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Original Article

Shear strength optimization for FSSW AA6060-T5 joints by Taguchi and full factorial design

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ABSTRACT

Statistical tools have shown to be very useful in the optimization of processes such as welding. Optimization is understood as the determination of the welding combinations that will lead to the maximization of a desired property, such as strength. This work proposes a statistical methodology to determine the optimum combination of welding parameters of FSSW in 6060-T5 aluminium alloy. Two Design of Experiment (DOE) statistical tools, Taguchi and Full Factorial Design (FFD) were used to determine the optimum combination of three welding parameters: rotational speed, plunge rate and dwell time. Four samples were produced for each welding combination and then subjected to shear test to evaluate joint strength. Quadratic regression was used to obtain an equation correlating joint strength and welding parameters. With the methodology presented, it was obtained an equation to correlate welding parameters and joint strength with acceptable accuracy. The results have shown that a proper combination of DoE tools like Taguchi and FFD is key to determining the optimum set of welding parameters in the FSSW process.

1. Introduction

Friction Stir Welding (FSW) uses a non-consumable rotating tool comprising a pin and shoulder to join the sheets. The primary functions of the tool is to create heating and plastic deformation of the workpiece, and finally to stir the material to produce the joint in the solid state. The material undergoes intense plastic deformation at elevated temperature, resulting in fine and equiaxed recrystallized grains [1].

FSW has become a revolutionary welding technique because of its energy efficiency, environmental friendliness, possibility to produce high-quality joints and its suitability in the joining of Al, Mg and Ti alloys, polymers and other dissimilar materials [2], and even steel [3]. Recently, FSW has gained considerable scientific and technological attention in several fields, including aerospace, railway, renewable energy and automobile [2].

Friction Stir Spot Welding (FSSW) is a process derived from FSW for spot joining the sheets in overlap configuration, as

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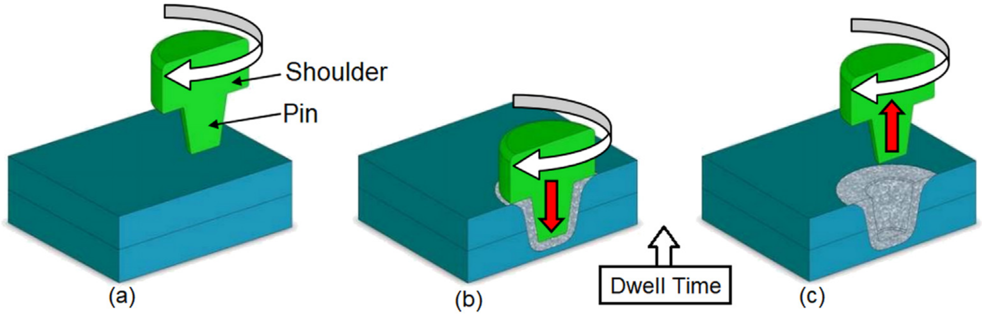

Fig. 1 – Schematic representation of FSSW process: (a) welding tool positioning, (b) plunge (c) tool retraction [3].

schematically explained in Fig. 1. The process can be divided in three main stages: a) tool rotation and position on the upper sheet surface; b) tool plunging; and c) retraction of the welding tool.

After plunged into the sheets up to a determined depth, the tool can be held in position for some time (dwell time), and finally retracted to its initial position. Mazzaferro et al. [3] outlined the importance of dwell time to improve the heat input and the material flow.

According to Gopi and Manonmani [4] the welding tool and its geometry are the keys to obtaining the desired weld properties. Furthermore, Badarinarayan et al. [5] emphasized the importance of the pin profile in the weld strength.

Mazzaferro et al. [3] explained that the energy necessary to produce the weld is provided by plastic deformation of the sheets as well as by the friction between the shoulder and upper sheet surface.

Rosendo et al. [6] studied the mechanical properties of overlap joint produced by Refill FSSW in aluminum alloy, while Tier et al. [7] investigated the characteristics of the joint interface. The results indicate the importance of tool rotational speed and welding time, which is direct influenced by plunge rate, in the quality of the sheet interface. It was reported that lower rotational speeds combined with longer welding times led to a better adhesion between the upper and lower sheets, resulting in stronger joints.

One of the difficulties in the study/optimization of fabrication processes such as welding is the high number of experimental tests that need to be done for a proper assessment of the many variables involved. In these cases, the Design of Experiment (DoE) is very useful.

According to Muhammad et al. [8] DoE can be defined as a scientific method that allows the identification of parameters associated with a process and permits to determine the optimal settings for the process parameters, reducing time, materials and labor efforts.

Table 1 – Chemical composition of the aluminum alloy 6060-T5 (%Wt.).

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Balance
0.45	0.19	0.06	0.08	0.53	0.003	0.01	0.03	98.62

The DoE comprises many statistical tools, such as the Full Factorial Design (FFD) and High-throughput screening method, the latter based on the marriage between massively parallel computational methods and existing database.

Huang et al. [9] reported the use of a high-throughput screening method to design the geometry of welding tool for high depth-to-width ratio FSW. The work focused on tool fracture, defect prediction, joint formation and heat affected zone (HAZ) width, and it demonstrated that the numerical evaluation model was accurate.

Plaine et al. [10] stated that FFD is adequate in situations where the number of factors and levels are reduced, and they emphasizes that, with the combination of Analysis of Variance (ANOVA) and the Response Surface Methods (RSM), it is possible to determine the relative importance of the welding process parameters on joint properties.

Hu et al. [11] explained that RSM is a method of regression that explores the relation between explanatory variables and one or more response variables. The authors stated that RSM, usually employing low-order polynomial functions, is fast, cheap to model computationally, while eliminating variables of little influence on the problem under study.

Shahi and Pandey [12] reported the use of RSM to develop mathematical models in their study of gas metal arc welding (GMAW), while Zhou et al. [13] used the RSM to optimize friction-based welding processes, by means of building mathematical models correlating welding parameters to the desired output variables. Furthermore, second order equations were reported by Yue et al. [14] as being satisfactory in

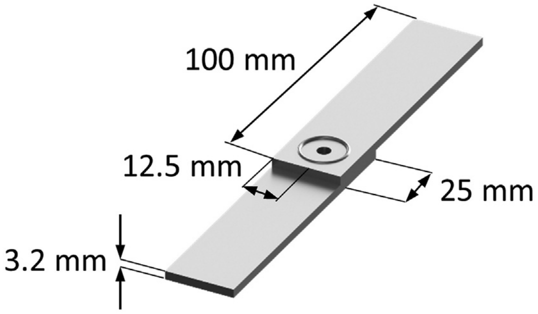

Fig. 2 – Overlap of FSSW joints.

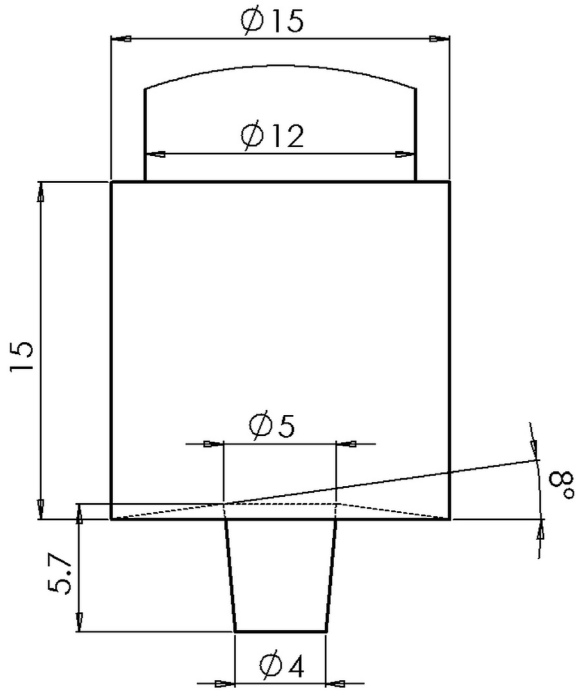

Fig. 3 – Welding tool dimensions in mm.

predicting the results of different welding parameters in Resistance Spot Welding process.

Taguchi is another method suitable to the optimization of welding processes that can be used in the design of high quality system without increasing costs, allowing to understanding the effect of individual and combined process parameters from reduced experimental tests.

Tutar et al. [15] have reported successful use of the Taguchi method for optimize the joint strength of AA3003-H12 welded by FSSW, while Bozkurt and Bilici [16] selected Taguchi with an L9 orthogonal array combined with ANOVA to investigate FSSW dissimilar joints of AA2024-T3 and AA5754-H22. In this way, it was possible determine the percentage of contribution of the welding parameters on joint properties.

Bilici [17] reported the satisfactory use of Taguchi to study FSSW in polypropylene and stated the importance of planning the characterization tests for FSSW due to the large number of parameters affecting the material properties.

Mohamed et al. [18] applied a multi-objective Taguchi method to optimize the governing parameters of FSW for AA6061-T651 butt joints; the approach allowed the assessment of the effect of the welding parameters on multiple response: tensile strength, hardness profile and weld quality class. Furthermore, Vidal and Infante [19] used the Taguchi method to optimize the FSW parameters for improving the mechanical behavior of the AA2024-T351, achieving successful results with minimum cost and time.

Table 2 – Welding parameters.

	Levels		
	1	2	3
Rotational Speed – RS (RPM)	1500	2000	2500
Plunge Rate – PR (mm/min)	120	160	200
Dwell Time – DT (s)	0	2	4

Table 3 – Welding combinations by the Taguchi method.

Parameter sets	Rotational Speed (RPM)	Plunge Rate (mm/min)	Dwell Time (s)
1500/120/0	1500	120	0
1500/160/2	1500	160	2
1500/200/4	1500	200	4
2000/120/2	2000	120	2
2000/160/4	2000	160	4
2000/200/0	2000	200	0
2500/120/4	2500	120	4
2500/160/0	2500	160	0
2500/200/2	2500	200	2

Although presenting satisfactory results, the Taguchi method has the limitation of not allowing the assessment of the interaction level between the input variables; to obtain this information, FFD is usually performed. Thus, the selection and use of the right statistical methods is important to obtain proper results and make the correct conclusions.

Taguchi and FFD were already used by Kechagias et al. [20] in the study for the machinability prediction of titanium turning, when it was reported the importance of applying complementary techniques to have a better interpretation of data.

The aim of this work is to investigate the influence of the welding parameters on the joint strength of FSSW overlap spot joints produced with AA6060-T5, using a combination of Taguchi and FFD. First, the Taguchi method is used to determine the importance of the different welding parameters (input) on joint strength (output). Then, the FFD is applied, using only the most statistically significant welding parameters. The final goal is to obtain an equation that permits to predict the joint strength for given welding parameters.

2. Materials and methods

FSSW joints were produced in overlap configuration using AA6060-T5 sheets supplied by Irmãos Galeazi ltda (Porto Alegre, RS – Brazil). The thickness of the plate was 3.2 mm aiming a study for structural applications for welded joints. Table 1 shows the chemical composition of the base material used to produce the joints.

Fig. 2 shows a schematic representation of the welded joint. An overlapping of 25 mm was applied with the weld spot at the center. The plunge depth was kept constant at 6 mm.

The joints were produced using a CNC machining center Romi D800 and a M2 steel welding tool. Tool dimensions are shown in Fig. 3.

Rotational speed, plunge rate and dwell time, with three levels each, were used to produce the welds, as shown in Table 2.

Table 4 – Layout of the 3^2 full factorial design.

Welding combinations	Parameter 1	Parameter 2
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

Table 5 – Order of influence of the welding parameters.

Level	RS (RPM)		PR (mm/min)		DT (s)	
	Mean (N)	S/R ratio	Mean (N)	S/R ratio	Mean (N)	S/R ratio
1	1876	65.3	1742	64.73	1311	62.34
2	1740	64.6	1721	64.55	1886	65.48
3	1583	63.9	1737	64.53	2003	65.99
Delta	293	1.40	21	0.20	692	3.65
Ordering	2		3		1	

The Taguchi method was then used to obtain the welding combinations that are shown in Table 3. The three different processing variables combined with each of the three levels led to an L9 orthogonal matrix. This set of welding combinations allows the mapping of the entire sample space without the need of a complete factorial set of combinations, which would demand 27 (3^3) different experiments.

Four samples were produced for each welding combination. After welding, the joints were subjected to shear tests to evaluate the joint strength. The tests were performed in a Shimadzu AGS-X 5 kN testing machine, with a loading speed of 0.5 mm/min. The joint strength of each welding combination was assumed to be correspondent to the average strength measured for the four tested samples.

Two Taguchi tools (*mean of means* and *signal to noise ratio*) were combined with analysis of variance (ANOVA) to analyze the results and determine the parameters that have more influence on joint strength.

A new set of welding was then created using the two most effective parameters (on joint strength) determined by the Taguchi/ANOVA analysis. This time, a full factorial design (FFD) was used in order to have insights on the correlation between parameters. An amount of 9 (3^2) welding combinations were necessary, as shown in Table 4.

The joints produced with the welding combinations in Table 4 were subjected to shear tests to evaluate the mechanical strength, while a response surface method (RSM) was used to obtain equations that correlate the welding parameters to the shear strength.

3. Results and discussion

3.1. *Taguchi analysis*

The Taguchi method produces the results in the form of two charts: mean of means and signal to noise ratio, S/N, as reported in Fig. 4(a) and (b), respectively.

The mean of means indicates the arithmetic average of the response (shear strength) for each level of welding parameter,

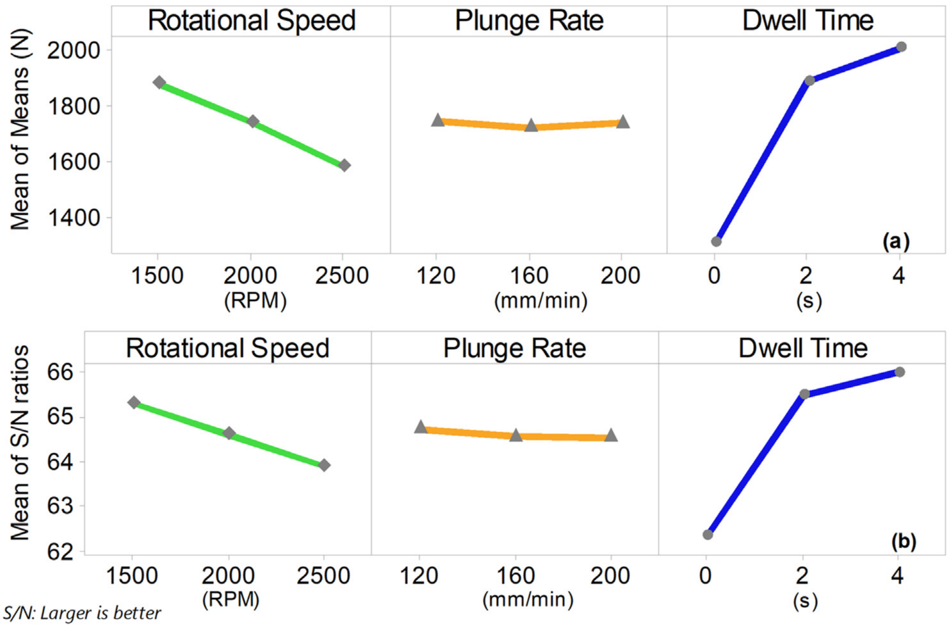

Fig. 4 – Joint strength in terms of: (a) mean of means and (b) S/R ratio.

Table 6 – ANOVA for the Taguchi method.

	DOF	Sum of Square	Contribution (%)	Adjusted Sum of square	Mean Square	F-Value	P-Value
RS	1	129,014	12.56	129,014	129,014	3.57	0.117
PR	1	42	0	42	42	0	0.974
DT	1	718,038	69.88	718,038	718,038	19.90	0.007
Error	5	180,447	17.56	180,447	36,089		
Total	8	1,027,541	100				

Table 7 – Welding combinations for the FFD.

Set of parameters	Rotational Speed (RPM)	Dwell Time (s)
1500/0	1500	0
1500/2	1500	2
1500/4	1500	4
2000/0	2000	0
2000/2	2000	2
2000/4	2000	4
2500/0	2500	0
2500/2	2500	2
2500/4	2500	4

while the S/N ratio indicates the deviation (noise) of the response to its mean (signal). As for the importance of the S/N ratio to the optimization of processes, for the spot weld strength, usually a “the bigger the better approach” is applied, as it have already been explained by Bilici [17].

The data from Fig. 4 are organized in Table 5; *delta* is the difference between the maximum and the minimum values obtained, and it allows to organize the welding parameters in order of significance: DT, RS and PR, in descending order.

It can be seen in Fig. 4 and Table 5 that, in the range of welding parameters, rotational speed (RS) and dwell time (DT) are of major importance on joint shear strength, being the DT the most significant of these two, while Plunge Rate (PR) was found the least effective.

According to the Taguchi results, the best welding combination is RS 1500 rpm, PR 120 mm/min and DT 4 s. It is important to observe that the Taguchi orthogonal (L_9) does not evaluate all possible combinations, neither the interactions between variables. For these evaluations, a full factorial design (FFD) was performed.

FFD can allow to determine the order of importance of the welding parameters, but does not quantify the influence of each. Analysis of Variance (ANOVA) is the technique used to obtain the magnitude of each parameter. In this regard, Cao et al. [21] applied an ANOVA to obtain the percentage of contribution of the welding parameters on joint strength and stated the importance of reducing the variations of such variables to maximize the output (joint strength).

As it can be seen in Table 6, DT and RS have contributions of 69.88% and 12.56% on the joint strength, respectively. PR has statistically no effect on the joint strength.

In order to predict the joint strength, a quadratic regression was performed, as presented Eq. (1), with the coefficient of determination R^2 of 96.16%.

$$R_{max} = 1477 - 0.083 * RS + 692 * DT - 7.2 * (DT)^2 \\ - 0.1212 * RS * DTN - 0.400 * PR * DT \quad [N] \tag{1}$$

Response surfaces for the effect of each pair of welding parameters on the joint strength are plotted in Fig. 5.

Other authors reported good results with this approach: quadratic regression and response surface to correlate welding parameters and joint properties. Plaine et al. [10] used a second order regression equation to predict lap shear strength for Friction Spot Welding in AA6181-T4 and Ti6Al4V dissimilar joints; errors lower than 6.2%, in comparison to experimental tests, were reported.

Gopi and Manonmani [4], in a study of double side friction stir welded 6082-T6 aluminium alloy, used the RSM to develop a mathematical model to predict joint strength, obtaining 95% of confidence level. Moreover, Zhou et al. [13] reported the development of a statistically significant mathematical model to predict lap shear fracture load on Refill Friction Spot Welding of AA6061-T6 using the RSM.

3.2. *Full factorial design analysis*

The Taguchi analysis showed that the PR has no effect on the shear strength of the joint, being DT the most significant variable, followed by RS. However, that analysis does not provide information on the interaction between variables. To study this relationship, a FFD is necessary. To reduce the total

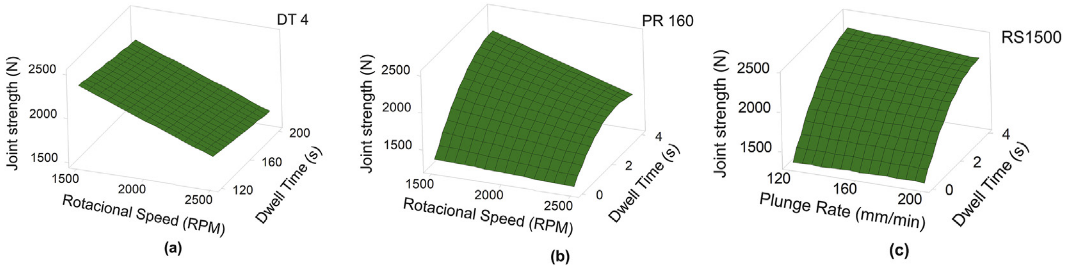

Fig. 5 – Response surfaces for the quadratic regressions by the Taguchi approach.

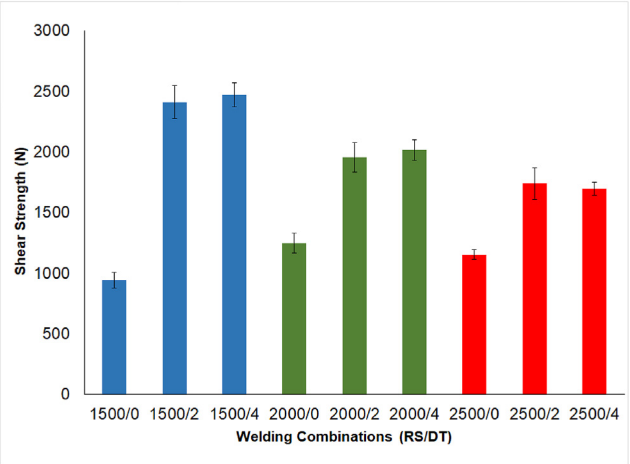

Fig. 6 – Shear strength for the FFD analysis.

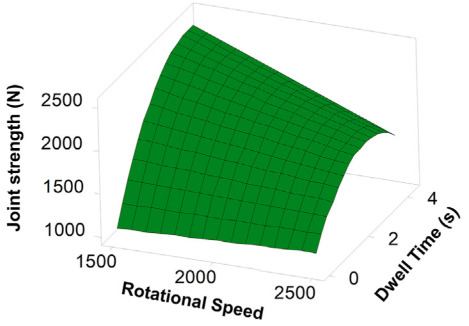

Fig. 7 – Response surface for the full factorial design.

welding time, that is desirable in terms of process optimization, the PR was kept high and constant at 200 mm/min. Table 7 collects the welding combinations used in the FFD.

Four samples for each welding combination were produced and subjected to shear tensile test. Fig. 6 shows the joint strength in terms of the average of four tests and their respective standard deviations.

To quantify the influence of the welding parameters and their interaction on the joint strength, an ANOVA was performed, as shown in Table 8.

Again, DT is the welding parameter with more influence on joint strength (57.69%), while RS has 10.89% of influence and the combination DT*RS has 10.42%.

To obtain an equation that allows to predict the joint strength from the welding parameters, a quadratic multiple regression was employed and found to produce good results, leading to Eq (2). The coefficient of determination R^2 of Eq (2) is 96.13%.

$$R_{max} = 1114.2 + 1127 * DT - 111.7 * DT^2 - 0.2219 * RS * DT \quad [N] \tag{2}$$

The effect of DT and RS on the joint strength is plotted in Fig. 7.

3.3. *Test of the equations: validation test*

One of the objectives of this work is to find an approach that allows to predict the joint strength analytically from the welding parameters. To verify the effectiveness of Eq. (2), a validation test was performed in a similar way that has been done by Muhammad et al. [8] in a study of resistance spot welding. In their study, an experimental test to validate the mathematical model obtained by the multi-objective Taguchi method was evaluated.

New samples were produced using a welding combination different than those of the Taguchi and full factorial analyses. The curves from Fig. 4 indicate that an optimal welding combination would be 1500/120/4. Three samples were welded using this set of parameters and then subjected to shear tensile tests. The results are presented in Table 9, including the joint strength calculated by Eq (1) (Taguchi method).

The joint strength of this welding combination was found to be very similar to the one obtained in the Taguchi analysis (1500/200/4).

The joint strength calculated analytically was very close to the experimental results, validating the equation and the approach used (multiple quadratic regression). The error column in Table 9 shows that the validation test and Taguchi are statistically the same. This result is in accordance to the Taguchi analysis, which revealed that PR has little influence on joint strength.

The empirical equation of the Taguchi approach (Eq (1)) was also applied to calculate the joint strength for the FFD experiments as summarized in Table 10.

Eq. (1) presents a substantial error (>15%) for welding combinations 1500/200/0 and 1500/200/2, probably due to the fact that these welding are out of range (extrapolated points). For all the other welding combinations, the predicted results are satisfactory.

In a statistical point of view, if the experiment had more points (welding combinations), Eq. (1) would tend to produce results even more accurate. However, having more points

Table 8 – ANOVA for the FFD.

	DOF	Sum of Square	Contribution (%)	Adjusted Sum of square	Mean Square	F-Value	P-Value
RS	1	253,749	10.89	3973	3973	0.04	0.848
DT	1	1,344,567	57.69	510,692	510,692	5.22	0.071
RS * DT	1	242,724	10.42	242,724	242,724	2.48	0.176
Error	5	489,452	21.00	489,452	97,890		
Total	8	2,330,493	100				

Table 9 – Validation test for the regression equation (Taguchi).

Welding Combination	Parameters			Shear Strength[a] (N)	Analitical prediction (N)	Error (%)
	RS	PR	DT			
Validation test	1500	120	4	2256.97	2286.10	1.30
Taguchi (1500/200/4)	1500	200	4	2277.00	2158.10	5.00

[a] Values obtained experimentally.

Table 10 – Taguchi equation applied to FFD experiments.

Parameters			Shear strength[a] (N)	Calculated shear strength – Taguchi (N)	Error (%)
RS (RPM)	PR	DT (s)			
1500	200	0	941.70	1352.50	−44
1500	200	2	2410.10	1984.10	18
1500	200	4	2470.20	2158.10	13
2000	200	0	1247.50	1311.00	−5
2000	200	2	1955.20	1821.40	7
2000	200	4	2016.20	1874.20	7
2500	200	0	1153.40	1269.50	−10
2500	200	2	1738.10	1658.70	5
2500	200	4	1696.60	1590.30	6

[a] Values obtained experimentally.

Table 11 – FFD equation applied to estimate FFD experiments.

Parameters			Shear strength[a] (N)	Calculated shear strength – FFD (N)	Error (%)
RS (RPM)	PR	TP (s)			
1500	200	0	941.70	1114.20	−18
1500	200	2	2410.10	2255.70	6
1500	200	4	2470.20	2503.60	−1
2000	200	0	1247.50	1114.20	11
2000	200	2	1955.20	2033.80	−4
2000	200	4	2016.20	2059.80	−2
2500	200	0	1153.40	1114.20	3
2500	200	2	1738.10	1811.90	−4
2500	200	4	1696.60	1616.00	5

[a] Values obtained experimentally.

would demand more experimental efforts, opposite to the idea of this work.

As comparison, Eq. (2), obtained by the FFD analysis, was also used to calculate the joint strength of the FFD experiments. The results are presented in Table 11.

As expected, Eq. (2) produced results more accurate than Eq (1), since all the welding combinations are inside the range of Eq (2). The comparison of the results shown in Tables 10 and 11 indicate an average error of - 0,33% and - 0,44%, for Taguchi and FFD, respectively. This result indicates that the approach of DoE/Taguchi was very suitable to predict the joint strength, despite demanding less experimental efforts.

It is worth mentioning that correlations reported in this work are valid in the range investigated. Extrapolations in terms of welding parameters, welded alloy, tool geometry and sheet thickness are expected to have different correlations to joint strength. The screening of such extrapolations was not the scope of this work.

4. Conclusions

This work investigated the applicability of the Taguchi method to determine a set of welding parameters to produce overlap spot joints by the FSSW process in 6060-T5 aluminum alloy. The Taguchi method was then used to obtain an equation to predict the joint strength from the welding parameters. To verify the suitability of the Taguchi method, a Full Factorial Design (FFD) was also used to produce FSSW joints and to obtain another strength predicting equation. The equations obtained by the Taguchi and the FFD were then compared.

Based on the results obtained in the present study, the following can be stated:

(1) The Design of Experiment (DoE)/Taguchi was suitable to the determination of the most significant welding parameters, giving the same accuracy as the FFD in predicting the joint strength.
(2) The Taguchi method can be used as a first approach to determine the most significant input variables (welding parameters) on the desired output variable (shear strength), allowing to identify and disregard input variables that have no effect on the output.
(3) The plunge rate had minor influence on joint strength and should be set high in order to reduce processing time.
(4) Multiple quadratic regression was very effective in obtaining an equation to predict joint strength from the welding parameters, in both Taguchi and FFD. The average error was 0,33% and 0,44% for Taguchi and FFD, respectively.
(5) A theoretical analysis based only on the mathematical model indicated that the ideal welding combination should be 1500/120/4. A validation test revealed the mathematical model to be accurate.
(6) The establishment of the range of the welding parameters for the experimental tests is of major importance, since the predicting equation fails for extrapolated points. An error as high as 44% was found when predicting joint strength by Taguchi method, for a welding combination outside the regression range.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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