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Process parameters optimization in friction spot welding of AA5754 and Ti6Al4V dissimilar joints using Response Surface Methodology

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Abstract

This study shows experimental and numerical results of friction spot welding of AA5754 and Ti6Al4V alloys. The determination of proper welding parameters plays an important role for the weld strength. Experimental tests, conducted according to combinations of process parameters such as tool rotational speed (RS) and dwell time (DT), were investigated with response surface methodology using a 3^k factorial design of experiments. Sound joints with elevated shear strength were achieved and the influence of the main process parameters on joint strength evaluated. DT was the parameter with the largest influence on the joint shear resistance (59.9%), followed by its interaction with RS (38.1%). Higher strength was correlated to the thickness and morphology of the joint interface. A numerical model for predicting lap shear strength was successfully developed and used to optimize welding parameters in order to produce high performance joints with less energy consumption and high efficiency.

Keywords

Aluminum alloy; Titanium alloy; Dissimilar joint; Friction spot welding; Response surface methodology.

Highlights

- Friction spot welding of AA5754/Ti6Al4V single-lap joints was demonstrated

- The influence of joining parameters on joint mechanical performance was determined
- RSM successfully optimized the joint response in terms of lap shear strength with respect to input variables
- A set of welding parameters was obtained to produce economic and efficient joints

1. Introduction

Multi-materials structures made of titanium and aluminum alloys have great potential applications in the transportation sector as they could reduce weight and cost (aluminum alloy) and improve strength and corrosion resistance (titanium alloy). However, due to their large physical and chemical differences, the welding of most dissimilar metals is challenging. Several attempts to join titanium and aluminum using different technologies have been conducted in the past [1-8]. Mainly owing to the formation of brittle intermetallic phases at the interface, the joints are either limited in performance or too expensive. Therefore, the successful joining of Ti and Al demands more efforts in developing feasible joining techniques that could reduce or eliminate the formation of potentially brittle intermetallic compounds.

Friction spot welding (FSpW), also known as refill friction stir spot welding, which is a solid state technique is a potential candidate for joining dissimilar materials, especially for structural transport applications, due to its various advantages: 1) low process temperature cycles; 2) less energy consumption in comparison to other fusion welding processes, like resistance spot welding (RSW) [9]; and 3) geometry compatibility to replace rivets. FSpW is performed using a tool assembly comprised of three parts: clamping ring, sleeve and probe. The process is performed in four stages. On stage one the sheets are clamped together by the clamping ring against a backing anvil and both probe and sleeve start to rotate producing frictional heat on the upper sheet surface. On the second stage, pin and sleeve move in opposite directions; one is plunged into the material while the other moves upwards, creating a cylindrical cavity to accommodate the plasticised material. After reaching a predetermined plunge depth the process is reversed, where both pin and sleeve retract back to the surface of the upper sheet. Stage four is marked by the removal of the welding head from the work pieces resulting in a flat surface connection with minimum material loss. A schematic illustration of the FSpW process is shown in Fig. 1.

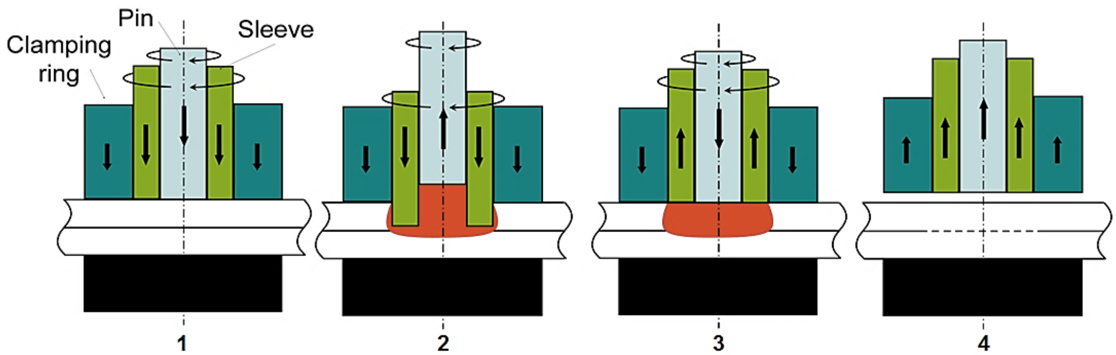


Fig. 1. Friction spot welding process illustration.

The use of designed experiments is extremely advantageous in testing simultaneously a large number of factors. It precludes the use of an extensive number of independent runs when the traditional one-factor-at-time (OFAT) approach is used. Response surface methodology (RSM) is one of the methods in designing experiments to model relationships between the response of interest and the essential controllable variables [10]. These models are used in determining the optimum welding process parameters. The RSM has also been used in optimizing process parameters to reduce the welding cost through reduced energy consumption or increased welding productivity [11-12]. One popular experimental design for the RSM is the 3^k factorial design, which allows for short computational time, high accuracy and easy understanding. This design is most adequate in situations where a reduced number of parameters can be selected. In welding, this scenario can be found when the initial trials allowed for the identification of the most important process parameters, such as for FSpW. When coupled with analysis of variance (ANOVA), 3^k factorial design can also be used to quantify the relative importance of each joining process parameter on joint properties. Amancio-Filho et al. [13] used a 3^2 factorial design to understand the influence of the main FSpW process parameters and their interactions on joint strength of AA2024-T3 alloy. Altmeyer et al. [14] successfully explained the effect of the friction riveting process parameters on the joint formation and performance of Ti alloy/short-fibre reinforced polyether ether ketone joints using a 2^4 FFD. Olabi et al. [15] used a 3^3 FFD and Taguchi designs combined with RSM to effectively minimize the residual stresses in laser welded structures.

This paper aims to apply RSM using a 3^k factorial design to (1) investigate systematically the influence of important process parameters on the lap shear strength (LSS) in AA5754 and Ti6Al4V dissimilar FSpW joints and (2) optimize these process variables considered to produce joints with suitable LSS, less energy consumption and high efficiency.

2. Experimental procedure

A 2-mm-thick 5754 Al alloy and a 2.5-mm-thick Ti-6Al-4V Ti alloy were friction spot welded. The chemical compositions of the base materials used in this study are presented in Table 1. During welding, the Al sheet was placed on top of the Ti sheet. No special surface treatment was performed, i.e., the surfaces were only cleaned with acetone. The tool used for welding had diameters of 14.5 mm, 9 mm, and 6 mm for the clamping ring, the sleeve, and the pin respectively.

Table 1. Nominal chemical compositions of base materials (wt.%).

Alloys	Ti	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	V	C	O	N	H
AA5754	0.04	Bal.	0.15	0.20	0.05	0.08	3.1	0.012	0.010	-	-	-	-	-
Ti6Al4V	Bal.	6.25	-	0.14	-	-	-	-	-	3.91	0.023	0.126	0.003	0.002

The effect of two independent FSpW process variables, rotational speed and dwell time, on LSS was evaluated through RSM. Sleeve plunge depth and clamping ring force were kept constant in 1.8 mm and 12 kN respectively. Lap shear testing was performed using a Zwick–Roell universal testing machine, with crosshead speed of 2 mm/min at room temperature and specimen geometry in accordance with DIN EN ISO 14273 standard [16]. A 3^k factorial design was selected to screen out the process. Prior to applying 3^k factorial design, a preliminary study was performed to find the appropriate ranges of each process parameter. Based on the results, the level ranges for each factor were selected as (1) rotational speed: 1800–2000–2200 rpm and (2) dwell time: 2–5–8 s. Since the factorial design contains two factors on three levels, the number of welding combinations tested were $N = 3^2 = 9$. Two replicates were produced for each condition to enable a statistical analysis of variance. The running order of the experiments was randomized to minimize the effects of unexplained variability in the actual responses due to extraneous factors.

Since all the variables are measurable, the regression model relating the response to the factor levels were expressed mathematically as,

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum\sum_{i<j} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \epsilon \quad (1)$$

where, i and j vary from 1 to the number of process variables, β_0 is the response mean of all the experiments, β_i is the coefficient representing the effect of the variable (x_i), β_{ij} and β_{ii} are the coefficients representing the effects of interactions of variables $x_i x_j$ and x_i^2 respectively, while ε is the experimental error. The developed response surface model was then optimized to determine the required conditions for energy consumption and high efficiency of FSpW Al/Ti joints.

3. Results and Discussions

3.1. Three-level factorial design

Table 2 lists the 3^k factorial design for the FSpW parameter combinations along with the experimental mean values of the LSS for the AA5754/Ti6Al4V single overlap joints.

Table 2. Summary of the 3^k factorial design combinations and the experimental values of LSS.

Condition	RS (rpm)	DT (s)	LSS (N)		Average LSS (N)
			1	2	
1	1800	2	5821	5756	5788
2	1800	5	5827	6033	5965
3	1800	8	6249	5804	6026
4	2000	2	6924	7001	6962
5	2000	5	6378	5908	6143
6	2000	8	4328	4103	4215
7	2200	2	6636	6439	6537
8	2200	5	6318	6501	6409
9	2200	8	4201	4025	4113

The joints exhibited LSS varying from 4113 N (condition 9) to 6962 N (condition 4). Fig. 2 shows that the LSS average of seven of the nine weld combinations evaluated exceed the minimum value of 4270 N according to AWS D17.2/D17.2M standard [17], for a 2 mm nominal thickness of Al alloys (the weakest material in the joint) having ultimate tensile strength from 135 to 240 MPa. These outstanding results are likely to be associated with the reduction of the brittle IMC formation at the interface due to the low temperature cycles involved in friction welding processes. Tanaka et al. [18] established that joint strength increased exponentially with a decrease in IMC thickness during friction stir welding. Watanabe et al. [19] confirmed this trend by showing that the presence of IMC leads to a decrease in the mechanical properties of the weld.

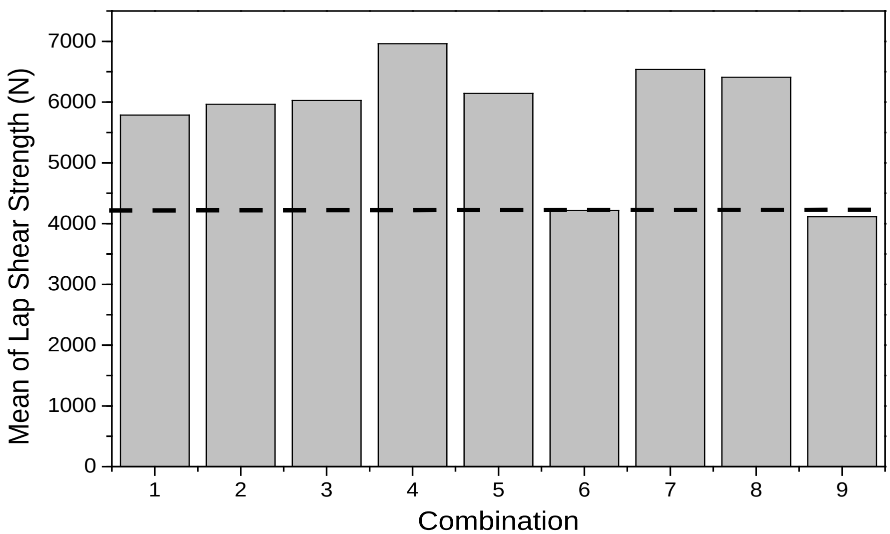
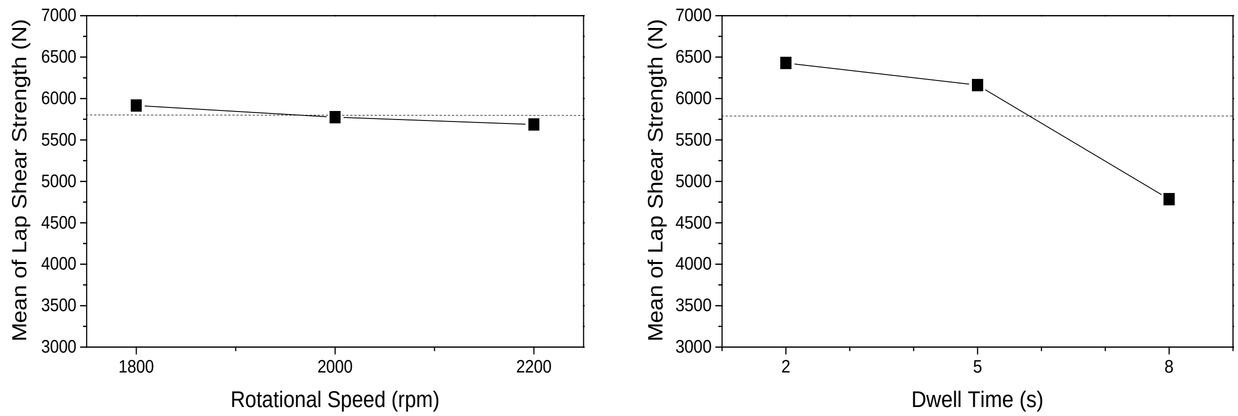


Fig. 2. Mean lap shear strength for each parameter combination. The horizontal dashed line displays the minimum value required for AWS D17.2/D17.2M standard (minimum avg. LSS = 4270 N).

3.2. Effect of process variables on LSS

The effect of the joining process parameters on LSS has been statistically evaluated. The main effect plots in Fig. 3, generated using the MINITAB® software, display the effect of individual process parameters on LSS. The dashed line shows the value of the total mean of LSS. The steeper the slope, the higher the influence of one parameter in the selected response. According to Fig. 3(b), dwell time is the parameter with the largest influence on the LSS for the material combination studied. The joints performance considerably decreases with the increase of DT from low to high values. Although the effect of the RS on the joint performance is not remarkable, its trend is similar to DT, Fig. 3(a).



(a) (b)

Fig. 3. Main effect plots of rotational speed (a) and dwell time (b) on the mean lap shear strength. The horizontal dashed line is referred to the average value of all observations in all factor levels in the experiment (avg. LSS = 5792 N).

Fig. 4 presents a two-dimensional plot between RS and DT in terms of mean of LSS, which provides insights into the presence of interactions between the factors. It is observed that high LSS values depend on a proper balance of RS and DT. When RS = 1800 rpm, DT has no significant influence on the response. However, for higher values of RS the effect of DT on LSS becomes important. This behavior shows a significant interaction between the welding parameters. Such interaction could be associated with the changes in the heat input regime related to variations in the temperature cycles, critical temperature and exposure time; all of which affect the diffusion process taking place at the joining interface.

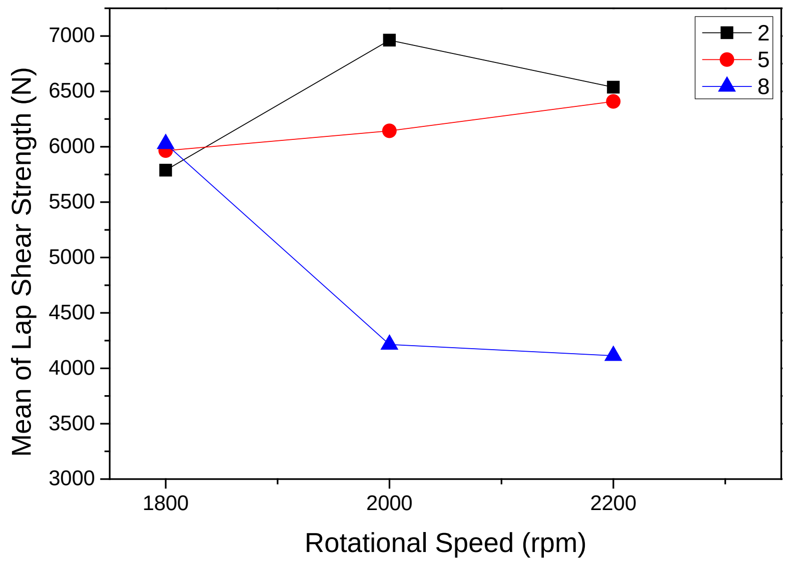


Fig. 4. Effects of the interaction between rotational speed and dwell time on the mean lap shear strength.

An analysis of variance (ANOVA) was carried out to quantify the effect of each FSpW process parameter and also their interaction on the LSS of the joints. The contribution percentage was calculated by the ratio of the sum of squares (SS) of the selected factor and the total sum of squares. Table 3 shows the ANOVA performed with the acquired data for an interval of confidence of 95%. The factors are physically significant when its percentage of contribution is smaller than the associated error. The results showed in this table are in agreement with the results shown in Fig. 3 in which the tool dwell time is the most important process parameter affecting the LSS (59.9%), followed by rotational speed*dwell time interaction (38.1%). RS itself has no significant influence on the response LSS for the used range of welding parameters. The total contribution rate of the FSW parameters was 99.1 %.

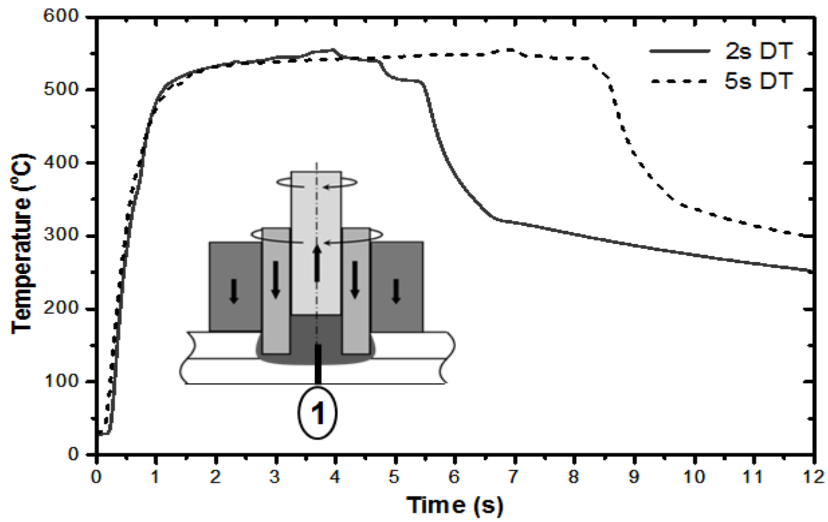
Table 3. Analysis of variance for LSS data

Source	SS	df	MS	p-value	Contrib. [%]
RS (rpm)	177156	2	88578	0.124409	1.1
DT (s)	9391171	2	4695586	0.000001	59.9
RS (rpm)*DT (s)	6070776	4	1517694	0.000006	38.1

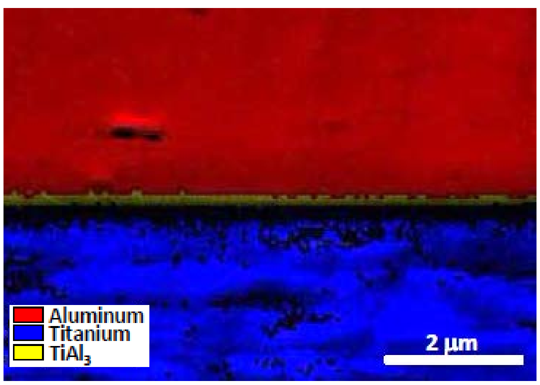
Error	300737	9	33415		0.9
Total SS	15939840	17			

According to the literature, the mechanical properties of FSpW dissimilar joints are mainly affected by the thickness and morphology of the intermetallic compounds of the interfacial area, therefore, their formation and growth may be effectively controlled [20-21]. Minimizing or optimizing Ti-Al intermetallic phases has become the key issue to achieve a high strength Ti/Al dissimilar joint. Thereby, it is reasonable to assume that a sound interface depends on an optimum diffusion balance to (i) sufficiently consolidate the joint and to (ii) form no excessive intermetallic compounds. Considering the diffusion phenomena, RS and DT are welding parameters that mainly affect temperature and exposure time respectively. Therefore, the exposure time seems to be the physical variable mostly affecting the interface formation within the range of parameters selected in this study, thus significantly affecting the mechanical performance of the lap shear strength of the proposed joints.

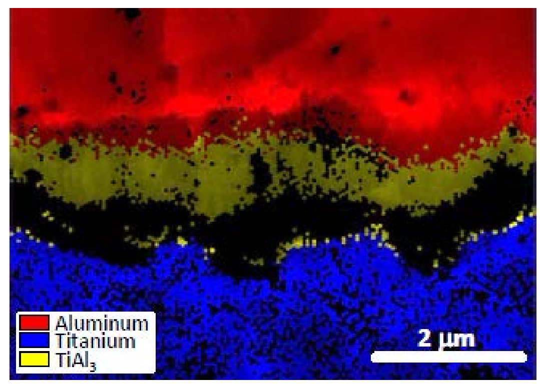
In order to confirm the hypothesis, the temperature profile and micrographs with an integrated EBSD-EDS scan were taken from the interface of two different parameter combinations, condition 4 (LSS = 6962 N) and 5 (LSS = 6143 N), with same rotational speeds (2000 rpm) and different dwell times as presented in Fig 5. The temperature measurements recorded at the center of the weld (Fig. 5a) show that both interfaces were exposed to the same temperatures for approximately 4 and 7 s during welding respectively. Condition 4, with the shorter exposure time, reveals the presence of a continuous $TiAl_3$ intermetallic compound layer of approximately 0.5 µm produced at the interface (Fig. 5b). In contrast, condition 5 shows a considerable non-continuous and thicker $TiAl_3$ layer (Fig. 5c). Since the same rotational speed was employed for both conditions the maximum temperature reached was practically the same. Based on these observations, it can be assumed that a longer thermal exposure time (dwell time) extends the diffusion process, thereby increasing the thickness of the IMC and negatively affecting the lap shear strength of the joints. The interface formation and characterization will be described in more details in a future report.



(a)



(b)



(c)

Fig. 5. Temperature profiles obtained from the center of the weld (measuring position indicated by "1") (a) and micrographs with an integrated EBSD-EDS scan of the joint interfaces from the samples processed with dwell times of 2 s and 5 s, (b) and (c) respectively.

3.3 Modelling and optimization of process parameters

The structure of the numerical relationship between the response and the independent variables is generally unknown. The objective of using RSM is to develop a mathematical model of the second order response surface with the best fit in order to find the optimal set of experimental parameters that produce a maximum or minimum value of response. Based on the results obtained from the 3^2 factorial design, a second-order regression model for LSS was developed in terms of the actual values of the significant factors, Eq. 2. Although the effect of a primary factor is not statistically significant, like RS, it must be considered in the numerical model if its interaction with others factors are significant.

$$LSS\ (N) = -130237.5 + 137.60 * RS - 0.03452 * RS^2 + 26109.80 * DT + 321.36 * DT^2 - 27.695 * RS * DT - 0.0977 * RS * DT^2 + 0.00736 * RS^2 * DT - 0.000047 * RS^2 * DT^2 \quad (2)$$

Eq. 2 is depicted in the response surface plot shown in Fig. 6. The interaction of dwell time and rotational speed showed that high values of LSS, over 6 kN, can be achieved at dwell times lower than 5 s independently of the rotational speed, providing a considerably wide process window for industrial applications.

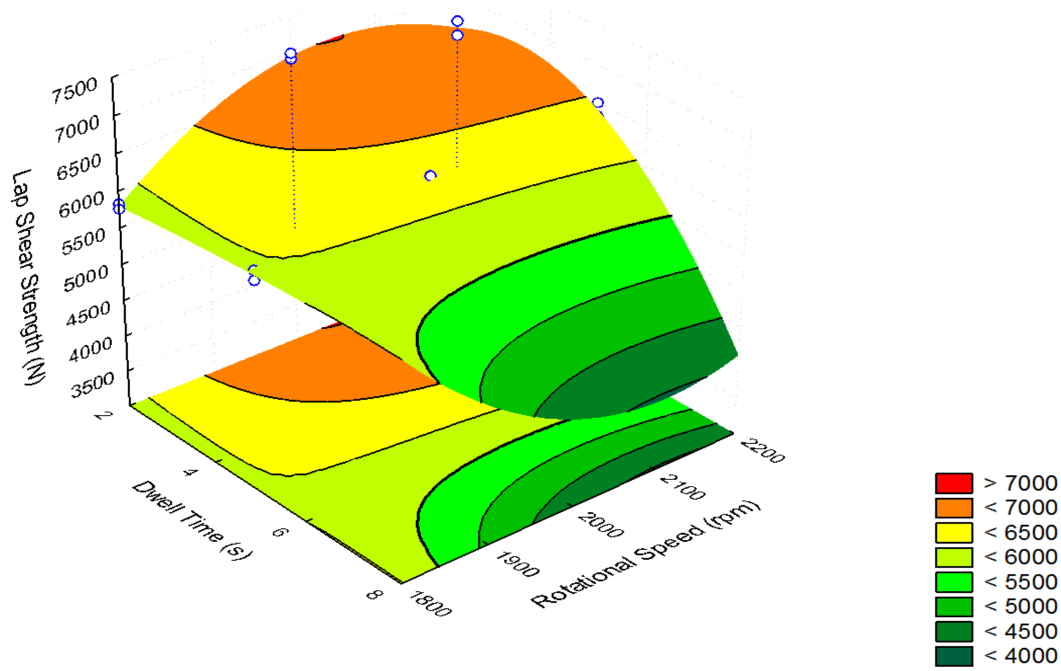


Fig. 6. Response surface plot for LSS as a function of RS and DT.

The plot of the predicted versus actual values, shown in Fig. 7, indicates the satisfactory agreement between the response surface model and the actual values. In order to verify the adequacy of the developed model, three confirmation experiments were carried out with new process parameters chosen within the ranges from which the equation was derived. Table 4 shows the new process parameters in verifications 1, 2 and 3, where the actual and predicted values and the percentages of error are also included. Compared with the experimental data, the error of LSS prediction varies from 0.3 % to 1.9%. The results indicate that the developed model has acceptable accuracy for LSS prediction.

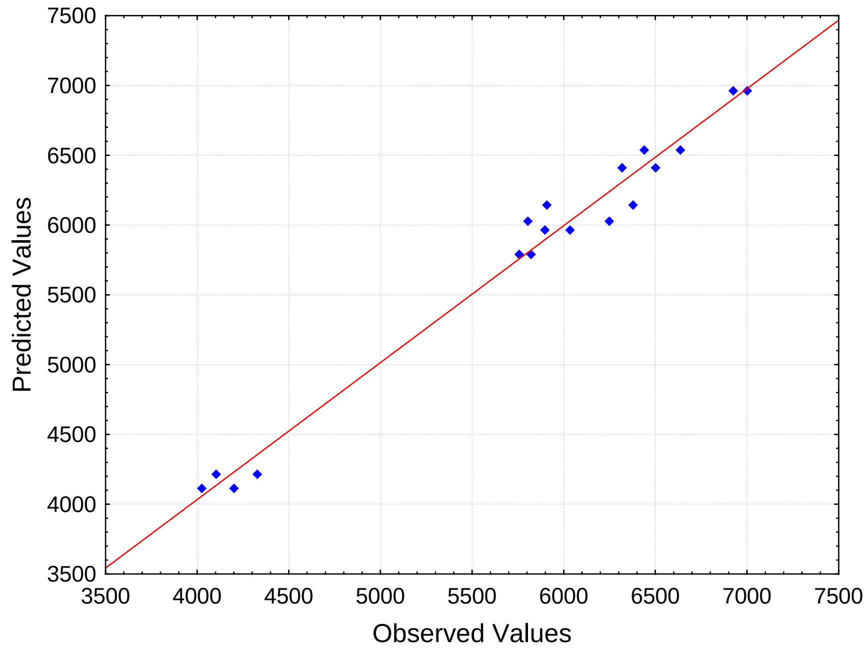


Fig. 7. Comparison of predicted LSS with experimental data.

Table 4. Experiment tests for model verification.

Verifications	Actual LSS (N)	Predicted LSS (N)	Error %
1 (RS = 2200 rpm, DT = 4 s)	6556	6681	1.9%
2 (RS = 1900 rpm, DT = 4 s)	6382	6278	1.7%
3 (RS = 1900 rpm, DT = 7 s)	5350	5334	0.3%

For the numerical optimization a criteria was implemented in order to produce high performance joints with less energy consumption and high efficiency. As presented in Table 5, there are constrains on RS (minimum) and DT (minimum). The level of importance of each factor in terms of industrial application is represented by the "+" sign, increasing from 1 to 5. Table 6 shows optimization analysis results based on their desirability (conversion of the response values into a dimensionless measure of performance, based on the weight or importance of the factors). The parameters of RS = 2000 rpm and DT = 2 s were chosen as the optimal operating parameters, by using a sleeve plunge depth of 1.8 mm and a clamping ring pressure of 12 kN.

Table 5. Optimization criteria and importance.

Variables	Criteria	Lower Limit	Upper Limit	Importance
RS (rpm)	Minimum	1800	2200	++
DT (s)	Minimum	2	8	++++
LSS (N)	Maximum	6500	-	+++++

Table 6. Optimal solutions based on the criteria.

N°	RS (rpm)	DT (s)	LSS (N)	Desirability
1	1900	2	6567	0.89
2	2000	2	6953	0.91
3	2000	3	6803	0.77
4	2000	4	6529	0.68
5	2100	2	6941	0.91
6	2100	3	6893	0.78
7	2300	4	6664	0.69
8	2200	2	6528	0.88
9	2200	3	6726	0.76

4. Conclusions

The individual effect of the friction spot welding (FSpW) process parameters on the lap shear strength of aluminum AA5754/Ti6Al4V joints was investigated using statistical analysis. The obtained joints showed good mechanical performance with lap shear strengths varying from 4113 N (condition 9) to 6962 N (condition 4). The use of a three-level (3^2) factorial design of experiments and an analysis of variance allowed the determination of the influence of the main joining parameters on lap shear strength of the joints. The analysis indicated that the dwell time is the parameter with the largest influence on the lap shear strength of the joints (59.9%), followed by rotational speed and dwell time interaction (38.1%). It was demonstrated that the dwell time extends the diffusion process, thereby increasing the thickness of the IMC and negatively affecting the lap shear strength of the joints. By utilizing the experimental results, a mathematical model for lap shear strength prediction was successfully developed on the basis of RSM. For a sleeve plunge depth of 1.8 mm and a clamping ring pressure of 12 kN, the optimum welding parameters to satisfy engineering demands are the rotational speed of 2000 rpm and dwell time of 2 s.

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