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Optimization of Friction Stir Spot Welding Parameters of Lap Joint between AA1100 Aluminum Alloy and SGACD Zinc-coated Steel

Surat Triwanapong[1], Jesada Kaewwichit[2], Waraporn Roybang[3], Kittipong Kimapong[4]

[1,2,3,4]*Department of Industrial Engineering, Faculty of Engineering,*
Rajamangala University of Technology Thanyaburi, Pathumthani, THAILAND,
surat.t@en.rmutt.ac.th[1], jesada.t@hotmail.com[3],
waraporn2029@gmail.com[4],kittipong.k@en.rmutt.ac.th[5]

Abstract

This article aims to apply a friction stir spot welding for producing a lap joint of AA1100 aluminum alloy and SGACD zinc coated steel. The experiment was designed by MINITAB and then investigated the relation among the friction spot joint parameters. The experimental results are as follows. The friction spot joining could successively produce the lap joint of AA1100 aluminum alloy and SGACD zinc coated steel. Interaction between the rotate speed, the hold time and the tool insert speed affected to vary the tensile shear strength of the lap joint. The prediction of the optimized welding parameters that indicated the tensile shear strength of 1966 N was the rotated speed of 4000 rpm, the pin hold time of 6 sec, the pin insert rate of 6 mm/min with the S/N ratio of 66.56 that was higher than that of the total mean S/N ratio. The practical experiment of the predicted welding parameters indicated the tensile shear strength of 2165 N and had the S/N ratio of 66.70 that was higher than the predicted tensile shear strength.

Keywords*: friction stir spot welding, lap joint, aluminum, steel,*

1. INTRODUCTION

In automobile manufacturing, lap joint is an important joint and has an application number that was larger than 60% when compared to other joint such as butt joint or T-joint, *etc* [1]. However, RSW is a fusion welding process that consumed a high energy and also produced an undesired microstructure in a weld metal such as a cast structure (a similar materials joint) or a brittle intermetallic compound (a dissimilar materials joint). For decreasing the energy that was applied to weld the joint, some automobile manufacturer has invented a friction stir spot welding (FSSW) [2] and has a welding principle as shown in figure 1. A welding tool that was rotated at a high speed was inserted into the lap joint until a tool shoulder was plunged to an upper surface of the lap joint. The welding tool that was plunged at the given depth was held for a given time

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Corresponding Author: surat.t@en.rmutt.ac.th
Tel: +66 2549 4083, Fax: +66 2549 4900
Dept. of Industrial Engineering, Faculty of Engineering, Rajamangala University of Technology Thanyaburi

and then was removed from the lap joint.

Recently, some researchers have applied FSSW to welding the lap joint between aluminum and steel. Tanaka and Kumagai [2] welded the lap joint between A6061 aluminum alloy and low carbon steel and studied the relation between the distance between the pin end that was inserted into the lap joint and the rotate speed. The formation of the intermetallic compound on the lap joint interface was found but was not affected by the joint strength because the fracture path was not occurring at this IMC phase. Fujimoto *et al*. [3] welded the lap joint between A6061 aluminum alloy and low carbon steel and reported that the FSSW lap joint tensile strength was equal to the RSW lap joint tensile strength.

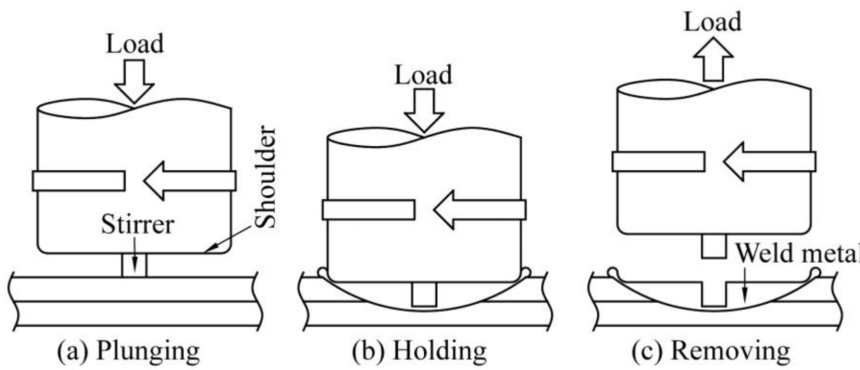

Figure 1. Friction stir spot welding principle [3].

As above discussion, the application of FSSW for welding the lap joint between aluminum and steel are limited and has a few paper to report systematically. Therefore, this paper aims to design the experiment using Taguchi method, to apply FSSW for producing the lap joint between AA1100 aluminum alloy and SGACD zinc coated steel and to study the relation between the welding parameters and the lap joint properties was investigated.

2. EXPERIMENTAL PROCEDURE

Table 1. Chemical composition of the experimental materials (%wt)

Mateials	Al	Fe	C	Zn	Mg	Mn	Cu	P	S
AA5052	Bal.	-	-	-	4.6	-	0.15	-	-
SGACD	-	Bal.	0.15	0.25	-	-	-	0.014	0.240

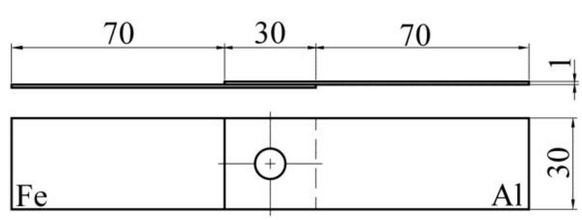

Figure 2. FSSW specimen dimension. (Unit: mm.)

Materials used in this experiment were AA1100 aluminum alloy (hereafter, Al) and SGACD zinc coated steel (hereafter, Fe) that had a chemical composition as shown in Table 1. The dimension of both plates was a length of 100 mm, a width of 30 mm and a thickness of 1 mm. The Al plate was set to be 30 mm overlapping the Fe plate by 30 mm as shown in figure 2. The lap joint was mounted in a jig as shown in figure 3 and then, clamped on a moving table of a CNC vertical milling machine. The FSSW tool was made of heat treated JIS-SKD 11 steel and had a shoulder diameter of 10 mm, a pin diameter of 4.0 mm and a pin length of 1.0 mm as shown in figure 4. The design of the experiment was performed using MINITAB15 and defined the symbol of the welding parameter as listed in Table 1. The welding parameter in this study consisted of a tool rotate speed of 3000-4500 rpm, a tool insert speed of 2-6 mm/min, a hold time of 2-6 seconds and a pin depth of 1.00 mm. After welding, the lap joint was investigated for a tensile shear strength, a fracture path and fracture location of the joint. A microstructure examination of the joint interface structure was also performed.

Figure 3. a jig for setting up the experimental specimen.

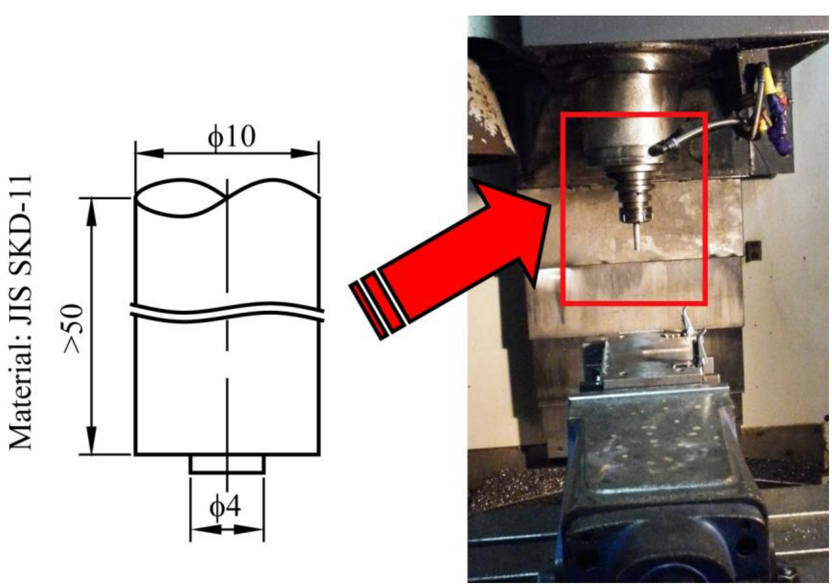

Figure 4. FSSW tool configuration and setup.

Table 1. The welding parameters in this study.

Symbol	Welding parameter	Unit	Level 1	Level 2	Level 3
A	Rotate speed	rpm	3500	4000	4500
B	Hold time	second	2	4	6
C	Pin insert rate	mm/sec	2	4	6

3. RESULTS AND DISCUSSION

This experiment was started by specifying 3 levels of the welding parameters as listed in Table 1. The welding parameters were defined as A, B and C for the rotate speed, the hold time and the pin insert rate, respectively. The depth of the pin end that was inserted to the lap joint was 1.0 mm. (0.0 mm was the location where the pin end was touched the upper surface of the lap joint.) Taguchi method with L_9 orthogonal array and MINITAB were the tools that applied to design and analyze the experimental results. The results of the design of experiments were listed in Table 2. The welding conditions that were designed in Table 2 were systematically applied to weld the lap joint between Al and Fe. Each welding condition was 2 times performed repeatedly for assuring the design of experiments. The lap joints that were completely welded as shown in figure 5 by the defined welding condition were tensile shear tested and showed the tensile shear load in Table 3.

Table 2. L_9 orthogonal array experimental design

Experiment No.	Welding parameter		
	A rotate speed	B hold time	C pin insert rate
1	3500	2	2
2	3500	4	4
3	3500	6	6
4	4000	2	4
5	4000	4	6
6	4000	6	2
7	4500	2	6
8	4500	4	2
9	4500	6	4

Table 3. Average lap shear fracture force (N) and S/N ratios

Experimental No.	Lap-shear fracture force (N)	S/N ratio (dB)
1	630	55.99
2	1336	62.52
3	1853	65.36
4	1113	60.93
5	1530	63.69
6	1631	64.25
7	1876	65.46
8	1151	61.22
9	880	58.89

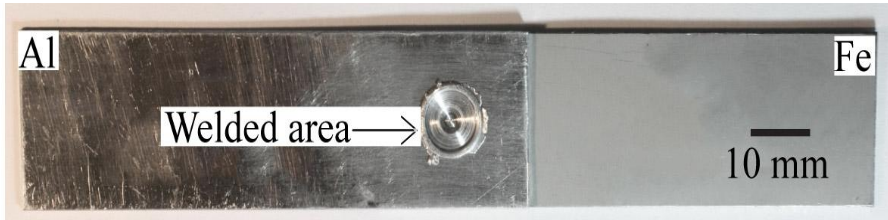

Figure 5. the welded specimen.

A Taguchi method was used to estimate a signal of noise (S/N) ratio [4] and showed the results as in column 3 of Table 3. The term "signal" in this experiment represents the desirable value of output characteristic. Therefore, the S/N ratio is the ratio of the mean to the square deviation (S.D.). Taguchi uses S/N ratio to measure the quality characteristic deviating from the desired value. The S/N ratio (η) is defined as [5]:

$$\eta = -10\log(MSD) \tag{1}$$

Where *MSD* is the mean square deviation for the output characteristic. For the FSSW strength, the higher - the better characteristic is taken [6]. The MS for the higher - the better quality is expressed as [5]:

$$MSD = \frac{1}{n}\Sigma\left(\frac{1}{y_i^2}\right) \tag{2}$$

Where *n* is the number of tests and y is the value of tensile shear strength of the *i th* test. Table 3 shows the experimental results of the lap shear strength and shows the corresponding S/N ratio which were calculated by using Equations (1) and (2). In these tests, nine different welding parameter combinations were used. Therefore, the effect of each welding parameter on the tensile shear strength used MINITAB statistical software to explain the weld parameter effect [7]. From the results of Table 3, diagrams were drawn to display the welding parameters effects on the welding strength.

The design of experiments using the orthogonal array was separated each welding parameter result in various levels. The rotate speed of 1, 2 and 3 could calculate for the mean S/N ratio for the experiment of 1-3, 4-6, 7-9, respectively [11]. Table 4 shows the mean S/N ratio for the each level of the welding parameters that indicate the mean S/N ratio of 9 experiments was about 62.03 dB. The result from this table also shows the ranking of the welding parameter that was 1-3 for the pin insert rate, the hold time and the rotate speed, respectively.

Table 4. the S/N response table for tensile shear strength

Symbol	Welding parameter	Mean S/N ratio (dB)				
		Level 1	Level 2	Level 3	Max-Min	Rank
A	Rotate speed	61.29	62.96	61.86	1.67	3
B	Hold time	60.79	62.48	62.83	2.04	2
C	Pin insert rate	60.49	60.78	64.84	4.35	1

*Total mean S/N ratio = 62.03

Figure 6 shows the means S/N response graph for the tensile shear strength that obtained the test result from table 4 and shows the total means S/N of 62 dB. Each graph shows the relation between the mean of S/N ratio and the level of the welding parameters that were the rotate speed (A), the welding speed (B) and the pin insert rate (C), respectively. The results also showed that the welding parameter that affected mostly to increase the tensile shear strength was the pin insert rate (C). As the signal-to-noise in figure 6 that was “larger is better”, the optimized welding parameter was the rotate speed of 4000 rpm (A2), the hold time of 6 sec, and the pin insert rate of 6 mm/min.

The optimized welding parameter that was predicted by MINITAB was 2 times analysis and was compared to the practical experiment as shown in Table 5. The MINITAB prediction of the optimized welding parameter that was A2B3C3 was practically applied to weld the lap joint. The lap joint that was welded by the rotate speed of 4000 rpm, the hold time of 6 sec and the pin inset rate of 6mm/min was investigated for the tensile shear strength. The tensile strength of the lap joint was about 2165 N that was higher than that of the prediction tensile strength as listed in table 5. The results also showed that the Taguchi techniques could apply to investigate for the optimized welding parameter that had the S/N ratio that was higher than the total mean S/N ratio (62 dB).

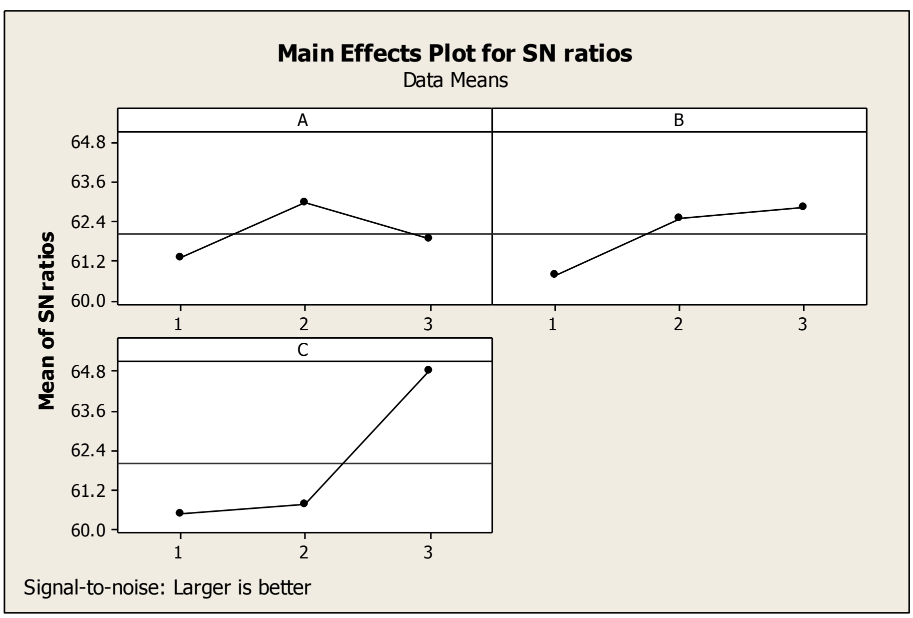

Figure 6. The mean S/N response graph for tensile shear strength

Table 5. Optimized welding parameter comparison

List	Optimized welding parameter	
	Prediction experiment	Practical experiment
Parameter level	A2B3C3	A2B3C3
Tensile shear strength (N)	1965.67	2165
S/N ratio (dB)	66.56	66.70

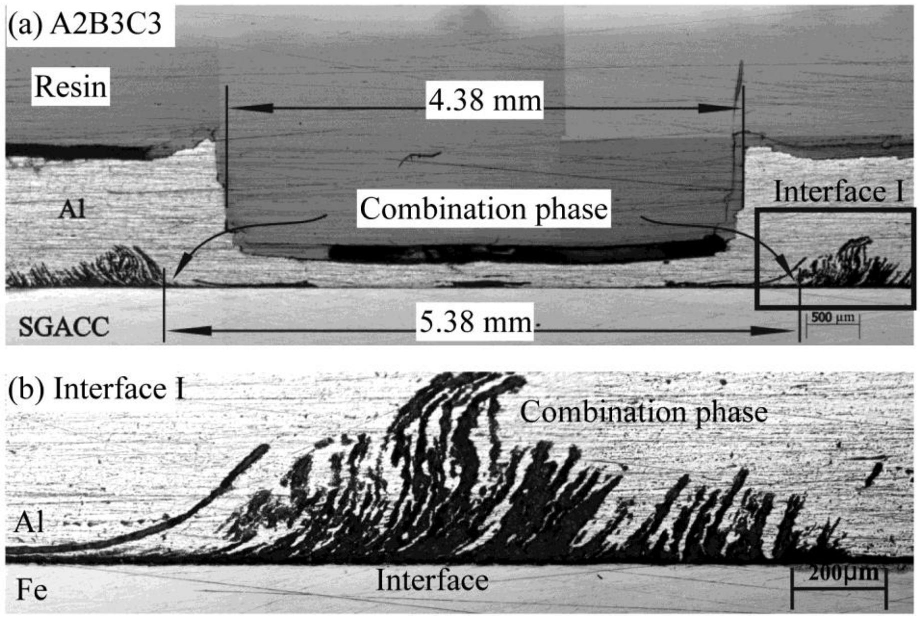

Figure 7. Interface structure of the lap joint produced by the optimized welding parameter.

Figure 7 (a) shows the macrostructure of the lap joint that was produced by the optimized welding parameters using MINITAB. The macrostructure of the joint showed the complete surface with no defect on the joint interface. A group of a dark area was formed at the joint interface between Al and Fe around the pin rotate area as shown by the arrows as seen in figure 7 (a). The interface at the location I in figure 7 (a) was enlarged and showed the combination phase between Al and Fe that might stir and sweep to the upper side of the joint as shown in figure 7 (b). This combination phase was unknown in this experimental study, but it seemed to be the intermetallic compound (IMC) between Al and Fe. This IMC phase should be analyzed by the high accurate instrument such as an X-ray diffraction (XRD) or a transmission electron microscope (TEM) in the near future.

4. CONCLUSION

4.1 FSSW could successfully produce the lap joint between AA1100 aluminum alloy and SGACD zinc coated steel. Interaction between the rotate speed, the hold time and the tool insert speed affected to vary the tensile shear strength of the lap joint.

4.2 The prediction of the optimized welding parameters that indicated the tensile shear strength of 1966 N was the rotated speed of 4000 rpm, the pin hold time of 6 sec, the pin insert rate of 6 mm/min with the S/N ratio of 66.56 that was higher than that of the total mean S/N ratio.

4.3 The practical experiment of the predicted welding parameters indicated the tensile shear strength of 2165 N and had the S/N ratio of 66.70 that was higher than the predicted tensile shear strength.

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