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Process Parameter Optimization in Refill Friction Stir Spot Welding of Dissimilar AA5754 and Electro Galvanized DP600 Joints

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The present study features analytical and experimental results of AA5754/DP600 dissimilar joints produced by the refill friction stir spot welding of 1.5-mm-thick sheets. The selection of proper parameters for this process, such as tool rotational speed (RS), welding time (WT), tool plunge depth (PD), welding force (WF) and backing plate material played an important role in assuring weld strength. In this work, experimental tests were carried out based on the welding conditions according to Taguchi method, in order to determine optimal welding parameters and investigate the effect of those in the joint's mechanical properties. Analysis of variance (ANOVA) was also applied to determine the individual importance of each parameter on the lap shear strength (LSS). The results showed that the use of a backing plate with high conductivity during the welding process is a critical factor for control the formation of intermetallic layer on the interface of the joints and consequently increase the mechanical properties of the joints. Additionally, the results based on lap shear strength indicated that tool rotational speed was the parameter with the largest influence on the joint shear resistance. In contrast, DT was shown to have no significant influence on the joints performance for the selected range tested.

Keywords: *Aluminum alloy, Dual-phase steel, Dissimilar joint, Refill friction spot welding, Taguchi method.*

1. Introduction

Energy saving, reduce weight and minimizing environmental impact are important challenges of the automotive industry. One efficient solution for overcoming such challenges is to produce multi-material lightweight car body structures. In this context, a common approach is to substitute conventional mild steels with advanced high strength steels (AHSS) and with aluminum alloys in the body-in-white, but without diminishing the crashworthiness of cars for maintaining the passenger safety. However, integrating dissimilar materials requires reliable and cost-efficient joining processes, mainly due to the formation of excessive brittle intermetallic phases at the welding spot, which are susceptible to crack propagation. Therefore, the successful joining of aluminum and AHSS demands more efforts in developing alternative joining techniques that could reduce or eliminate the formation of potentially brittle intermetallic compounds and make the joining possible in series production.

Friction-based processes for spot welding production were developed aiming to meet aircraft and automotive industries demand. They appear like an attractive alternative to mechanical fastening for joining of two or more workpieces since weight penalties, difficulties in automation and corrosion issues[1,2]. Friction stir spot welding (FSSW) were developed by Mazda Motor Corporation, as an adaptation of FSW, and was first used in 2003 for the assembly of pieces of the vehicle RX-8 replacing resistance spot welding (RSW) process[3]. Refill Friction Spot Welding RFSSW is a similar process developed in order to refill the residual key-hole left in FSSW, which may lead to corrosion and mechanical issues.

The refill of the residual key-hole left in welds is enabled by the design of the non-consumable 3-piece tool: pin, sleeve and clamping ring. The process is divided in four stages, as represented in Figure 1. The first stage consists in the clamping of the sheets together towards a backing plate and the head of the device, while the pin and sleeve start to rotate and reaches the upper surface of the workpiece. In the sequence, sleeve is forced against the sheet material generating sufficient frictional heat to plasticize and displace the material while the pin is moved in the opposite axial direction, creating a cavity between pin and clamping ring surface for the accommodation of the displaced material. When the set plunge and time are reached, both pin and sleeve are moved back to the original position simultaneously, forcing the imprisoned plasticized material to refill the key-hole left by the pin. Finally, the tool assembly is removed from the surface of the sheet, resulting in a refill friction spot weld[4].

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The feasibility of the technology has been studied for several authors, and the suitability has been demonstrated for aluminum[5-10], magnesium[11,12] and dissimilar welds e.g. aluminum and titanium sheets[13,14]. For dissimilar welds, in particular, sufficient heat input can be generated by the frictional heat related to the plunging of the upper sheet, which enables the interdiffusion of atoms at sheets' interface and result in the formation of the thinnest possible brittle intermetallic layer but ensuring the sufficient number of atoms to consolidate the joint[14]. Moreover, the formation and growth of the intermetallic phases can be effectively controlled by process related temperature–time cycles through the optimization of the process parameters.

The Taguchi approach is a simple and common statistical technique that enables optimizing the performance of a product, process, design and system with a significant reduction in time and costs. When used along with analysis of variance (ANOVA), Taguchi can be helpful to determine the relative influence of each welding parameter on the joint performance.

In current work, Taguchi method and ANOVA were used to investigate the influence of important process parameters, such as tool rotational speed (RS), dwell time (DT), plunge depth (PD) and welding force (WF) on the lap shear strength (LSS) of AA5754-H22 and DP600 dissimilar joints produced by RFSSW using different backing plate materials. The heat transfer through the backing plate is a critical factor for the optimization of process parameters in dissimilar joints, which directly influences on the interface thickness and has generally not been considered in previous studies.

2. Experimental Procedure

A 1.5-mm-thick AA5754-H22 alloy and electro-galvanized DP600 alloy were refill friction stir spot welded. These alloys have chemical compositions as shown in Table 1. For the mechanical analysis 100 mm (length) x 25.4 mm (width) workpieces were cut and welded with an overlap of 25.4 mm in accordance to the ISO 14273[15] that standardizes specimen dimensions and procedure for shear-testing spot welds. No special surface treatment was performed, i.e., the surfaces were only cleaned with ethanol. The welds were produced at HZG (Helmholtz-Zentrum Geesthacht) in a RPS 100 (Harms & Wende) machine, which was developed in partnership with the company RIFITEC GmbH, with a tool with diameters of 18, 9, and 6 mm for the clamping ring, sleeve, and probe, respectively (Figure 2).

Lap shear testing was performed using a Zwick–Roell 1478 testing machine, with crosshead speed of 2 mm/min at room temperature. Preliminary studies were performed to define maximum and minimum levels for the three factors of RFSSW - rotational speed (RS), plunge depth (PD), welding time (WT) and welding force (WF). Several welds were produced for the determination of the process parameters and its levels aiming the production of sound joints. The criteria for the definition of were based on visual aspects (absence of severe volumetric defects of the welds, such as lack of filling/mixing, porosity and cracks), followed by mechanical resistance of lap joints. Aiming industrial applications, where reduced welding time leads to higher production rates, it has used in the study the lowest welding time that could be used. Additionally, three materials (carbon steel, titanium and aluminum) with different thermal conductivities were used as backing plates under the same heat input conditions to understand the effect of heat loss on weldability. The factors and their levels set for the study are presented in Table 2.

Thermal cycle measurements were performed using a K type thermocouple of 0.5 mm diameter embedded in the sheets interface at the weld center. Optical microscopy analysis was carried out to evaluate the interface, presence of metallurgical and geometric defects and characteristics of the different weld zones by a Leica DM IRM optical microscope integrated with the Leica Application Suite 3.5 software. For more detailed analysis of the welded joints

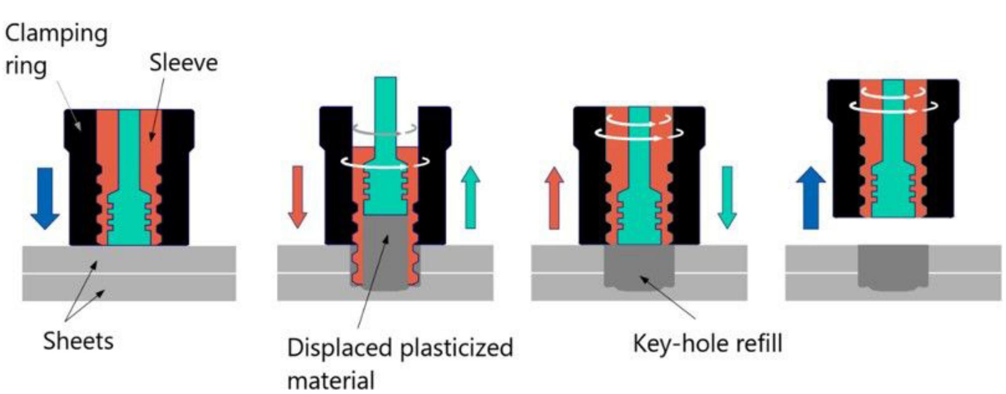


Figure 1. RFSSW process illustration[4].

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

Alloy	Mg	Si	Fe	Cu	Mn	Cr	Zn	Al	C	Mo
AA5754	3.1	0.15	0.20	0.05	0.08	0.012	0.01	Bal.	-	-
DP600	-	0.36	-	0.03	1.84	0.02	-	0.05	0.09	0.01

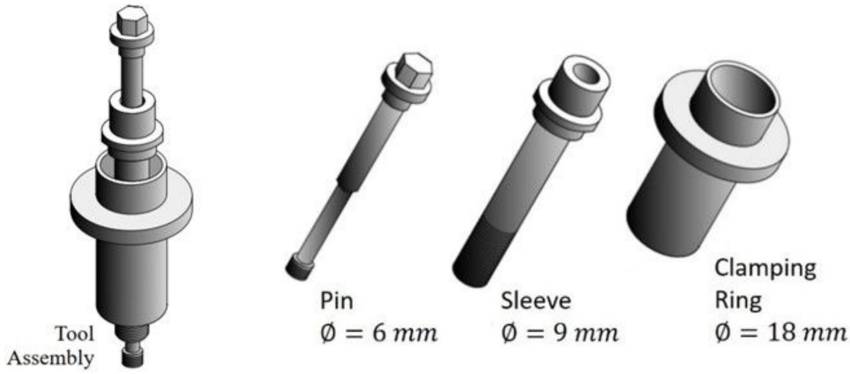


Figure 2. Schematic illustration of the Refill FSSW tool comprised of a pin, sleeve, and clamping ring.

Table 2. Welding parameters and levels.

Symbol	Welding parameter	Unit	Level 1	Level 2	Level 3
RT	Rotational speed	rpm	1200	1600	1800
DT	Dwell time	s	0	1	2
PD	Plunge depth	mm	1.0	1.2	1.4
WF	Welding force	N	10000	12000	14000

interface, Scanning Electron Microscopy (SEM) was used through a FEI Inspect S 50 microscope.

Taguchi analysis was carried out in order to determinate the effects of the variation of welding parameters (control factors) on the joint's strength and the intermetallic layer on the interface. To select an appropriate orthogonal array of experiments, the total degrees of freedom (DF) needs to be computed. Since each four-level parameter has two degrees of freedom (DF = number of levels - 1), the total DF required is eight. The DF of selected orthogonal array must be greater than or at least equal to the total DF, and hence an L9 array, resulting in nine experiments, is suitable for the present study. All the nine experiments were run in triplicates. LSS was taken as the performance metric for the Taguchi analysis, and the statistical study was generated using MINITAB® 18.

The signal-to-noise ratio (SNR) analysis is a logarithmic function used to optimize process parameters in order to minimize the variability. The appropriate SNR function is selected depending on the expected response: smaller-the-better, nominal-the-better and larger-the-better, the function used in this study since Taguchi approach response aims the best LSS. SNR can be calculated as[1]. ANOVA was then used technique to analyze results of experiments and determine the percentage of contribution of each parameter (factor). By testing the equality of several means, the statistical significance of the process parameter was demonstrated.

$$SNR = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \quad (1)$$

3. Results and Discussion

During preliminary tests, a high variation in lap-shear response was detected under the same welding conditions. In optimization studies, reproducibility is critical in order to obtain the optimized condition using the design of experiments. Usually, the reproducibility of dissimilar joints depends on the diffusion of an adequate number of atoms capable of consolidating the interface through the formation of intermetallic layers which, despite responsible for the joint, are generally brittle and contribute to increase the standard deviation[16,17]. Moreover, in case of dissimilar Al to Zn-coated steel, low reproducibility is also strongly affected by formation of eutectic liquid phase since eutectic temperature of the Al–Zn system (381°C) can be easily reached during the joining process.

Figure 3 shows a macroscopic cross section of a sound RFSSW joint between dissimilar AA5754 and DP600 welded using a rotational speed of 1200 rpm, dwell time of 2 s, plunge depth of 1.4 mm and welding force of 14000 N. It is possible to observe the presence of defects such as voids and micro-cracks at the interface comprised by the welding zone. It is supposed that due to the friction heat and pressure caused into the specimen, the Al diffuses into the Zn–Fe plating layer and some of the Zn in the Zn–Fe plating flows in the AA5457. Consequently, the Zn–Fe plating layer becomes Zn–Fe–Al layer, that is, a layer containing a FeAl(Zn) brittle intermetallic compound. Thicker FeAl(Zn) intermetallic layer might obviously decrease the mechanical strength of the joint, so it is extremely important to control its growth. In addition, the Zn that flows into the AA5457 forms eutectic liquid phase with the Al alloy, especially in the central region of the weld as shown in Figure 4, in which the thermal profiles always presented temperatures higher than the eutectic temperature of the Al-Mg-Zn system (381°C). Therefore, interfacial micro-cracks can originate from the difference between the thermal expansion coefficients of steel and intermetallic compounds, which during the welding cooling process can generate thermal stresses at the interface

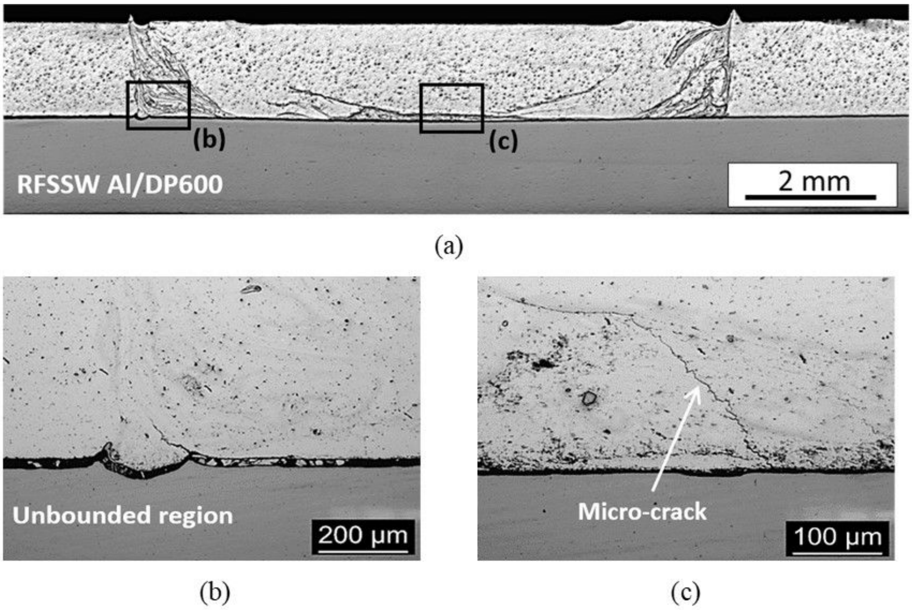


Figure 3. (a) Cross-sectional macrograph of a welded joint with carbon steel BP showing details of the joint interface: (b) region comprised by the sleeve; (c) center region of the weld.

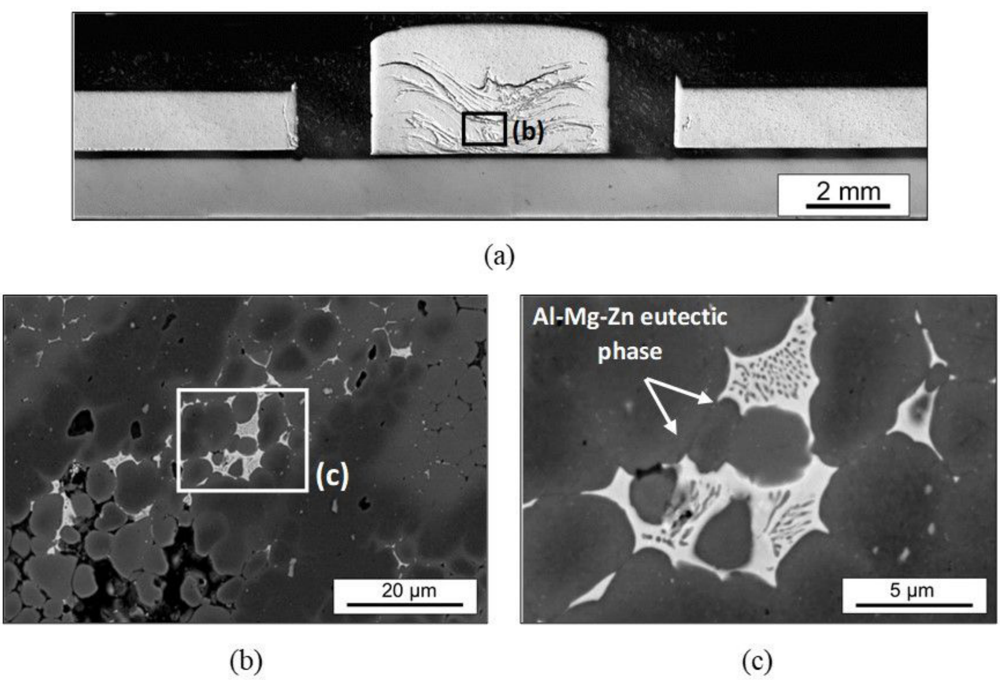


Figure 4. (a) Cross-sectional macrograph of a welded joint with carbon steel BP produced by "stop-action" technique with a plunge depth of 1.4 mm. (b) and (c) Microstructure detail confirming the formation of Al-Mg-Zn eutectic phase.

or from the brittle nature of the intermetallic compounds present at the interface[18-20].

It can be stated that higher heat inputs during the welding procedure negatively affect the mechanical strength of the welded joints, as they not only promote the formation of thicker intermetallic layers at the interface of the welded joints but also cause an increase in the tendency for liquation-induced cracking (LIC), which is the embrittlement of the solid metal immersed or covered by the liquid metal, and the consequent emergence of interfacial micro-cracks. According to some authors[21-23], the occurrence of LIC in joints produced through solid-state welding processes is linked to the formation of a eutectic liquid film early in the process, which is later incorporated into the mixing zone. Crack propagation can occur due to the torque applied by the tool rotation still during the welding process or as a result of thermal stresses during the cooling stage of the process. Thus, the presence of a greater number of cracks in welds produced with higher heat inputs is associated with a higher tendency for LIC[23].

The results obtained are in agreement with the interdiffusion experiments between pure aluminum and hot-dip galvanized steel for different temperatures and annealing times conducted by Springer et al.[24], which demonstrates an increase in the reaction zone thickness with the increase in annealing temperature. As reported by Amancio et al., the mechanical performance of a dissimilar friction spot joint is a function of metallurgical transformations, but are primarily affected by other geometric characteristics, such voids, incomplete refill, among others[7].

Therefore, thermal boundary conditions at the bottom of the work pieces to be joined is critical in determining the result of weld quality and its properties, since it directly affects the intermetallic layer. For a given alloy type, tool geometry and selected process parameters, the thermal boundary conditions are mainly depended on the backing plate (BP) used, being a crucial factor for the success of friction based processes. One of the few studies reporting the effect of BP on obtaining consolidated aluminum alloys joints through FSW was developed by Rosales et al.[16], who presented clear evidence that the heat transfer condition differs significantly with the thermal conductivity of the BP during FSW process and, consequently, influences the local and global mechanical properties. Upadhyay and Reynolds[25] achieved a 25% increase in tensile strength when using aluminum backing plate instead of steel backing plate in FSW of AA6061 alloys. In a similar study, Bakavos and Prangnell[26] used backing plate thermal management to optimize RFSSW process on similar AA6111 joints. It was shown that the use of ceramic backing plate resulted in a 45 °C increase in the maximum temperature, while shear strength was reduced by 15% compared to conventional steel backing plate.

In this study, the approach used in order to overcome the difficulties in the process of joining dissimilar materials and produce sound welds with good quality, reproducibility and satisfactory mechanical properties, was preliminarily testing three different 10 mm-thick BP's. Figure 5 shows the materials used as BP, their thermal conductivity and lap shear strength under the same welding conditions. As can be noticed, the use of aluminum BP increased the lap shear strength of the joints around 11% and 37% when compared with joints produced using steel and titanium BP`s, respectively. Figure 6 compares the temperature profile of the joining process using aluminum backing plate and titanium backing plate. As expected, the lowest temperatures were recorded for the joint produced with the aluminum BP, due to its higher thermal conductivity which, in turn, results in a higher heat extraction rate during the welding. Therefore, it can be stated that the degradation of mechanical properties of the joints related to the use of low thermal conductivity backing plates, like titanium and steel, might be associated

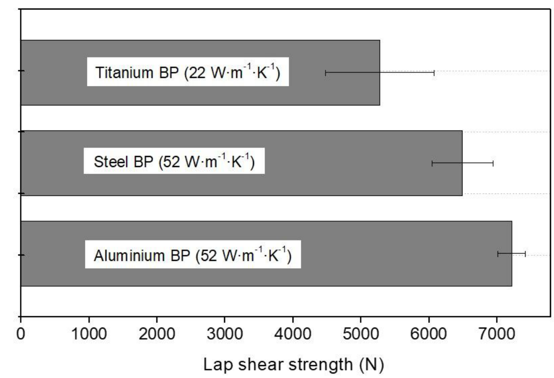
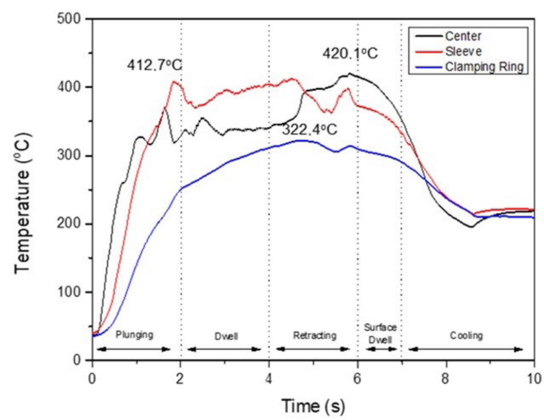
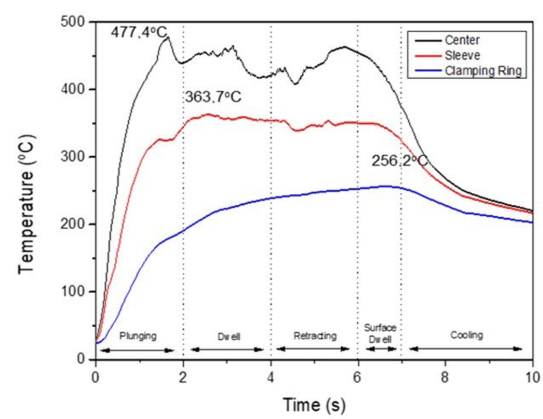


Figure 5. Effect of different backing plates materials on the LSS for dissimilar AA5754/DP600 produced with the same welding parameters.



(a)



(b)

Figure 6. Temperature profile for AA5754-H22/DP600 joint for the same welding condition using (a) aluminum backing plate and (b) titanium backing plate.

to an increase in thermal cycle during the welding process and, concomitantly, with the increase of the amount of intermetallic compounds at the interface due to the increase diffusion flux of atoms, as shown in Figure 7 (a) and (b). Figure 7 (c) and (d) highlights the micro-cracks formation at the interface in the central region of the weld nugget. As can be seen, by using a low thermal conductivity backing plate, such as titanium, these defects form with greater intensity. Based on these results, aluminum was chosen to be used as BP for the process parameters optimization in this study.

3.1. DoE: Taguchi L9 orthogonal array

The L9 orthogonal array given by the Taguchi is presented in Table 3, in which the set of parameters (RS, PD, DT and CF) for nine experiments are listed along with the LSS means – obtained from mechanical testing performed in triplicates – and the signal-to-noise ratio (SNR) calculated considering the-larger-the-better Taguchi approach.

According to Table 3, the highest value of LSS and SNR (6710 N and 76.43) are found for the C3 condition (1500 rpm, 3 s, 2.8 mm), which corresponds to the lowest level of RS and highest levels of PD, DT and CF. On the other hand, the condition associated to the lowest LSS and SNR (2616 N and 768.14) are C7 (1800 rpm, 1.0 mm, 2 s and 12000 N), with a set of parameters combining the highest levels of RS an DT. Almost all the conditions analyzed in the experiment, however, are able to produce

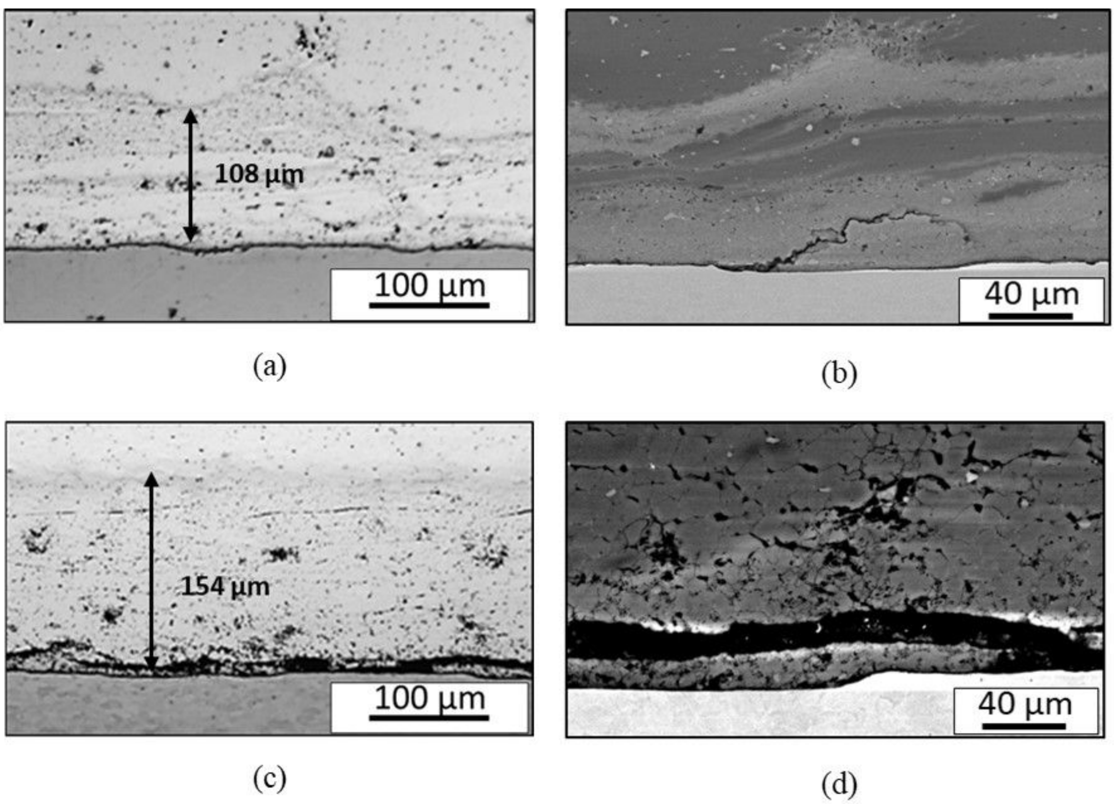


Figure 7. Details of AA5754-H22/DP600 welded joints interface using aluminum backing plate (a-b) and titanium backing plate (c-d).

Table 3. Experimental conditions for the Taguchi analysis, mean of experimental results for lap shear strength test (LSS) and calculated signal-to-noise ratio (SNR) for each welding condition.

WELDING CONDITION	RS [rpm]	DT [s]	PD [mm]	CF [N]	LSS [N]	SNR
C1	1200	0	1.0	10000	5280 ± 33	74.45
C2	1200	1	1.2	12000	5720 ± 218	75.01
C3	1200	2	1.4	14000	6990 ± 540	76.43
C4	1600	1	1.0	14000	4830 ± 131	73.55
C5	1600	2	1.2	10000	4500 ± 316	73.30
C6	1600	0	1.4	12000	4890 ± 638	72.59
C7	1800	2	1.0	12000	2780 ± 298	68.14
C8	1800	0	1.2	14000	4300 ± 320	72.68
C9	1800	1	1.4	10000	4080 ± 160	72.12

welds that exceeds the minimum LSS required by AWS-W-6858A[10] considering the AA5754 spot-welding of 1.5 mm sheets for aerospace applications. According to the standard and material properties, the minimum spot weld resistance required for aircraft structures is 3400 N, not reached only by the worst C7 condition. Nonetheless, it should be noted that this is a particular requirement for lap shear strength, and other aspects of joints' mechanical performance must be studied and taken in consideration.

Table 4 lists the outputs of the Taguchi analysis in terms of LSS means and SNR for RS, PD, DT and CF, while Figure 8 shows the main effect plots of these responses. Since the Taguchi method provides the responses of each level individually, the analysis indicates that RS is the most influent factor on LSS means and SNR considering the selected range of parameters. The variation (delta - δ) between maximum and minimum means and SNR is associated to the effectiveness parameters variation (RS, PD, DT and CF) – the greater the difference, the more effective the variation of the factor on joint's LSS. Delta highest values were found to RS, DT and PD in both terms of means: LSS (2374N, 1210 N and 1012 N) and SNR (4.78, 2.94 and 2.65). Contrarily, DT is related to the lowest effectiveness of levels variation on weld's strength: its delta values (140 N and 1.90) are significantly smaller than the other three observed factors.

Table 4. Response table for means and signal-to-noise ratio (SNR) for rotational speed (RS), plunge depth (PD), dwell time (DT) and clamping force (CF) based on LSS response.

Level	RS		PD		DT		CF	
	Means	SNR	Means	SNR	Means	SNR	Means	SNR
L1	6046	75.40	4221	71,23	4688	73.32	4662	73.22
L2	4620	73.28	4884	71,28	4821	73.42	4233	71.19
L3	3672	70.62	5233	73,88	4828	71.52	5443	74.12
Delta (δ)	2374	4.78	1012	2,65	140	1.90	1210	2.94
Ranking	1		3		4		2	

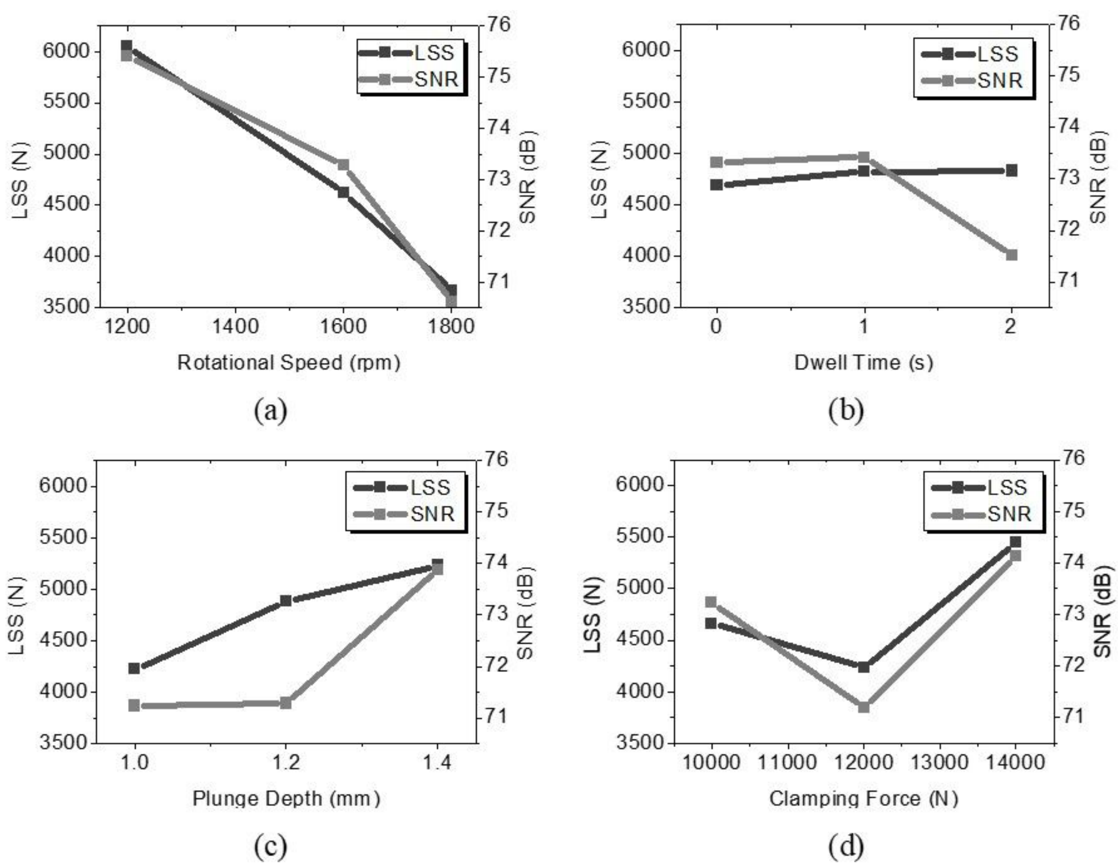


Figure 8. Main effect of the parameters in the LSS response and signal-to-noise ratio for (a) rotational speed, (b) dwell time, (c) plunge depth and (d) clamping force.

Table 5. Analysis of variance (ANOVA) and individual influence of parameters in LSS in terms of means and SNR.

	Factor	*df*	SS	MS	*F* value	%I
Means	RS	2	25714941	12857470	80.34	63.9%
	PD	2	4758985	2379493	14.87	11.8%
	DT	2	111430	55715	0.35	0.3%
	CF	2	6774541	3387270	21.16	16.8%
	Error	18	2880800	160044	-	7,1%
SNR	RS	2	90.826	45.4131	59.35	59.5%
	PD	2	19.387	9.6937	12.67	12.7%
	DT	2	1.934	0.9672	1.26	1.3%
	CF	2	26.759	0.7652	17.49	17.5%
	Error	18	13.773	0.7652	-	9.0%

Discrepancies on each plot's behavior presented in Figure 8 are also an indicative of the factor's effectiveness associated to the variance of levels. It is noted that for DT and PD the increment-in-level results in a positive contribution to welds' resistance, indicating the possibility of obtaining better results using higher levels. However, there are some limitations related to increase these factors. Thinking about industrial applications and productivity, DT and PD should be as low as possible. Moreover, for 1.5 mm-thick sheets the use of larger values of PD becomes impracticable as it can generate high tool wear since it might come into contact with the steel sheet. Likewise, the decreasing trend presented by RS indicates the possibility of obtaining better LSS using lower levels. Nevertheless, such evidence has not been experimentally proven since joints with lower levels presented poor surface quality or even no joining between the sheets. Finally, the convex profile of the CF curve demonstrates that the process is optimal for an intermediate level, and values above and below this value seems to be not satisfactory to increase the mechanical strength of joints.

Considering the selected window of parameters and aiming to the highest lap shear strength of the welds, the best welding condition would be found by the combination of the highest levels of each factor – 1500 rpm, 1.4 mm, 2 s and 14000 N, which is already represented by C3 condition in the orthogonal array.

Analysis of variance (ANOVA) was used to investigate the individual influence of the factors and the outputs of this analysis is presented in Table 5; the interaction between the variables was not taken into consideration. These results point to RS being the ultimate influence factor on LSS, corresponding to 64% of contribution percentage. The relevance of effect of RS variation on LSS is also verified in studies reported by Plaine et al.[13] on dissimilar RFSSW of AA6168 and Ti-6Al-4V 1.5-mm-thick sheets, and similar AA7975 0.8-mm-thick sheets presented by Kubit et al.[27].

On the other hand, the presented ANOVA results indicate that *PD, DT and CF* variations are not able to produce a relevant effect on *LSS* considering the selected range of parameters, in both terms of *means* and *SNR.* The irrelevance of these factors is especially verified when compared along ANOVA's error (7% and 9%) in face of *RS* percentage of influence. These findings are in accordance with the presented by Campanelli et al.[11] about the RFSSW of thin Mg alloy sheets, which shows that DT's percentage of influence (4.38% and 6.55% in terms of *means* and *SNR,* respectively) is significantly smaller than error's (16.58% and 17.87%), leading to the conclusion that dwell time shows no statistical influence on *LSS* of these welds considering the process window used for such evaluation.

4. Conclusions

The effects of refill friction stir spot welding parameters on the mechanical behavior of aluminum AA5754-H22 and DP600 joints were investigated using parameter design of the Taguchi method. The following conclusions can be drawn based on the experimental results of this study:

- The mechanical performance of dissimilar joints is conditioned to the state of the interface between the sheets, particularly by the presence of brittle intermetallic layer at the interface. The results showed that the control of the amount of intermetallic layer formed in the interface is a determining factor to obtaining welds with good mechanical properties. The formation and growth of these IMC are closely dependent of temperature, this is, on the thermal input developed during the welding procedure, which was conditioned by the backing plate selected in the present study.
- The produced spot joints by the L9 orthogonal array showed very good mechanical performance with maximum lap shear force of approximately 6.7 kN (condition 3), which meets the standard requirements for transport application the minimum lap shear strength according to SAE AWS-W-6858A (3400 N).
- For the selected range of welding parameters, RS was the parameters with the highest percentage of contribution on the lap shear of the joints. In contrast, DT was shown to have no significant influence on the joints performance because its percentage of contribution was no statistical significance.
- The Taguchi method successfully maximized the response and therefore the best welding condition was found. The optimized combination of process parameters was identified as being: 1200 rpm for RS, 1.4 mm for PD, 2 s for DT and 14000 N for CF.

5. Acknowledgments

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