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Optimization of friction stir spot welding between aluminium alloys and titanium alloy by the Taguchi method

Suriya Prasomthong, Apisit kaewchaloon, Sittichai Charoenrat*
Industrial Technology, Faculty of Industrial Technology, Nakhon Phanom University, 214 Moo 12, Nong Yat Sub-district, Mueang District, Nakhon Phanom, 48000 Thailand
***Corresponding Author**: Akecharone@gmail.com

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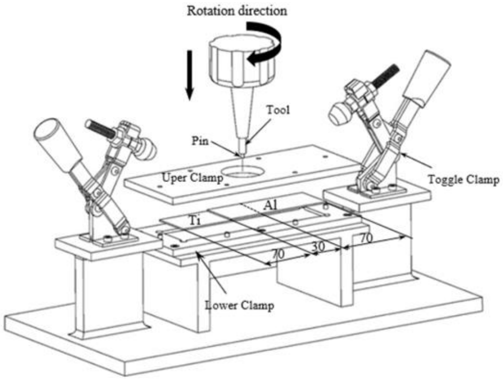
Abstract



This research investigated the shear force of dissimilar welding processes between Ti-4V-6Al titanium alloys and Al5052 aluminium alloy by friction stir spot welding (FSSW). The Taguchi L9 orthogonal was used in the experimental design**.** The welding process parameters are rotation speed (A), feeds (B), and dwell time (C). ANOVA analyzed the S/N ratio of shear force to determine the optimal parameters for statistically significant factors**.** In addition, analyze for process parameters on the response and the level of the indispensability factor, as well as predict and regression model for optimal tensile strength**.** The investigation revealed that the optimum parameters were $A_2B_2C_3$, and the shear force was 2.84 kN. Furthermore, the experiment found that rotation speed and dwell time significantly on the shear force since both factors had a P-value of less than 0.05 ($p \leq 0.05$). Therefore, rotation speed and dwell time parameters are the most critical parameters in the process at a 95% confidence level. On the other hand, an investigation of feeds demonstrates an insignificant shear force of the weld due to a P-value above 0.05 ($p \geq 0.05$).

Keywords: Friction Stir Spot Welding; Titanium Alloy; Taguchi method

1. Introduction

The advantages of titanium are its high strength, excellent corrosion resistance, and fatigue, which are currently used in modern industries [1]. However, there are often limitations in production due to the high cost. Recently, popular lightweight materials such as aluminum have been used in the automotive industry to reduce structure weight and save fuel [2] due to the excellent properties of both titanium and aluminum alloy. Combined, they are beneficial to the industry in terms of strength and weight reduction of components. However, the problem between the two materials is the different melting temperatures affecting the joining, especially in the fusion welding process. Therefore, researchers have received much attention from Ti/Al welding [3]. The advantages of Al/Ti weld joints, in addition to the low weld density, high strength, and excellent corrosion resistance of both base metals (BM), are also cost and resource savings [4] similar to aluminum welding, titanium alloy welding is prone to defects such as hot crack, porosity, and residual stress, leading to decreased weld quality [5]. In addition, intermetallic compounds (IMCs) are more prone to forming in fusion welding. In most cases, IMC, after welding, tends to have high hardness and low ductility [6]. In order to avoid the problem of IMC formation, solid state welding technology has been considered for joining the two materials, such as pressure welding, diffusion welding [7, 8], and friction welding [9]. Considering the complexity of these processes, friction stir spot welding (FSSW) is ideal as the welding process is simple and easy to prepare.

The welding of both materials by the FSSW process is a lap joint widely used in applications. Today, there is a wide range of studies investigating the mechanical properties and microstructures of joints. Such as, Yang *et al.* [10] investigate the mechanical and microstructure properties of 2A12 aluminum alloy and TC4 titanium alloy in the FSSW process. It was found that dwell time and rotation speed increased, and the tendency of weld strength increased. Furthermore, the microstructure Al side has changed significantly. Asmael *et al.* [11] studied welding Al 7075 -T651/Ti-6Al-4V alloys by the FSSW process. Prediction of tensile shear strength applied machine learning algorithms. The investigation revealed that dwell time and rotation speed significantly on the microstructure and mechanical properties. Zhou *et al.* [12] investigated the factor of the Al/Ti friction stir welding (FSW) process on the IMCs and the ultimate tensile strength of the weld. An investigation found that rotation speed increased, the tendency for IMCs increased, and at 1,000 rpm rotation speed, joints had the ultimate tensile strength. Ma *et al.* [13] joining Ti-6Al-4V titanium alloy and 6061-T6 aluminum alloys by ultrasonic-assisted with FSW process. The welding factor is the rotation speed of 450 – 850 rpm, and the tool offset is 1.2 mm. Found that the tool offset was 1.2 mm, weld defects were reduced, and the tendency for IMCs was higher as the tool offset increased. Yue *et al.* [14] studied the lab jointing of 6061-T6 aluminum alloy and Ti-6Al-4V alloy by FSW process using a lower rotation speed. It was found that the voids in the weld zone decreased as the rotation speed decreased. Several studies study the mechanical properties and microstructures in welding titanium and aluminum alloys.

Experimental design guidelines are currently proposed to predict experimental results [15] and optimize FSW welding to obtain the desired mechanical properties. Nakowong *et al.* [16] the optimization of the production factor for FSW welding was studied using the Taguchi method and analysis of variance for tensile strength and weld hardness analysis. Prasomthong *et al.* [17] Taguchi method was used to design an experimental forming of Al5052 aluminum by using the incremental forming process (TPIF) to verify the residual stress of the workpiece. It was found that the Taguchi method was very efficient in predicting and modeling. Namkaew *et al.* [18] experimental burnishing process Al5052 aluminum alloy, practical design with Taguchi method. Found that the Taguchi method was able to predict the experimental results effectively. Silachai *et al.* [19] investigate the lab joints of aluminum alloy 6061-T6 and HSS-590 by applying the Taguchi method to the experimental design. The repeat confirmation test found that the values obtained near the first test by Taguchi calculations were acceptable, with a coefficient of determination of 95.21%. In addition, much research has been done on using the Taguchi method in experimental design [20, 21].

According to previous research, the FSSW process between AA5052 aluminum alloy and Ti-6Al-4V alloy has not been discussed. Furthermore, the process factor adjustment and the various responses in the FSSW process have not been studied. Therefore, this research aims to experimental design and apply the Taguchi method to study the relevant factors of welding, i.e., rotation speed, feed, and dwell time, on the shear force of the weld. As a result, it an anticipated that Taguchi Method is designing an efficient and beneficial welding process of AA5052 aluminum alloy and Ti-6Al-4V alloy with the FSSW process for manufacturers and those interested in further FSSW process studies.

2. Materials and Methods

Experimental produecs

The objective of the FSSW process experiment was to study the experimental factors, including rotation speed, feed, and dwell time. In welding, a machining center model ACCUWAY UL-15 is used that can control the welding factor. Initially, the experiment used a cylindrical welding tool with a diameter of 10 mm, a pin diameter of 4 mm, and a length of 1.20 mm. Welding tools are manufactured from hardened D2 tool steel Al lab joint on Ti at a spacing of 30 mm, as shown in Fig. 1. It clamped on jigs explicitly designed for the FSSW process. Finally, the Joint Strength (Shear Force, kN) was investigated using the WAW - 1000D Electro-hydraulic Servo Control Universal Testing Machine, using a test speed of 150 mm/min. The maximum Shear Force is then used to analyze the process efficiency, which will be discussed in the next section.

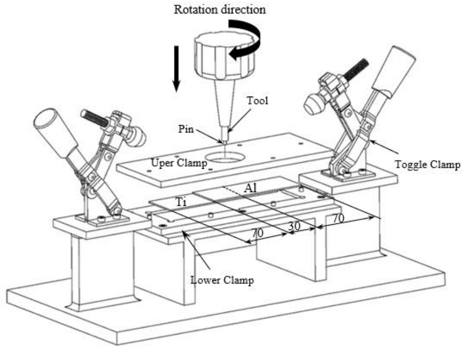


Fig.1 Symmetric diagram of friction stir spot welding in the experimental (mm)

Materials experimental

The experimental material was aluminum alloy Al5052 and Ti-6Al-4V titanium alloy, cut into pieces 100 × 25 × 1 (length × width × thickness), as demonstrated in Fig. 1. Before welding, the test specimen surface was emery paper and washed with acetone. The chemical composition and mechanical properties of the material experimental are demonstrated in Tables 1 and 2.

Table 1 Mechanical Properties and chemical composition of the AA5052

Material	Element								Mechanical Properties		
	Si	Cu	Mn	Mg	Cr	Zn	C	Al	F_u (MPa)	F_y (MPa)	%El
AA5052	0.25	0.10	0.10	2.32	0.19	0.10	0.00	Bal.	216	184	11

Table 2 Mechanical Properties and chemical composition of the Ti-6Al-4V

Material	Element								Mechanical Properties		
	Ti	Fe	N	C	H	O	V	Al	F_u (MPa)	F_y (MPa)	%El
Ti-6Al-4v	Bal.	0.40	0.05	0.10	0.01	0.20	3.61	5.53	930	862	15

Experimental Design

The experiment investigated rotation speed, feeds, and dwell time. In addition, an experiment was designed using the Taguchi method to analyze welding factor responses. This study used the L-9 (3^3) Orthogonal Array (OAS). The experimental factors are shown in Table 3. For the target value selection experiment, the larger-is-better equation of tensile strength illustrates eq (1). Where S/Ns is the signal-to-noise ratio, n is the number of datasets, and y_i is the dependent variable or response.

Table 3 Factors and parameters of the experiment

Experimental factors	**Experimental level**		
	–1	**0**	**1**
Rotation speed (rev/min^{-1}) (A)	3,000	3,500	4,000
Feeds (mm rev^{-1}) (B)	1	2	3
Dwell time (sec) (C)	6	8	10

Larger-is-better; (1) [15, 17 – 19]

$$S/N_L = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{1}$$

3. Results and Discussion

Signal-to-Noise Ratio (S/N Ratio)

Optimal parameters of the welding process with the Taguchi method were analyzed by signal-to-noise ratio analysis; S/N analyzed the main effect of the factor and S/N Ratio values on the shear force values. Larger-the-better [17 – 19] values were determined. The results of the analysis are as follows.

This research is to study the welding factor on the shear force, experimental model, experimental results, and S/N ratio for weld shear force and mean S/N of response for shear force, as demonstrated in Table 4. The effect of welding factors analysis revealed that the shear force and S/N ratio were at the appropriate level: $A_2B_2C_3$, the rotation speed is 3,500 rev min^{-1}, feed is 2 mm rev^{-1}, and dwell time is 10 sec.

Table 4 Experimental layout: L9 Orthogonal Array, S/N Ratio values, and shear force

Experiment No.	**A Rotation speed (rev min^{-1})**	**B Feeds (mm rev^{-1})**	**C Dwell time (sec)**	**Shear force (kN)**	**S/N Ratio**
1	3,000	1	6	1.75	4.86
2	3,000	2	8	1.94	5.76
3	3,000	3	10	2.04	6.19
4	3,500	1	8	2.55	8.13
5	3,500	2	10	2.84	9.07
6	3,500	3	6	2.41	7.64
7	4,000	1	10	2.61	8.33
8	4,000	2	6	2.23	6.97
9	4,000	3	8	2.33	7.35

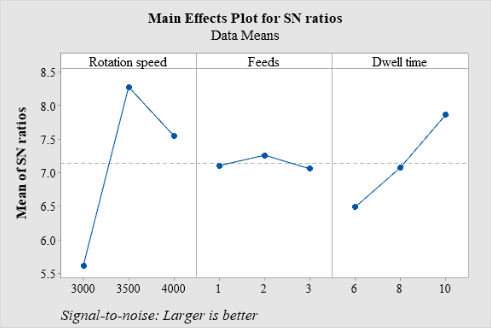


Fig.2 Main effects plot for the S/N ratio for shear force.

Fig. 2 illustrates the main effect plot for the factor on the shear force of the S/N ratio. The analysis revealed that the maximum S/N ratio of rotation speed was at level 2 at 3,500 rev min^{-1}, the maximum S/N ratio of seed at level 2 was 2 mm rev^{-1}, and the maximum S/N ratio of dwell time was at level 3 was 10 sec.

Table 5 illustrates the response table for signal-to-noise ratios on the shear force of each level factor. The analysis revealed that the level 2 rotation speed (A) maximum response was 8.28, the level 2 feed (B) maximum response was 7.26, and the level 3 dwell time (C) maximum response was 7.86.

Table 5 Response Table for Signal to Noise Ratios of shear force.

Level	Rotation speed	Feeds	Dwell time
1	5.60	7.11	6.49
2	8.28	7.26	7.08
3	7.55	7.06	7.86
Delta	2.68	0.20	1.38
Rank	1	3	2

The optimal parameter analysis results of shear force using signal-to-noise ratio values. The suitable parameters for welding Ti-4V-6Al alloy with Al5052 aluminium alloy by FSSW process are as follows: Optimal factor A is the rotation speed of level 2 is 3,500 rev min^{-1}, Optimal factor B is the feed of level 2 is 2 mm rev^{-1}, and Optimal factor C is dwell time, Level 3 is 10 sec. Therefore, the optimal shear force parameter for this welding is $A_2B_2C_3$.

Analysis of Variance (ANOVA)

Table 6 shows the ANOVA analysis of the mean shear force of the weld. In general, the probability distribution of the data takes into account DF, where DF = 2 was used for specifying the number of variables in ANOVA calculations. An analysis of the process

coefficient of determination (R-square) of 99.69% indicates that welding factors such as rotation speed, feed, and dwell time were significant for the process. Additionally, for the parameters of the Seq SS, the Adj SS, and Adj MS, a high F-value indicates the importance of the factor. However, this experiment found that rotation speed and dwell time significantly on the shear force since both factors had a P-value of less than 0.05 ($p \leq 0.05$). Therefore, rotation speed and dwell time parameters are the most critical parameters in the process at a 95% confidence level. On the other hand, an investigation of feeds demonstrates an insignificant shear force of the weld due to a P-value above 0.05 ($p \geq 0.05$).

Regression Analysis and Confirmation

The experiment obtained the optimum factor for welding on the shear force: a rotation speed of 3,500 rev min^{-1}, feed of 2 mm rev^{-1}, and dwell time of 10 sec. As a result, the Taguchi method has predicted shear force has 2.83 kN. The regression equation analysis for the predicted shear force is exhibited in eq. (2).

The experimental comparison with statistical analysis found that the test confirmation of shear force averaged 2.84 kN. Prediction by Taguchi Method and the regression analysis were 2.83 kN and 2.48 kN, respectively.

Table 6 Analysis of Variance for SN ratios for shear force.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Rotation speed	2	11.4799	11.4799	5.73997	257.96	0.004
Feeds	2	0.0674	0.0674	0.03369	1.51	0.398
Dwell time	2	2.8548	2.8548	1.42739	64.15	0.015
Residual Error	2	0.0445	0.0445	0.02225		
Total	8	14.4466				

R–Sq = 99.69 %; R–Sq(adj) = 98.77

$$\text{Shear force (kN)} = -0.070 + 0.000480\ \text{Rotation speed} - 0.022\ \text{Feeds} + 0.0917\ \text{Dwell time} \quad (2)$$

Predictive the Shear force for regression equation was:

$$\text{Shear force} = -0.070 + 0.00048(3500) - 0.022(2) - 0.0917(10) = 2.48\ \text{kN}$$

Table 7 Confirmation of experimental results for shear force.

Level	**Shear force (kN)**			**Average shear force (kN)**
	No.1	**No.2**	**No.3**	
1	2.56	2.72	2.48	2.58
2	2.78	2.81	2.47	2.68
3	2.44	2.62	2.55	2.54
Total Average				2.60

The confirmation of experimental results was the final setup of the optimal parameters obtained from the predicted shear force base on the Taguchi method *(*$A_2B_2C_3$*)*. The experiment was repeated in three of these factors, nine tensile test specimens were prepared each, and the mean shear force was obtained at 2.60 kN. The results of the repeated experiments are exhibited in Table 7.

4. Conclusion

Optimal parameters of dissimilar welding process between Ti6Al4V/Al5052 with FSSW process affecting shear force using Taguchi method. It was found that the process parameters using mean shear force and S/N ratio were the most suitable level was $A_2B_2C_3$. The predicted shear force from the Taguchi model was 2.83 kN, and the regression analysis was 2.48 kN. The experimental confirmation of shear force tends to have a similar aspect. An analysis of variance (ANOVA) found that welding factors on shear force were rotation speed and dwell time, whereas feeds were insignificant on the shear force of weld at a 95% confidence level. The microstructures and chemical compositions should be investigated in subsequent studies to confirm the results.

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