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Process Parameters Optimization of Friction Stir Spot Welding of Dissimilar Aluminum Alloys

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Abstract. In the present investigation, dissimilar AA1050-O and AA6061-T6 aluminum alloy plates were joined using friction stir spot welding (FSSW). The influences of tool rotational speed, dwell time and plugging depth on the tensile-shear load of the friction stir spot welded (FSSWed) lap joints were studied. The FSSWed dissimilar plates were joined using a tool having a tapered pin profile and concave shoulder. The plates were joined using three tool rotational speeds of 710, 1120, and 1400 rpm, and three dwell times of 4, 7, and 10 seconds and three plugging depths of 2.95, 3.05, and 3.15 mm. The tool plunging rate was kept constant at 8 mm/min. The results indicated that the plunging depth has the most significant influence on the tensile-shear load of the welded joints followed by the tool rotational speed and the dwell time. The maximum tensile-shear load (5.32 kN) was obtained for weldments FSSWed at tool rotational speed, dwell time and plunging depth of 700 rpm, 10 seconds and 3.15 mm, respectively.

KEYWORDS: Friction stir spot welding, Aluminum alloys, Tensile-shear load, Microstructure, Optimization.

1. INTRODUCTION

Traditional methods used for Al alloys welding in the automotive industry are resistance spot welding (RSW) and self-piercing riveting (SPR). In RSW, the high temperature which used to weld Al alloys can decline the mechanical properties of the work piece. In SRR, high forces used to apply during the process, which means machines must be built with the ability to handle high loads. The initial cost of the rivets and the limited shape of joint design are the main limitations [1]. The friction stir spot welding (FSSW) technique has many of advantages in welding process of aluminum alloys. High joint efficiencies (competitive with riveting and bonding), excellent mechanical properties as demonstrated by fatigue, tensile, and bend tests, environmentally friendly, energy efficient, long tool life, and dissimilar material conditions or dissimilar alloys can be joined are the main advantages of FSSW.

Several investigations have been published on FSSW of similar aluminum alloys, most of them dealing with the micro structural and mechanical properties [2-6]. Fewer investigations were reported on the effect of FSSW process parameters such as tool rotational speed, dwell time, and plunging depth on the aforementioned characteristics of dissimilar aluminum FSSWed joints [7-10]. For example, Puccini and Svoboda [8] studied the effect of the plunging depth during FSSW process, as well as, the change of position of the alloys used in the superimposed joints, when AA5052 and AA6063 sheets specimens were welded. The found that the fracture load increases with tool plunging depth for both configurations. Kim et al. [9] studied the effect of tool geometry (concave and convex shoulder) and process parameters on mechanical properties of FSSWed AA5052-H32 with AA6061-T6 sheets of 2 mm thickness. They found that the joint strength is significantly influenced by the shoulder geometry as well as the material combination and the process parameters.

In this investigation, the mechanical characteristics of aluminum AA1050/AA6061 FSSWed joints were studied. The FSSW were performed using different tool rotational speeds, dwell times and plunging depths. Optimization of the FSSW process parameters was carried out to obtain the highest tensile-shear load of the AA1050/AA6061 lap joints.

2. EXPERIMENTAL PROCEDURES

2.1. Materials

The materials used in the current investigation were AA1050-O and AA6061-T6 wrought aluminum alloys. The chemical compositions of such alloys are listed in Table 1. The aluminum sheets have dimensions of 100 mm length, 50 mm width and 2 mm thickness.

TABLE 1. Chemical composition of AA1050 and AA6061 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-T6	0.552	0.0264	0.26	0.00434	1	0.00592	0.333	0.0245

2.2. Design of Experiment (DOE)

Optimization of process parameters can improve quality and the optimal process parameters obtained from the factorial design and other noise factors [11]. In the current work, the full factorial design was performed adopted and the results was analyzed using Minitab statistical commercial software. The effect of FSSW process parameters on the tensile-shear load of the FSSWed joints was investigated using analysis of variance (ANOVA) technique.

2.3. Tools Geometry and FSSW Operation

The FSSW process of the dissimilar AA1050-AA6061 alloys is illustrated in Fig. 1. The FSSW was carried out using three different tool rotational speeds, typically, 700, 1120, and 1400 rpm, three different dwell time, typically, 4, 7, and 10 sec, and three different plunging depth, typically, 2.95, 3.05, and 3.15 mm from the bottom surface of tool pin. The AA1050-O was placed at the bottom side while the AA6061-O was placed at the top side. The feed rate of tool inside sheets has been constant at 8 mm/min. It was found from the literature that the low strength alloy should be kept on the bottom side [10]. Figure 2 shows a schematics illustration of the tool. The tool was made from K110 tool steel. The tool has tapered pin profile with 4 mm diameter with tapered angle of 5˚. The tools have shoulder diameter of 12 mm with concave surface with angle 10˚.

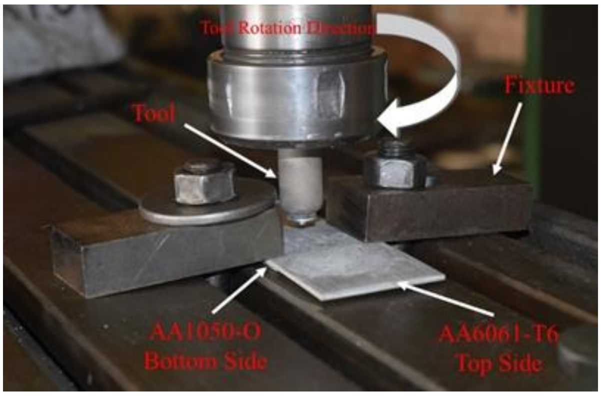

FIGURE 1. The FSSW process.

2.4. Metallographic Examinations

After FSSW, the welded joints were cross-sectioned from middle of welding spot for metallographic analysis. The metallographic specimens were mechanically ground using a series of emery papers with increasing fines up to 2500 grit followed by polishing using 0.1 µm diamond suspension. To reveal the microstructure, the sections were etched using Keller's reagent. The microstructures of the welded regions were examined using optical microscope.

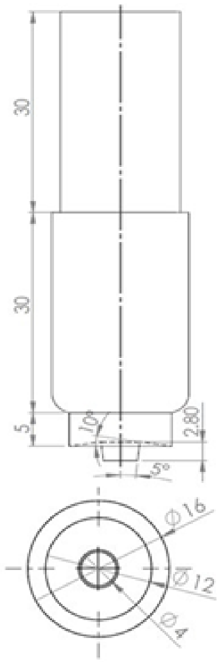

FIGURE 2. Schematic illustration of the tool used in the present study (dimensions in mm).

2.5. Tensile-Shear Tests

All tensile-shear tests were carried out at room temperature at a crosshead speed of 1 mm/min using a universal testing machine. The fracture load was evaluated by testing three specimens from each weld condition and the average value was determined.

3. RESULTS AND DISCUSSION

3.1. Tensile-Shear Results

The microstructure of the AA1050-O was difficult to examined, so that, only the microstructure of AA6061-T6 has been examined and it is nearest region to the bottom surface of shoulder. In all conditions, no visible macroscopic defects such as bond interface defects have been observed in the welded regions. Figure 3 shows the macro cross-section views of three samples FSSWed at different welding parameters. The stir zone (SZ) has been appears clearly around the pin and under shoulder at AA6061-T6, and some of AA6061-T6 plunging into AA1050-O under the pin. Figure 3a shows that the hook is near to the pin hole contrariwise. In Fig. 3b the hock is far from the pin hole. In Fig.3c it is noted that the hock at mid-distance of shoulder diameter. It is clear from Fig. 3 that the bonding between the AA1050-O and AA6061-T6 alloys is complete. In all conditions, no visible macroscopic defects such as bond interface defects have been observed in the welded regions. Figure 4 shows typical microstructures at the stirred zones of samples FSSWed using different conditions.

Table 2 lists the average values and standard deviations of the tensile-shear tests.

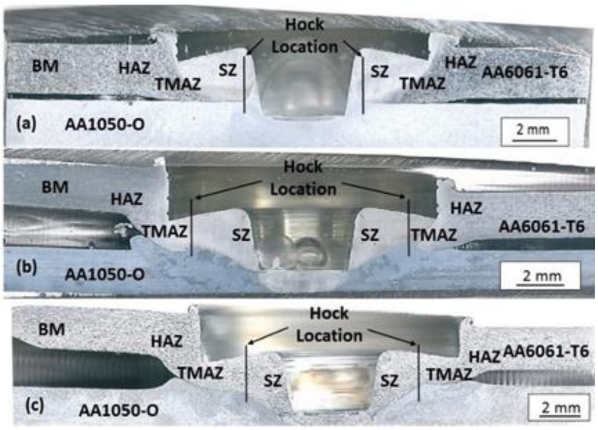

FIGURE 3. The macro cross-section views of friction stir spot joints FSSWed at (a) 710 rpm, 4 sec., 3.05 mm, (b) 710 rpm, 10 sec., 3.15 mm, and (c) 1120 rpm, 7 sec., 3.05 mm.

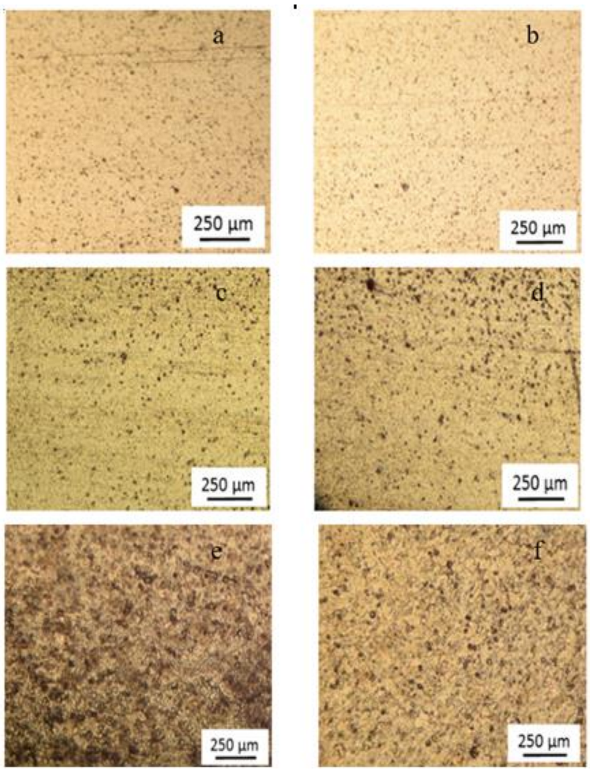

FIGURE 4. Microstructure of at the stirred zone of samples FSSWed at: (a,b) 710 rpm, 4 sec., 3.05 mm, (c,d) 710 rpm, 10 sec., 3.15 mm, and (e,f) 1120 rpm, 7 sec., 3.05 mm.

3.2. Analysis of Variance (ANOVA)

Table 3 shows the ANOVA results for tensile shear load. The results of ANOVA indicate that the considered process parameters are highly significant factors affecting the tensile-shear load of FSSW joints in the order of rotational speed, plunging depth and dwell time. The plunging depth (27.35 %) exhibited more contribution than tool rotational speed (19.14 %) and the dwell time (12.8 %). P-value for plunging depth (0.006) is smallest value comparing by tool rotational speed (0.022) and dwell time (0.077).

TABLE 2. The results of tensile-shear tests and grain size measurements of FSSWed joints.

Conditions			Sample 1	Sample 2	Sample 3	average Tensile-Shear Load (kN)	Standard deviation of Tensile-Shear Load (kN)
Tool Rotational Speed (rpm)	Time (Sec.)	Depth (mm)					
710	4	2.95	4.01	4.525	4.46	4.33	0.28
710	4	3.05	2.2	2.16	2.25	2.2	0.045
710	4	3.15	4.22	4.395	4.54	4.39	0.16
710	7	2.95	4.56	4.575	4.505	4.55	0.037
710	7	3.05	2.22	2.765	2.37	2.45	0.282
710	7	3.15	4.6	4.585	4.485	4.56	0.063
710	10	2.95	5.025	4.21	4.595	4.61	0.408
710	10	3.05	3.2	3.91	3.78	3.63	0.378
710	10	3.15	5.34	5.31	5.31	5.32	0.017
1120	4	2.95	3.26	3.075	2.865	3.07	0.198
1120	4	3.05	3.225	3.635	2.94	3.27	0.349
1120	4	3.15	3.52	3.605	3.565	3.56	0.043
1120	7	2.95	3.19	3.105	3.4	3.23	0.152
1120	7	3.05	3.4	3.5	3.6	3.5	0.1
1120	7	3.15	3.98	3.725	3.8	3.84	0.131
1120	10	2.95	3.54	3.725	3.17	3.48	0.283
1120	10	3.05	4.53	3.925	3.845	4.1	0.375
1120	10	3.15	4.105	4.47	4.455	4.34	0.207
1400	4	2.95	2.55	2.55	2.78	2.63	0.133
1400	4	3.05	2.875	3.46	3.2	3.18	0.293
1400	4	3.15	3.66	3.25	3.11	3.34	0.286
1400	7	2.95	2.63	3	2.8	2.81	0.185
1400	7	3.05	2.99	3.27	3.31	3.19	0.174
1400	7	3.15	3.82	3.92	3.705	3.82	0.108
1400	10	2.95	2.9	2.8	2.85	2.85	0.05
1400	10	3.05	3.325	3.335	3.16	3.27	0.098
1400	10	3.15	3.9	4	3.8	3.9	0.1

TABLE 3. ANOVA results for tensile-shear load.

Source	DF	Contribution (P, %)	Adj SS	Adj MS	F-Value	P-Value
Tool Rotational Speed (rpm)	2	19.14%	2.762	1.3812	4.62	0.022
Dwell Time (sec.)	2	12.08%	1.745	0.8723	2.92	0.077
Plunging Depth (mm)	2	27.35%	3.948	1.9739	6.60	0.006
Error	20	41.43%	5.981	0.2991		
Total	26	100 %				

3.3 Main Effects Plots for Means

From Table 2, the maximum tensile-shear load and the smallest average grain size are 5.32 kN and 3 µm, respectively, for weldments FSSWed at tool rotational speed of 700 rpm, dwell time of 10 seconds and plunging depth of 3.15 mm. Figure 5 shows the main effects plot for means of tensile-shear load for AA1050-O and AA6061-T6 dissimilar welded joints. It is clear that the tensile-shear force reaches a maximum value at the optimum value of process parameters of tool rotational speed of 700 rpm (level 1), dwell time of 10 sec (level 3) and plunging depth of 3.15 mm (level 3).

3.4. Interaction Plots

The interaction plot represents the effect of one factor on the others to give the behavior of response [11]. Figure6 shows the effect of all FSSW parameters on tensile-shear load of AA1050-O and AA6061-T6dissimilar FSSW joints. The general response of tensile-shear load is increases by increase plunging depth except at tool rotational speed of 710 rpm, tensile shear load decrease to certain level and the increases by increase plunging depth. And the general response of tensile shear load is decrease to certain level and the increases by increase dwell time and/or tool rotational speed.

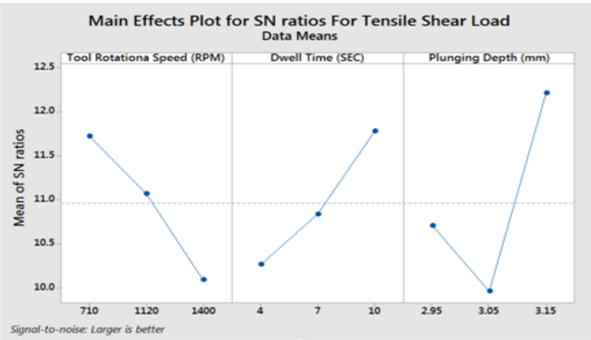

FIGURE 5. Main effects plot for tensile-shear load.

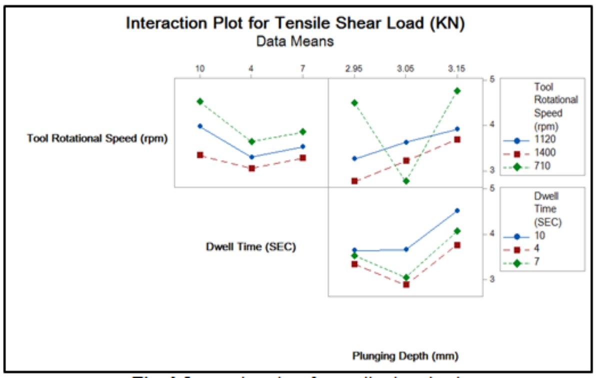

FIGURE 6. Interaction plots for tensile-shear load.

4. CONCLUSIONS

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

1- The tool rotational speed of 710 rpm, dwell time of 7 sec., and plunging depth of 3.15 mm are the optimized values to achieve the maximum tensile-shear load of the AA1050-O and AA6061-T6 dissimilar FSSW joints.

2- The plunging depth exhibited the highest significant effect on the tensile-shear load of the FSSWed joints when compared with the tool rotational speed and the dwell time. The ANOVA results showed that the rotational speed, plunging depth and dwell time exhibited percentage of contribution of 19.14 %, 27.35 % and 12.8 %, respectively.

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