, the experiments are carried out as the designed orthogonal array. In the third step, after some complicated data analysis, the best level for the factors will be confirmed. Then, in the final step, the optimized results will be verified through the test. If the predicted quality characteristics are near the test results, the optimized results will work on the problem.(11)

In the present work, in order to investigate the influence of each FSpW parameter on lap shear strength of AA5754 aluminium alloy welds Taguchi method is applied. Furthermore, the combination of parameters that leads to the highest weld strength was evaluated.

2 MATERIALS AND EXPERIMENTAL PROCEDURE

AA 5754 Al alloy sheets with 2 mm thickness have been used in this work. Sheets were cut in 100 mm long and 25 mm test specimens. The friction spot welded coupons were prepared in lap-shear configuration with 25 mm overlap.

The FSpW process was carried out using a RPS 100 machine, which was developed by Helmholtz-Zentrum Geesthacht GmbH. The welding tool was made of tool steel and consists of a clamping ring, Ø 9 mm threaded sleeve and Ø 6 mm threaded pin.

The two specimens, properly cleaned with acetone, were placed in lap shear configuration using a fixed holder on the base table. The welding process was manually started and the weld was performed in order to give the welding parameters. During the whole process, the tool temperature was controlled by a thermocouple and the initial temperature was in the range of 25 to 35°C.

A series of welds were performed with a range of parameters, set in order to find the levels for the three factors (rotational speed, plunge depth and dwell time). Then, these three factors with three different levels were arranged in a L9 orthogonal array, resulting in 9 experiments. Each experiment was carried out in triplicate. Taguchi Method was applied using Minitab software in order to define both the optimal result

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from finite analytical data and the dominant factors involved in the optimization of friction spot welding.

After reached the optimized welding condition, the influence of each individual variable on shear strength behavior, by keeping two variables constant and varying the levels of the other, was evaluated. The welding specimens were produced and studied through mechanical testing.

3 RESULTS AND DISCUSSION

The optimization analysis of the similar welded parameters was made using Taguchi method. In this study, three parameters as rotational speed, plunge depth and dwell time with three levels each one were used and can be seen in Table 1.

Table 1. Factors and levels for DOE

Parameters	Level 1	Level 2	Level 3
Rotational Speed (RS)	2000	2500	3000
Plunge Depth (PD)	2.2	2.5	2.8
Dwell Time (DT)	1.0	2.0	3.0

The conditions to be welded were based on Taguchi method and L9 array was elaborated considering the number of factors and levels. The results were given in terms of Means and S/N ratio values, which used “the-larger-the-better” criterion for response. The lap shear tests were performed in triplicate. The experimental conditions and their respective results of average shear strength can be observed in Table 2.

Table 2. Experimental conditions and results

Run	Rotational Speed (RPM)	Plunge Depth (mm)	Dwell Time (s)	Clamping Force (kN)	Average Lap Shear Strength (kN)
1	2000	2.2	1.0	12.0	6.96
2	2000	2.5	2.0		6.92
3	2000	2.8	3.0		7.03
4	2500	2.2	2.0		6.95
5	2500	2.5	3.0		6.20
6	2500	2.8	1.0		7.38
7	3000	2.2	3.0		5.90
8	3000	2.5	1.0		6.84
9	3000	2.8	2.0		6.15

“The-larger-the-better” standard type of S/N ratio was used because the system response (lap shear strength) is desired as large as possible. The objective of developing a qualified process is not only the attempt to maximize the mean lap shear strength (LSS), but also the signal-to-noise ratio for the respective parameter, which means considering the higher values of the charts for each parameter. Figure 2 shows the main effects plot for i) S/N ratio and ii) Means in terms of the three welding parameters.

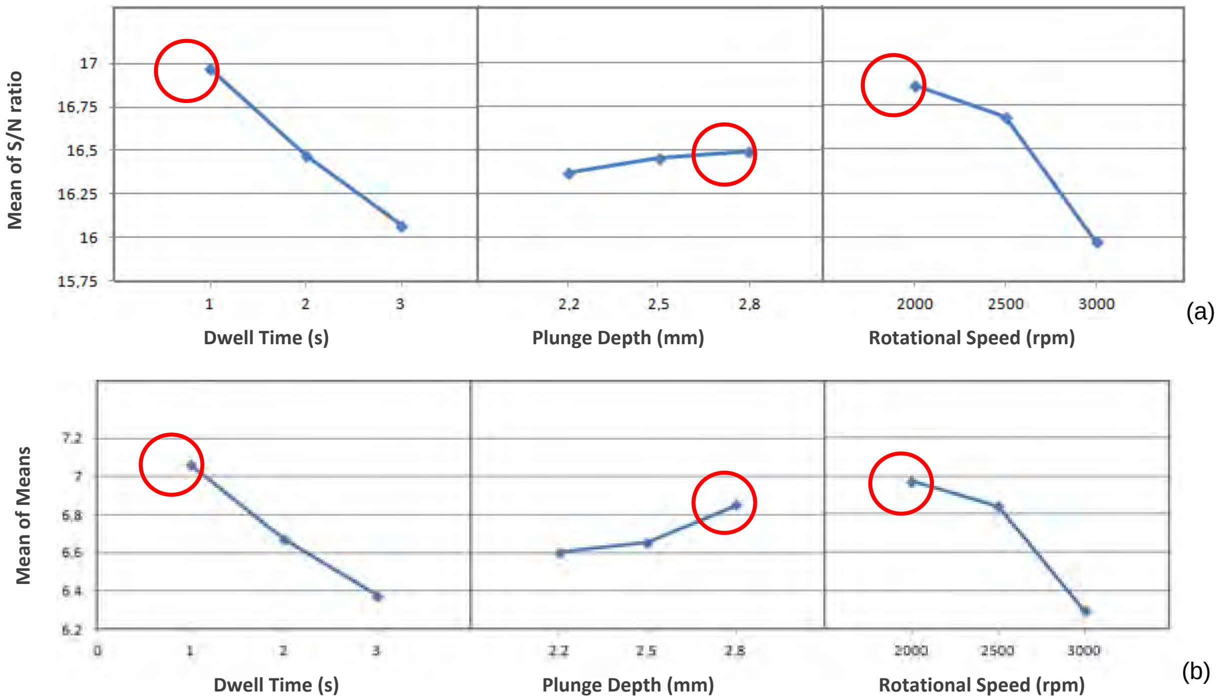

Figure 2. Main effects plot for (a) S/N ratio; and (b) Means for the welding parameters. In terms of dwell time, plunge depth and rotational speed.

The response of means and S/N ratio produced by the L9 orthogonal array is shown in Table 3. The values in last two rows represent the delta value and the rank which allows understanding which parameter has the greatest effect on the response (LSS). The delta is measured by taking the difference between the highest and the lowest value of the analyzed data. Finally, the rank gives the parameters from the greatest to the poorest effect on the response characteristic, considering the delta values.

Table 3. Response table for means and S/N ratio

Level	**S/N ratio**			**Means**		
	RS	**PD**	**DT**	**RS**	**PD**	**DT**
1	16.86	16.37	16.97	6.970	6.603	7.060
2	16.68	16.45	16.47	6.843	6.653	6.673
3	15.97	16.69	16.07	6.297	6.853	6.377
Delta	0.90	0.32	0.90	0.673	0.250	0.683
Rank	**2**	**3**	**1**	**2**	**3**	**1**

The greatest variation of the mean and S/N ratio was observed for dwell time, showing that this parameter has the most important influence on LSS. Plunge depth showed the lowest delta value, which means that it has the less influence in the process.

The best combination of welding parameters suggested by Taguchi analysis is the condition C10, which is presented in Table 4. As the condition was not illustrated on the L9 orthogonal array provided by the Taguchi Method, new welds and experimental lap shear tests were performed using the expected optimized welding

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parameters in order to verify the response. The average strength obtained for C10 condition is presented in Table 4.

Table 4. Optimized condition predicted by Taguchi analysis

Welding Condition	RS (rpm)	PD (mm)	DT (s)	Clamping Force (kN)	LSS Values (kN)	Average LSS (kN)
10	2000	2.8	1.0	12.0	7.74 7.46 7.54	7.58

In order to determine the relative influence of each factor to the variation of results and their significance on FSpW joints, analysis of variance (Anova) was calculated and its results for lap shear of means and S/N ratio are depicted in Table 5. The percentage of contribution (%P) is the portion of the total variation observed in an experiment attributed to each significant factor and/or interaction. Figure 3 presents the parameters percentage of contribution.

Table 5. Anova for lap shear strength (S/N ratio and means)

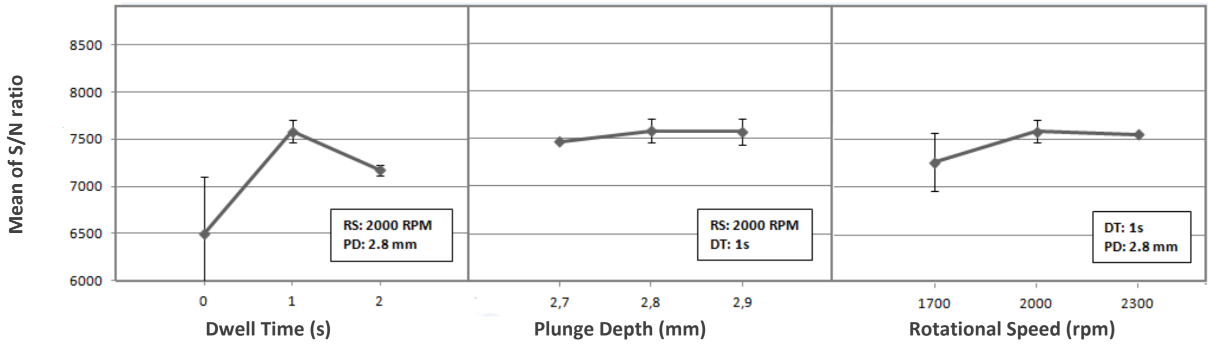
Source	DF	Sum of Squares		Mean Squares		Fisher Ratio		Percentage of Contribution (%)	
		Means	S/N ratio	Means	S/N ratio	Means	S/N ratio	Means	S/N ratio
RS	2	0.7045	1.2288	0.3522	0.6144	1.83	1.83	35.91	35.87
PD	2	0.105	0.1695	0.0525	0.0847	0.27	0.25	5.35	4.95
DT	2	0.7683	1.3567	0.3841	0.6783	2.00	2.02	39.16	39.61
Error	2	0.3841	0.6706	0.192	0.3353	--	--	19.58	19.58
Total	8	1.9618	3.4255	--	--	--	--	--	--

Figure 3. Graphic of parameters percentage contribution.

New experiments were performed in order to evaluate the effect of each individual variable in the LSS. Based on the best parameters condition C10 (2000 rpm, 2.8 mm and 1.0 s), this evaluation was performed for the three factors by keeping two variables constant and varying the levels of the other. The conditions for this evaluation and their LSS values are presented in Table 6 and Figure 4 shows the same average values on a graphic, comparing each factor with the LSS.

Table 6. Conditions used for the individual effect analysis and their LSS average values

Welding Condition	RS (rpm)	PD (mm)	DT (s)	Clamping Force (kN)	LSS Values (kN)	LSS Average (kN)
11	2300	2.8	1	12.0	7.50 7.57 7.57	7.55
12	1700	2.8	1		7.61 7.06 7.11	7.26
13	2000	2.9	1		7.69 7.62 7.42	7.57
14	2000	2.7	1		7.47 7.46 7.48	7.47
15	2000	2.8	0		7.13 6.6 6.7	6.81
16	2000	2.8	2		7.23 7.17 7.12	7.17



(a) (b) (c)

Figure 4. Effect of (a) dwell time, (b) plunge depth and (c) rotational speed on Lap Shear Strength of the welded joints.

It is observed in Figure 4a that the variations in dwell time lead to a significant change in the LSS. The modification in the dwell time from 1.0 to 2.0s causes a decrease of 410N in the LSS. Also, the change in dwell time to 0s affects the welds in a significantly way, implying in a decrease of 1080N in LSS. Therefore, 1.0s is the lowest value of dwell time, in this group of parameters used, that could produce good welds. Furthermore, the observed behavior confirms that dwell time is the variable with greater influence in the shear strength of the welds.

The graphic of plunge depth, in Figure 4b, shows that variation in the LSS is not much significant. It confirms that the plunge depth presents the lowest influence in the shear strength of the joints.

Finally, Figure 4c shows that the variation in the rotational speed from 2000 to 2300 rpm was not much significant for the shear strength. Although, the decrease from 2000 to 1700 rpm leads to a decrease in the LSS of 320N, proving that the rotational speed is a significant factor for the joints and also that a rotational speed' value lower than 2000 rpm leads to a slight decrease in the LSS.

4 CONCLUSIONS

The feasibility and optimization of the similar welding between two AA5754 aluminium alloy plates by Friction Spot Welding has been successfully demonstrated. The following conclusions can be observed:

- Taguchi Method predicted the optimum parameters by Minitab Software which were rotation speed (2.000 rpm), dwell time (1.0 s) and plunge depth (2.8mm);
- the importance of each factor in the FSpW process was evaluated. The dwell time had an importance of 39%, rotational speed 36% and the plunge depth just 5% of contribution to the lap shear strength. The error calculated was 20%.

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