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Study of Friction Stir Spot Welding of Aluminum/Copper Dissimilar Sheets using Taguchi Approach

H. Khatami, T. Azdast*, M. Mojaver, R. Hasanzadeh, A. Rafiei

Mechanical Engineering Department, Faculty of Engineering, Urmia University, Urmia, Iran

P A P E R   I N F O

A B S T R A C T

Friction stir spot welding of dissimilar aluminum and copper sheets was investigated in details using Taguchi approach in this study. Analysis of variance was conducted to identify the effective parameters and their contributions on the mechanical performance. The findings revealed that the outputs followed normal distribution. The results indicated that the rotational speed with the contribution of 87.7% was the most effective parameter on the maximum tensile force tolerated by the welded samples. Dwell time and penetration depth were in second and third ranks from effectiveness viewpoint with the contributions of 8.8 and 2.9%, respectively. The results revealed that the maximum tensile force was significantly improved with the rotational speed. The maximum tensile force was enhanced by almost 228% by increasing the rotational speed from 550 rpm to 1500 rpm. Increasing the dwell time from 10 to 20 s led to improve the maximum tensile force by 31%.The sequence of the parameters was as rotational speed, dwell time and penetration depth from standpoint of influence on the maximum force according to the results of signal to noise ratio analysis. The signal to noise ratio analysis showed that the rotational speed of 1500 rpm, the penetration depth of 2.85 mm, and the dwell time of 20 s were the optimum conditions.

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1. INTRODUCTION

Friction welding is a type of solid-state welding. Heat is generated using mechanical friction between two workpieces in this process. Rotary friction welding, linear friction welding, friction surfacing, and friction stir welding (FSW) are the most improtant classes of friction welding. FSW is a solid-state bonding process invented in 1991 by the British Welding Association used to bond metallic and polymeric materials [1]. In this method, the base parts are heated by friction with a non-consumable rotational tool and then, are pressed to each other. This causes two parts to be joined to each other. The main advantage of this method is the non-melting of the work pieces and the solid phase bonding. Friction stir spot welding (FSSW) is a subset of the FSW with this difference that there is no linear motion in this process and it is used to make point bonding in thin sheets. Several studies have been done on the FSSW process, including the study of the influence of various parameters on the mechanical properties of the bonded area.

Azdast et al. [2] investigated the influence of nanoparticle addition and processing parameters on the behavior of welds of polycarbonate nanocomposites parts using the FSW process. The results showed that the amount of nano-alumina powder, rotational speed, and transverse speed had the greatest effects on the impact strength, respectively. Sun et al. [3] used the FSSW process to bond aluminum AA6061 sheet and mild steel with a thickness of 2 mm. Bisadi et al. [4] used the FSW process to bond aluminum AA5083 and pure copper at different rotational and transverse speeds. Ozdemir et al. [5] investigated the effect of the penetration depth of the tool pin in the FSSW of aluminum 1050 and pure copper. Lin et al. [6] investigated the effects of different parameters on the FSW of aluminum alloys. Sun et al. [7] investigated the mechanical properties of the FSSW process of aluminum 1050 and 6061-T6 sheets.

Corresponding Author Institutional Email: t.azdast@urmia.ac.ir (T Azdast)

Pure copper is a soft, malleable, and ductile metal with very high electrical conductivity with applications in building construction, power generation and transmission and aerospace industry. Aluminum alloys with good heat transfer, high strength, ductility and good weldability are used in aerospace, railway cars and shipbuilding.

Previous researches have shown that different process parameters affect the mechanical properties of the FSSW welds. However, a comprehensive study of the effects of these parameters on dissimilar metal welding is still challenging and needs further study. Therefore, in this research work, it is attempted to comprehensively investigate the main and interaction effects of the processing parameters on the mechanical properties of aluminum and copper dissimilar welds using Taguchi method. The contributions of different parameters on the mechanical performance of the welded samples are recognized using the analysis of variance. Furthermore, the optimization of the process conditions to achieve the maximum mechanical properties is investigated using the signal to noise ratio analysis of Taguchi approach.

2. MATERIALS AND METHODS

Industrial grade of aluminum sheets with the thickness of 2 mm and copper sheets with the thickness of 1 mm were purchased. The sheets were cut to 50×100 mm sheets. Alloying elements are shown in Table 1.

The copper sheets were placed as the upper layer and the aluminum sheets were positioned as the lower layer. The schematic of the sheets layout and their dimensions are presented in Figure 1.

TABLE 1. Alloying element of materials [8, 9]

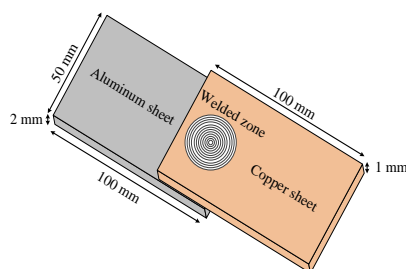| Aluminum			
Al	Cu	Fe	Mg+Mn+Si+Ti
99.5	0.05	0.4	0.05
Copper			
Cu	Al	Zn	Ti	Cr+Mg+Pb+Si
99.86	0.001	0.009	0.0002	0.0014

Figure 1. Schematic of sheets layout and their dimensions

Welding was done at ambient temperature using a H13 stainless steel tool with hardness of 52 HRC (hardness Rockwell-C). The pin height and diameter were 2.6 mm 2.2 mm, respectively. The tool height was 90 mm and the shoulder diameter was 18 mm. Figure 2 shows the real picture and schematic of the used tool.

The welding operations were performed on the LUNAN ZX6350 (China) milling machine with the aim of an appropriate designed and manufactured fixture.

The tool was in touch with the copper sheet. The rotating tool penetrates the sheets with a specific depth. In the following, the tool was held there for an adjusted time called dwell time. During welding, a stopwatch was used to calculate the time.

In the present study, the rotational speed, the penetration depth, and the dwell time were selected as the variable parameters. Each parameter was set at three different levels according to the pre-experiments. Table 2 shows the variable parameters and their levels.

The rotational speed was set at 550, 950, and 1500 rpm. The reason for choosing the rotational speed of 1500 rpm as the highest level of the rotational speed is the limitation of the device used for welding. The welds performed at the rotational speeds lower than 550 rpm were inappropriate due to the insufficient heat produced at these rotational speeds. Figure 3 shows a representative inappropriate weld performed at the rotational speeds lower than 550 rpm. Therefore, the rotational speed was set between 550-1500 rpm.

The levels of the dwell time were considered as 10, 15, and 20 s. The dwell time was not chosen lower than 10 seconds because of the incomplete mixing and melting of the materials during the welding operation. Also, the dwell time selection above 20 seconds caused the aluminum side to fracture due to overheating.
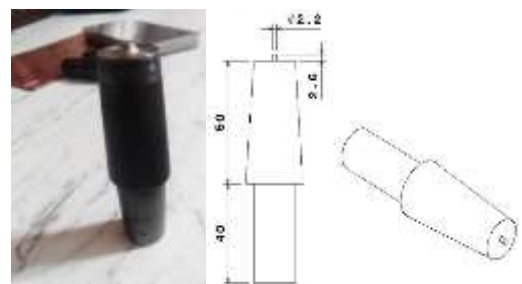

Figure 2. Real picture and schematic of the tool used in the present study (all dimensions are in mm)

TABLE 2. Variable parameters and their levels

Parameters	Low	Middel	High
Rotational speed(rpm)	550	950	1500
Penetration depth(mm)	2.80	2.85	2.90
Dwell time(s)	10	15	20

Figure 3. Representative inappropriate weld performed at rotational speeds lower than 550 rpm

Nowadays, design of experiment (DOE) methods have a broad range in engineering applications [10-14]. Taguchi method is one of the most popular DOE methods [15-18].

Studying the effect of the input parameters on different responses, investigating the contribution of the input parameters on the response variables using analysis of variance (ANOVA), and optimizing the process using the signal to noise ratio (S/N) analysis are different tools of Taguchi approach.

Signal to noise has different formulations with respect to various problems. In the present study, the main aim is to maximize the tensile properties. Therefore, the "larger-is-better" state is used as follows in Equation (1) [17]:

$$S/N = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \qquad (1)$$

where y is the response variable and n is the number of the experiments.

All the statistical analyzes were performed using Minitab-18 software.

According to the considered parameters and their levels, the L_9 orthogonal array of Taguchi approach was utilized in order to investigate the process as Table 3.

TABLE 3. L_9 orthogonal array of Taguchi approach utilized in the present study

Trial	Rotational speed (rpm)	Penetration depth (mm)	Dwell time (s)
T1	550	2.80	10
T2	550	2.85	15
T3	550	2.90	20
T4	950	2.80	15
T5	950	2.85	20
T6	950	2.90	10
T7	1500	2.80	20
T8	1500	2.85	10
T9	1500	2.95	15

The welds were performed according to Table 3.

The tensile tests were performed using Santam-ST150 tensile testing machine with a tensile speed of 10 mm/min. For each trial, at least three specimens were tested and the results were reported as mean ± standard deviation.

3. RESULTS AND DISCUSSION

Figure 4 shows the representative force-extension diagrams of nine different welded samples.

The maximum tensile force tolerated by the welded samples was considered as the response variable. Table 4 indicates the response variable i.e. the maximum tensile force tolerated by the welded samples. Also, the standard deviations of the measurements are represented in Table 4. According to the results, the standard deviations were desirable and were below 10%.

Normal probability diagram of the maximum tensile force according to the Anderson-Darling method showed that the p-value=0.506 was larger than the statistical error considered by the Minitab software (0.05), and therefore, the distribution of the results was normal. Therefore, the analysis of variance could be performed.

Table 5 shows the analysis of variance of the maximum tensile force. The results indicated that the rotational speed was the most effective parameter on the maximum tensile force. The contribution of the rotational speed was 87.7% on the maximum tensile force. The dwell time and the penetration depth were in the
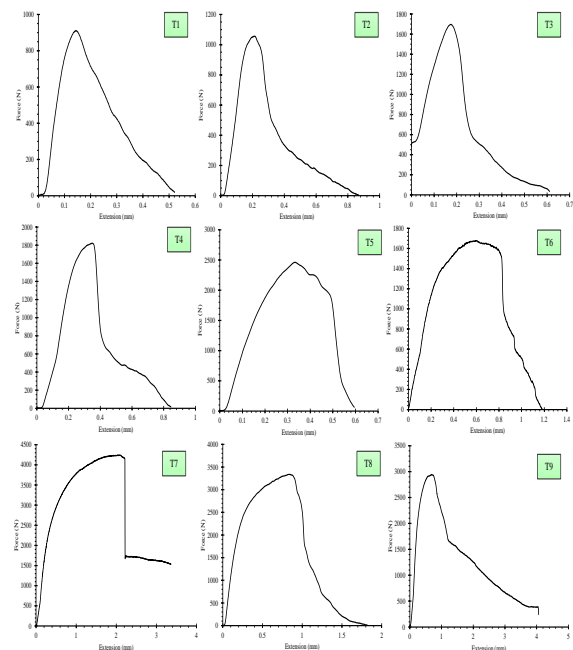

Figure 4. Representative force-extension diagrams of the welded samples

TABLE 4. Experimental results

Trial	Maximum tensile force (N)
T1	924 ± 15
T2	995 ± 85
T3	1163 ± 77
T4	1734 ± 122
T5	2376 ± 119
T6	1599 ± 90
T7	4040 ± 282
T8	3267 ± 98
T9	2789 ± 192

second and the third ranks from effectiveness viewpoint on the maximum tensile force, respectively. The contributions of the dwell time and the penetration depth on the maximum tensile force were 8.8% and 2.9%, respectively. Also, the contribution of the error in this model was 0.6%. In other words, the R^2 value was 99.4%. Therefore, the results had high validity.

The main effects of the considered parameters on the maximum tensile force are depicted in Figure 5.

TABLE 5. Analysis of variance results

Source	DF	SS	MS	Contribution (%)
Rotational speed (rpm)	2	8371455	4185727	87.7
Penetration depth (mm)	2	277864	138932	2.9
Dwell time (s)	2	835803	417901	8.8
Error	2	58172	29086	0.6
Total	8	9543294	4185727	100
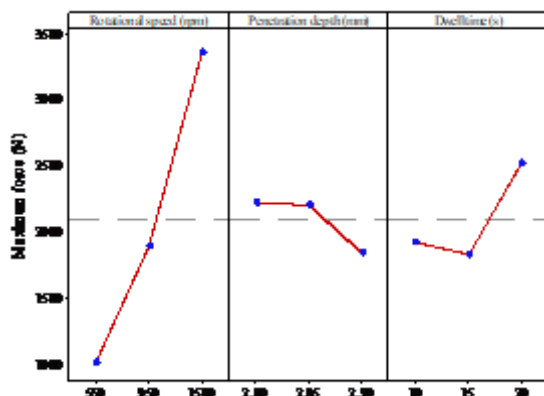
As the results showed, the maximum tensile force was improved significantly by the rotational speed. The maximum tensile force was increased from 1027 N to 1903 N by increasing the rotational speed from 550 rpm to 950 rpm. In other words, an improvement of 85.3% in the maximum tensile force was observed by increasing the rotational speed from 550 rpm to 950 rpm. This improvement was continued by more increment in the rotational speed and the maximum tensile force was increased to 3365 N at the rotational speeds of 1500 rpm. The maximum tensile force at the rotational speed of 1500 rpm was improved by 76.8 and 227.7% compared to the rotational speeds of 950 rpm and 550 rpm, respectively. More heat is generated in higher rotational speeds because there are more friction and stirring phenomena at higher rotational speeds. Therefore, the welded samples had higher mechanical properties at higher rotational speeds. The results indicated that the maximum tensile force was reduced by increasing the penetration depth. This reduction was more considerable at the highest level of the penetration depth. A reduction of 17.2% (from 2233 N to 1850 N) was observed by increasing the penetration depth from 2.80 mm to 2.90 mm. According to the results, the maximum tensile force was enhanced by increasing the dwell time. The maximum tensile force was improved by 30.9% (from 1930 N to 2526 N) by increasing the dwell time from 10 s to 20 s.

Figure 6 shows the interaction effect of the rotational speed and the penetration depth on the maximum tensile force. According to the results, the maximum tensile force was enhanced by increasing the rotational speed at all penetration depth. However, this enhancement was more significant at low penetration depths. The results revealed that the maximum tensile force was decreased by increasing the penetration depth at the rotational speed of 1500 rpm while it was slightly increased by increasing the penetration depth at the rotational speed of 550 rpm.
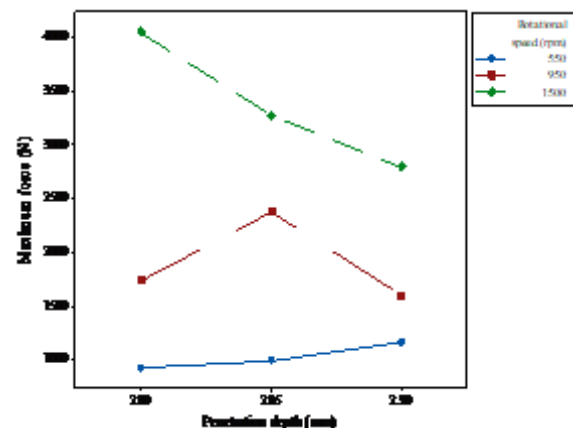

Figure 5. Main effect of processing parameters on maximum tensile force

Figure 6. Interaction effect of rotational speed and penetration depth on maximum tensile force

There was an optimum penetration depth to achieve the highest maximum tensile force at the rotational speed of 950 rpm.

The interaction effect of the rotational speed and the dwell time on the maximum tensile force is depicted in Figure 7. The results showed that the maximum tensile force was increased by increasing the rotational speed at all dwell times. Also, the maximum tensile force was improved by increasing the dwell time at all rotational speeds.

Figure 8 indicates the interaction effect of the penetration depth and the dwell time on the maximum tensile force. The results showed that the penetration depth in which the highest maximum tensile force occurred was different at different dwell times. The highest maximum tensile force was occurred at the penetration depth of 2.85 mm in the dwell time of 10 s, at the penetration depth of 2.90 mm in the dwell time of 15 s, and at the penetration depth of 2.80 mm in the dwell time of 20 s. The maximum tensile force is reduced by increasing the penetration depth at high level of the dwell time.

The signal to noise ratio analysis was performed to recognize the optimum conditions to achieve the highest maximum tensile force. Table 6 shows the results of the signal to noise ratio analysis. The level with the highest signal to noise value is the optimum level. Therefore, the optimum conditions were the third level of the rotational speed, the second level of the penetration depth, and the third level of the dwell time. In other word, the rotational speed of 1500 rpm, the penetration depth of 2.85 mm, and the dwell time of 20 s were the optimum conditions. According to Table 3, these conditions were not one of the experiments. Therefore, the prediction tool of Taguchi approach was utilized to estimate the maximum tensile force at the optimum condition. The results showed that the maximum tensile force was 4097 N at the optimum condition.

Another important result of the signal to noise ratio analysis is the ranking of the parameters from the
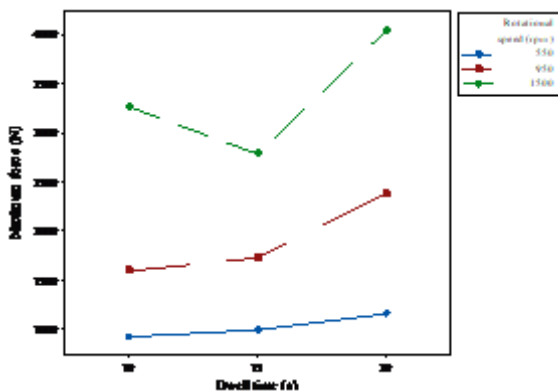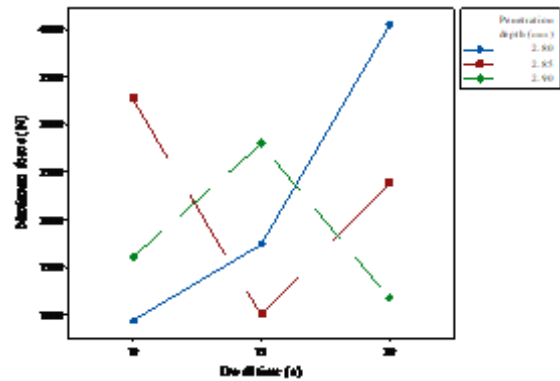

Figure 8. Interaction effect of penetration depth and dwell time on maximum tensile force

TABLE 6. Signal to noise ratio analysis for maximum force

Level	Rotational speed	Penetration depth	Dwell time
1	60.19	65.41	64.56
2	65.46	65.92	64.55
3	70.44	64.77	66.99
Delta	10.25	1.15	2.44
Rank	1	3	2

standpoint of the effectiveness. This ranking is according to the delta value. The delta is the difference between the highest and the lowest signal to noise values. The results revealed that the rotational speed was in the first rank followed by the dwell time and the penetration depth. According to the results, the ranking of the parameters obtained from the signal to noise ratio analysis was in agreement with the results of the analysis of variance.

4. CONCLUSIONS

Friction stir spot welding of dissimilar sheets of aluminum/copper was performed in the present study. Rotational speed, penetration depth, and dwell time were selected as the variable parameters and maximum tensile force was considered as the response parameter. Taguchi approach was utilized as the design of experiment method to study the process in details. Analysis of variance and signal to noise ratio analysis were used to recognize the effective parameters and optimize the process, respectively. The findings can be summarized as follows:

- Rotational speed was the most effective parameter on the maximum tensile force.
- Dwell time and penetration depth were in the second and third ranks from effectiveness viewpoint on the maximum tensile force.
- The maximum tensile force was enhanced with increasing the rotational speed.

Figure 7. Interaction effect of rotational speed and dwell time on maximum tensile force

- The maximum tensile force was improved by decreasing the penetration depth and increasing the dwell time.
- The optimum condition was the rotational speed of 1500 rpm, the penetration depth of 2.85 mm, and the dwell time of 20 s.
- The maximum tensile force was increased to 4097 N at the optimum conditions based on the prediction tool of Taguchi approach.

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Persian Abstract

چکیده

جوشکاری اصطکاکی اغتشاشی نقطه ای ورق های غیر همجنس آلومینیوم و مس، با استفاده از روش تاگوچی مورد بررسی قرار گرفت. آنالیز واریانس برای شناسایی پارامترهای مؤثر و سهم آنها در عملکرد مکانیکی انجام شد. مقادیر خروجی از توزیع نرمال پیروی نمودند. نتایج نشان داد که سرعت چرخشی با سهم ۸۷/۷ درصد، مؤثرترین پارامتر بر روی حداکثر نیروی کششی نمونه های جوش داده شده است. زمان مکث و عمق نفوذ با درصد مشارکت به ترتیب ۸/۸ درصد و ۲/۹ درصد در رتبه‌های دوم و سوم قرار گرفتند. نتایج نشان داد که حداکثر نیروی کششی با افزایش سرعت چرخشی به طور قابل توجهی بهبود یافته است. با افزایش سرعت چرخش از ۵۵۰ دور در دقیقه به ۱۵۰۰ دور در دقیقه حداکثر نیروی کششی تقریباً ۲۲۸٪ افزایش یافته است. افزایش زمان مکث از ۱۰ ثانیه به ۲۰ ثانیه منجر به بهبود حداکثر نیروی کششی به میزان ۳۱ درصد شد. مطابق نتایج آنالیز سیگنال به نویز، ترتیب اثرگذاری پارامترها بر روی حداکثر نیروی کششی بصورت سرعت دورانی، زمان مکث و عمق نفوذ است. تجزیه و تحلیل نسبت سیگنال به نویز نشان داد که سرعت چرخش ۱۵۰۰ دور در دقیقه ، عمق نفوذ ۲/۸۵ میلی متر و زمان ساکن ۲۰ ثانیه شرایط بهینه هستند.