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Optimization Of Friction Stir Spot Welding Process Parameters To Minimize The Corrosion Rate In The Stirred Zones Of

AA1050-O/AA6061-T4 Dissimilar Aluminum Lap-Joints

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ABSTRACT

In the present investigation, an optimization of the friction stir spot welding (FSSW) process parameters to minimize the corrosion rate in the stirred zone (SZ) of AA1050-O/AA6061-T4 dissimilar Al lap joints carried out. The joints were welded using different tool rotational speeds, dwell times and plunging depths. Full factorial design of experiments approach has been employed to examine the influences of the aforementioned process parameters on the corrosion rate of the friction stir spot welded (FSSWed) joints. The results revealed that the optimum FSSW process parameter that minimize the corrosion rate (about 6.22×10^{-4} mm/year) are tool rotational speed of 1400 rpm, dwell time of 7 sec. and plunging depth of 3.05 mm.

KEYWORDS: Friction Stir Spot Welding, Aluminum Alloys, Corrosion, Design of Experiments.

1. INTRODUCTION

Friction stir spot welding (FSSW) is a solid-state welding technique that is derived from friction stir welding (FSW). The FSW was originally invented by The Welding Institute (TWI), UK in 1991 as a new technique for joining Al alloys [1]. The FSSW exhibits the same advantages as FSW over fusion welding processes. These advantages are, the joining of similar/dissimilar materials that are difficult to weld using conventional fusion welding techniques, the elimination of cavities, solidification cracking and liquation cracking, the low residual stresses and distortion, and the better mechanical properties [2,3]. Moreover, it has been reported that the conventional fusion welding process would cause less resistance to corrosion as a result of having many defects on the edges such as high porosity, cracks, residual stress, incorrectly selected filler, and an incorrect design [4].

In FSSW, a rotating that tool consists mainly of a shoulder and a protruded pin is penetrated into the workpiece to a specified depth. A frictional heat is generated at the contact surface between the shoulder and the upper plate of the workpiece. Such a heat softens the surrounding materials and causes a material flow around the rotating pin. When the welding is completed, the tool is retracted leaving a pinhole. The applied pressure by the shoulder of the tool and the mixing of the plasticized materials results in the formation of the stirred zone [2,3]. The FSSW has several process parameters such as the tool rotational speed, dwell time, plunging depth and the plunging rate. It has been reported that these parameters play an important role in determining the quality of the welded joints [2]. Other FSSW parameters such as the tool design and the materials type and joint configurations are also important.

It is very important to predict the corrosion behavior of welded joints. This is because that the corrosion influences directly on the strength and fatigue life of the welded joint. The corrosion takes place most likely in the welded joints of dissimilar metals. It has been reported that the corrosion of FSW aluminum joints is mainly related to the structure-sensitive properties and the second phase of FSW joints [5]. The welded zone exhibits severe plastic deformation and recrystallization due to the stirring action that takes place by the shoulder and the pin of the tool. The stirred zone (SZ) is characterized by very fine grain structure of the primary α-Al phase. This increases the number of grains per unit area and the inhomogeneity of the grains which can deteriorate the corrosion resistance of the welded joint. The second phase has two contradictory effects, first it can improve the corrosion resistance due its refinement and densification, secondly it can reduce the corrosion resistance because it contains elements that can enhance the galvanic corrosion [6].

Unfortunately, there are very few investigations have been reported on the corrosion behavior of FSSWed similar and also dissimilar aluminum joints [7,8]. The effect of the influence of

FSSW process parameters on the corrosion behavior of similar/dissimilar Al joints are rarely reported. Accordingly, it is the aim of the present investigation to study the influence of the FSSW process parameters, typically, the tool rotational speed, dwell time and plunging depth on the corrosion rate of the stirred zone of AA1050-O/AA6061-T4 dissimilar Al lap joints. The proper choice of the FSSW process parameters can cause the improves the corrosion resistance of the welded joints.

2. EXPERIMENTAL WORK

2 mm sheets of the AA1050 and AA6061 wrought aluminum alloys were joined using FSSW. The chemical compositions of alloys are listed in Table 1. The sheets were cut into small pieces having dimensions of 100 mm length and 50 mm width. Before FSSW, the AA1050 and AA6061 sheets were heat treated to -O and -T4 conditions, respectively. The two sheets of AA1050-O/AA6061-T4 aluminum alloys are welded in a lap form as shown in Fig. 1. The AA6061-T4 and AA1050-O coupons were located at the upper and lower positions of the joint, respectively. The FSSW was performed using a tool has a tapered pin profile and a concave shoulder as shown in Fig. 2. Table 2 lists the FSSW parameters used joining the AA1050-O/AA6061-T4 sheets.

After FSSW, the welded joints were cut from cross-section from middle of welding spot for metallographic analysis. The samples were ground and polished using standard metallographic techniques. Microstructural examinations were conducted using optical microscopy. The macrostructural examinations were performed using image analyzing techniques. The macro- and micro-structural specimens were etched using Keller reagent. Potentio-dynamic polarization corrosion tests were used to determine the corrosion rates of the stirred zones of the AA1050-O/AA6061-T4 FSSWed joints. The corrosion properties of the SZs were measured using Autolap 302 N potentiostat/galvanostat workstation with NOVA 1.10 software. The electrochemical measurements were carried out at room temperature after rinsed the test samples with double distilled water, degreased with ethanol, connected to a copper wire and sealed with epoxy resin with the exposure area of 1 cm^2. The test solution was 3.5% NaCl. The Potentio-dynamic polarization curves were obtained on the potential range from -2.5 V to 2 V with scan rate of 1.0 mV s-1. Corrosion current density (i_{corr}) were determined by using Tafel extrapolation.

The full factorial design of experiments (DoE) technique was used to design the FSSW experiments. The analysis of experimental results of the corrosion tests was carried out using the analysis of variance (ANOVA) statistical approach. The ANOVA technique has been performed to examine the influences of the tool rotational speed, dwell time and the plunging depth and their interaction on the corrosion rate in the stirred zones of AA1050-O/AA6061-T4 FSSWed joints.

Table 1. Chemical composition the AA1050-O and AA6061-T4 aluminum alloys (wt.-%).

Alloy	Elements (wt.-%)							
	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti
AA1050-O	0.051	0.21	0.00942	0.00275	0.00432	0.0117	0.0001	0.00201
AA6061-T4	0.552	0.0264	0.26	0.00434	1	0.00592	0.333	0.0245

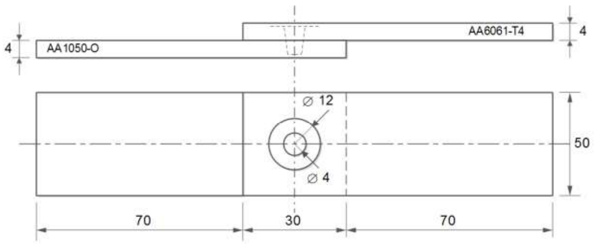
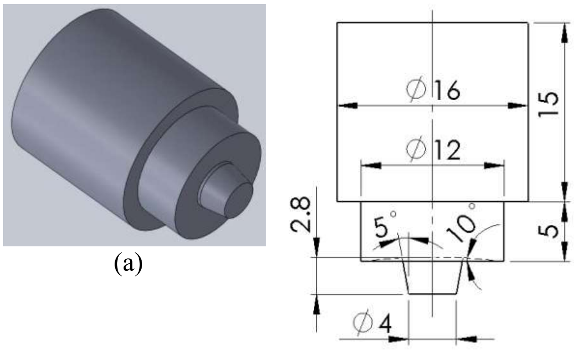


Figure 1. Tensile-shear testing specimen configuration (Dimensions in mm).



(a)

(b)

Figure 2. The FSSW tool (a) 3D view and (b) projected view (Dimensions in mm).

Table 2. The FSSW parameters and their levels.

Parameter	Level		
	Level 1 (min.)	Level 2 (avg.)	Level 3 (max.)
Rotational speed (rpm)	700	1120	1400
Dwell time (Sec.)	4	7	10
Plunging Depth (mm)	2.95	3.05	3.15

3. RESULTS AND DISCUSSION

3.1. Macro-& Microstructural Characterization

Figure 3 shows representative micrographs of the macrostructure of AA1050-O/AA6061-T4 joints welded using tool rotational speed of 1400 rpm and dwell time of 4 sec. and different plunging depths. The two sheets exhibited different grey color levels due to their different chemical compositions. The AA6061-T4 Al alloy appears darker than the AA1050-O Al alloy. The AA1050-O and AA6061-T4 Al sheets were successfully joined using FSSW. No defects such as cavities of superficial porosity were observed in the welded joints. The FSSW of the AA1050-O and AA6061-T4 Al alloy revealed the formations of the stirred zone (SZ). This zone has a structure that is characterized by fine recrystallized grains. At this zone a higher temperature and severe plastic deformation was taken place results in fine grains smaller than the base metal (BM) [2]. The heat-affected zone (HAZ) is not clearly observed in the macrostructural samples.

Typical micrographs of the microstructure of the stirred zones of welded regions of samples welded using constant tool rotational speed of 1400 rpm and 4 Sec. and different plunging depths are shown in Fig. 4. The SZs are characterized by very recrystallized grains structure of the primary α-Al grains and several particles of precipitates observed in the micrographs. The variation of the size of the primary α-Al grains in the stirred zones is shown in Fig. 5. The results revealed that increasing the tool rotational speed increases the average grain size. The influence of the dwell time and the plunging depth is not clear.

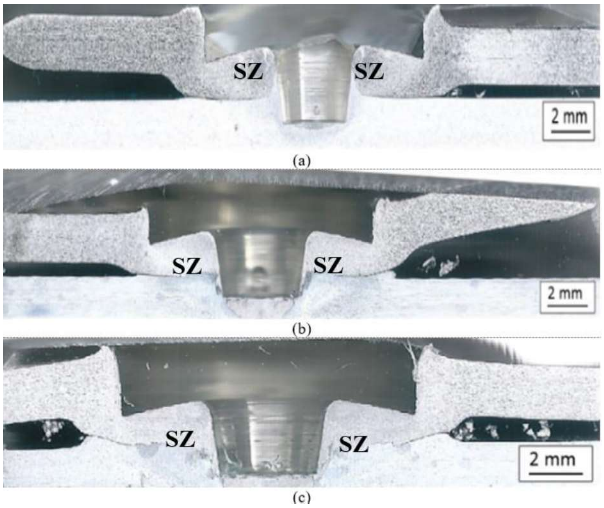


Figure 3. Macrographs of the cross-section of FSSW joints welded at 1400 rpm and 10 sec. and different plunging depths of (a) 2.95 mm ; and (b) 3.05 mm and (c) 3.15 mm.

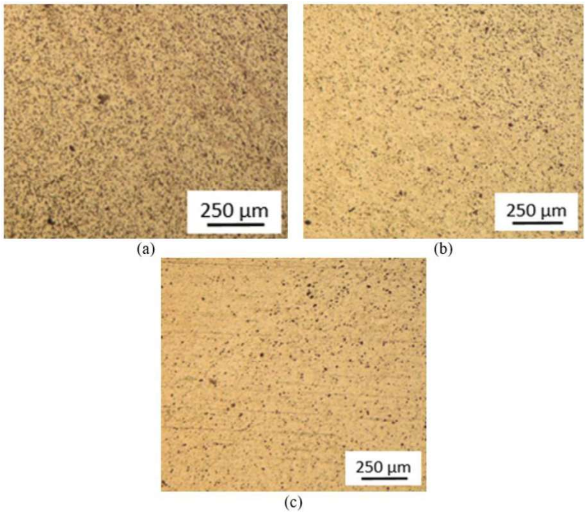


Figure 4. Micrographs of the microstructure of stirred zones from joints FSSW using constant tool rotational speed of 1400 rpm and 4 Sec. and different plunging depths of (a) 2.95 mm, (b) 3.05 mm and (c) 3.15 mm.

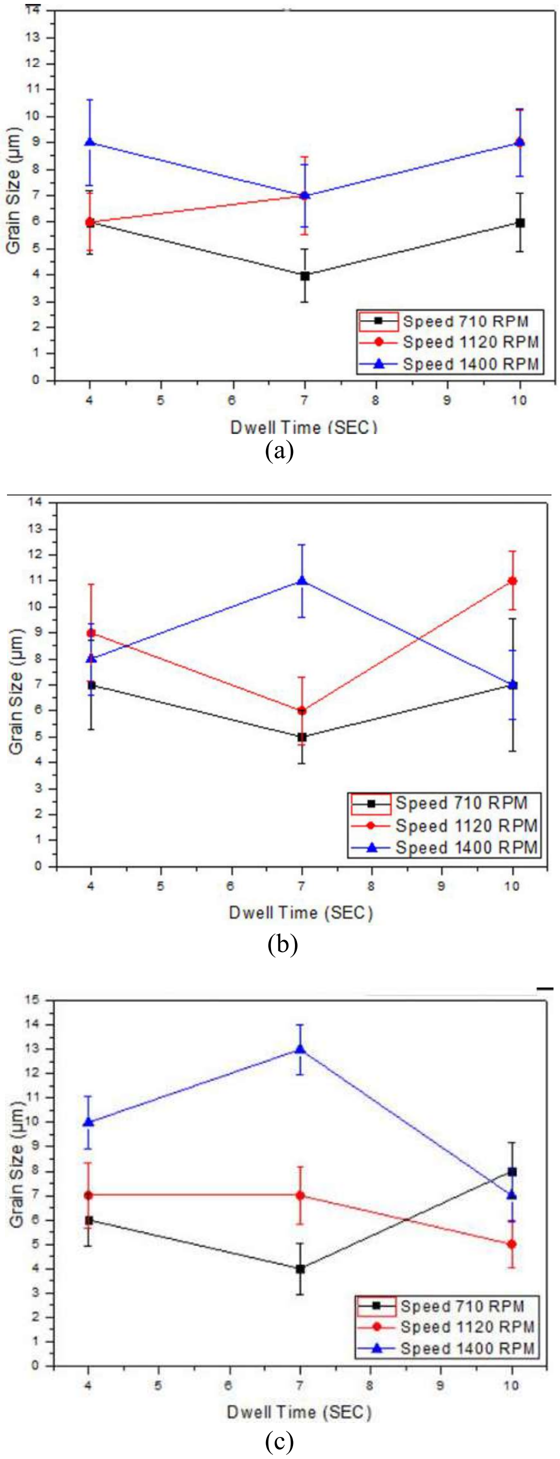


Figure 5. Variation of the average grains size at the center of stirred zone of the welded region of AA1050-O/AA6061-T4 lap joints with the dwell time and different tool rotational speeds and plunging depths of (a) 2.95 mm, (b) 3.05 mm and (c) 3.15 mm.

3.2. The Corrosion Behavior of Welded Joints

Figure 6 shows the variations of the average corrosion rate, at the center of the stirred zones, with the plunging depth at different tool rotational speeds and dwell times. The results revealed that increasing the tool rotational speed reduces the corrosion rate (i.e. improves the corrosion resistance) at the stirred zones. This is may attribute to the refinement and densification of the precipitates taken place at higher tool rotational speeds [6]. The minimum corrosion rate was about 6.22×10^{-4} (mm/year) for sample welded at tool rotational speed, dwell time and plunging depth of 1400 rpm, 7 sec. and 3.05 mm, respectively. Again, it was difficult to understand the influence of the dwell time and the plunging depth on the corrosion rate of the stirred zones. Accordingly, the statistical analysis of variance technique is used to analyze the results obtained from the experimental investigation.

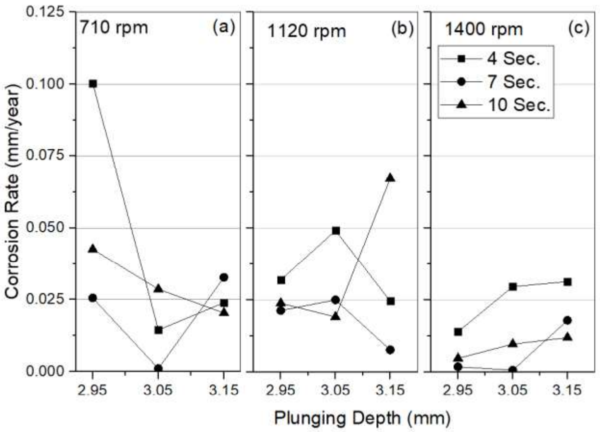


Figure 6. The variation of the corrosion rate at the stirred zone of welded regions of AA1050-O/AA6061-T4 joints.

3.3. ANOVA Results of the Corrosion Rate

Figure 7 shows the main effects plot for means for the corrosion rates of the stirred zones of AA1050-O/AA6061-T4 lap welded joints. It is clear that increasing the tool rotation speed (TRS) from 710 to 1400 rpm reduces the corrosion rate. Increasing the dwell time (DT) from 4 sec. to 7 sec. tends to reduce the corrosion rate. Prolonged dwell time (i.e. from 7 to 10 sec.) increases the corrosion rate at the stirred zone. Increasing the plunging depth (PD) from 2.95 mm to 3.05 mm reduces the corrosion rate at the stirred zone. Increasing the plunging depth to 3.15 mm tends to increase again the corrosion rate. It is clear from Fig. 7, that the minimum corrosion rate is at the lowest levels of the mean corrosion rates, i.e. at 1400 rpm, 7 sec. and 3.05 mm. This result agrees with those observed in the present investigation (see Fig. 6). Table 3 lists the results obtained from ANOVA calculations. The ANOVA analysis was carried out for a confidence limit equal to 95%. The last column in Table 3 shows the percentage of contribution (P_c) of each factor on the total variation indicating the effect of the FSSW process parameters on the corrosion rate in the stirred zones of AA1050-O/AA6061-T4 lap welded joints. The results revealed that the interaction of rotational speed/dwell time/plunging depth (P_c= 30.27%) has the most significant statistical and physical influence on the corrosion rate, followed by the interaction between the rotational speed/plunging depth (P_c= 22.83%). Both of the dwell time and the tool rotational speed exhibited lower statistical and physical significance on the corrosion rate. The interaction between the rotational speed and the dwell time exhibited the least (P_c= 3.38%) statistical and physical significance on the corrosion rate.

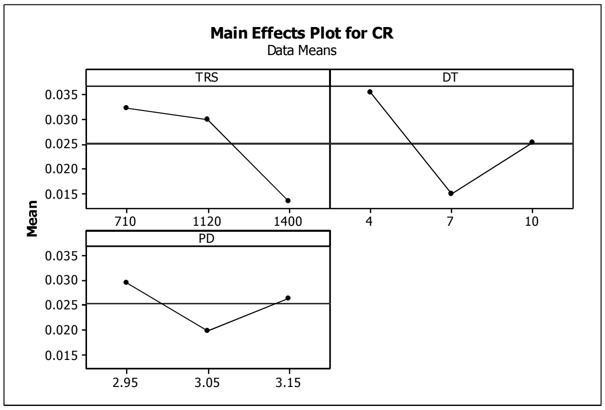


Figure 7. Main effects plot for means for the corrosion rate at the stirred zones of AA1050-O/AA6061-T4 lap welded joints.

Table 3. ANOVA table for corrosion rate.

Source	DF	Seq SS	Adj SS	Adj MS	P_c
Rotational speed	2	0.0018768	0.0018768	0.0009384	16.05
Dwell time	2	0.0019133	0.0019133	0.0009566	16.36
Plunging Depth	2	0.0004561	0.0004561	0.0002281	3.9
Rotational speed × Dwell time	4	0.0003951	0.0003951	0.0000988	3.38
Rotational speed × Plunging Depth	4	0.0026701	0.0026701	0.0006675	22.83
Dwell time × Plunging Depth	4	0.0008462	0.0008462	0.0002115	7.24
Rotational speed × Dwell time × Plunging Depth	8	0.0035398	0.0035398	0.0004425	30.27
Residual Error	0	-	-	--	-
Total	26	0.0116975			

DF, degrees of freedom; SS, sum of squares; MS, mean square; P_c, percentage of contribution.

4. CONCLUSIONS

Based on the results obtained from the present investigation, the following conclusions can be derived:

1. The 2 mm AA1050-O and AA6061-T4 dissimilar aluminum sheets were successfully joined using FSSW. The AA1050-O/AA6061-T4 lap joints exhibited no defects such as cavities of superficial porosity.
2. Increasing the tool rotation speed reduces the corrosion rate. While increasing the dwell time and/or the plunging depth to a certain value tends to reduce the corrosion rate. Increasing the dwell time and/or the plunging depth above this value increases the corrosion rate at the stirred zones of the welded joints.
3. The interaction between the tool rotational speed, dwell time and plunging depth showed the highest statistical and physical significance on the corrosion rate of the stirred zones of AA1050-O/AA6061-T4 lap joints produced using FSSW.

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