



Optimization of Ultrasonic-assisted Friction Stir Welded using Taguchi Approach

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ABSTRACT

Friction stir welding process (FSW) is a solid-state welding technique which has several unique advantages. On the other hand, FSW process has some limitations such as low speed and high torque which limit the productivity and applicability of the process. To overcome these limitations, several secondary energy sources were integrated with FSW process. In the present paper, FSW was assisted by ultrasonic vibration energy in a process known as ultrasonic assisted friction stir welding (UAFSW). This paper aims to optimize the main process parameters of UAFSW process using 4 levels for each parameter with a total number of 16 experimental trials using Taguchi technique to help welders to select the proper parameters to achieve the highest efficiency of the joint in terms of the ultimate tensile strength (UTS). The parameters to be optimized are vibration amplitude (20-80 μm), traverse speed (40-160 mm/min) and tool rotational speed (630-1200 rpm). In addition, ANOVA analysis was utilized to determine the contribution percentage of each process parameter. The effect of each process parameter on the UTS was also investigated and analyzed. The results showed that the optimum condition is 20 μm , 80 mm/min, and 800 rpm. ANOVA analysis demonstrated that the rotational speed is the most significant parameter. An UTS of 290 MPa is predicted by the model, where the actual value is 297 MPa with an error percentage of 3.5%.

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1. INTRODUCTION

Friction Stir Welding (FSW) is a new procedure employed to weld two metal pieces depending on the heat generated by friction between the tool and the base metal. AA 6082 is considered as one of the most promising alloys, as it has the highest strength of all 6xxx series alloys with excellent corrosion resistance, tensile strength, and hardness so; it can be used in aerospace industry and heat sink applications, bridges, beer barrels, cranes, and trusses. [1-3]. Traditional FSW depends on the frictional heat and plastic deformation. The process has some disadvantages such as the low welding speed, heavy welding loads on the tool [4]. The enhancement in the plastic material flow have been investigated [5- 8]. Mabrouk et al. [9] used a mathematical model to express the heat generation during ultrasonic vibration improved friction stir welding process. The moving heat source

technique was applied to simulate the welding process. The comparison between measured and simulated results showed acceptable accuracy of the model.

Thomä et al. [10] investigated the role of ultrasonic vibration in dissimilar FSW of aluminum to steel. The study showed that the steel particles from the base metal in the nugget zone produced by the assistance of ultrasonic vibration were less and smaller than those found in the nugget zone produced by conventional FSW. Hua et al. [11] investigated the influences of ultrasonic vibration on the mechanical properties, microstructure in terms of tensile properties, micro-hardness, weld formation, weld appearance by conducting a comparative study between conventional FSW and ultrasonic-assisted FSW. Ultrasonic vibration caused grain refinement at the stirring zone as well as its desirable role in improving the mechanical properties and eliminating some weld defects at high welding speeds. Several modeling techniques

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such as response surface methodology (RSM), Taguchi method, and artificial neural networks (ANN) were applied to FSW and UAFSW processes for several reasons such as: determining the contribution percentage of each process parameter, determining the optimum combination of process parameters, obtaining a mathematical model for the output in terms of the input process parameters [12-13]. Nourani et al. [14] analyzed the process variables of FSW process of AA 6061 using the Taguchi approach to minimize the heat affected zone (HAZ) distance from the weld line. Three process parameters i.e. traverse speed, rotational speed and axial force at three levels were involved in the model with a total number of 9 experiments. ANOVA analysis was also performed to evaluate the significant parameter. The optimum combination of process parameters is a traverse speed of 1.9 mm/s, rotational speed of 385 rpm, and axial force of 11 kN. Effect of the welding parameters (i.e. ultrasonic power, rotational speed, traverse speed, and axial force) in UAFSW process on the tribological and mechanical properties of AA 6061 joints was studied. The experiments were carried out according to the L9Taguchi design. The objective was to maximize the formability and tensile strength as well as, minimizing the surface roughness and sliding wear rate once as a single-objective optimization problem using Taguchi technique and again as a multi-objective optimization problem using grey relational analysis [15]. Taguchi technique was applied to FSW process of AA 6082-T6 to obtain the optimum combination of process parameters to achieve the best ultimate tensile strength. The welding speed, rotational speed, pin profile, and tool shoulder diameter were the input process variables that have been used at 4 levels with a total number of 16 experiments. ANOVA analysis was also performed to determine the contribution percentage of each parameter. The optimum combination is a welding speed of 30 mm/min, rotational speed of 1200 rpm and tool with a cylindrical threaded pin, and diameter of shoulder of 16 mm [16]. Rostamiyan et al. [17] analyzed the effect of the process parameters such as ultrasonic vibration, rotational speed, tool plunge depth, and dwell time on hardness and lap shear force (LSF) by developing L₁₈ Taguchi design. The contribution percentage of each parameter was also calculated using the analysis of variances. It was reported that ultrasonic vibration has a favorable effect on both LSF and hardness of welded joints and has the highest contribution percentage. The optimum condition was determined by grey relational analysis and a combination of applying ultrasonic vibration, 1200 rpm rotational speed, 6 mm tool plunge depth and 6 s dwell time was found to achieve the maximum LSF and hardness. The process parameters in FSW of AA 5083 were modeled and analyzed utilizing response surface methodology. The experiments were conducted according to the central composite design with a total number of 30 experiments.

The process parameters included in this model were traverse speed, rotational speed, tool tilt angle, and dwell time. The responses in the model are tensile strength and elongation. Empirical relationship was summarized between the responses input and process parameters. The established models have revealed that tool rotational speed and tool tilt angle have a more dominant influence on the responses as compared to other parameters [18]. It is clear from the review that there is a shortage in optimizing the UAFSW process. This study aims to analyze the effect of the process parameters such as tool rotational speed, vibration amplitude and traverse speed, in UAFSW process on the tensile properties using the Taguchi technique. In addition, determining the optimum combination of process parameters.

2. EXPERIMENTAL PROCEDURES

2.1. Materials

In this paper, the material used is Aluminum alloy 6082-T61. T61 is the temperature designation and refers to the alloy is solution heat-treated, artificially aged, and then stress relieved by stretching. The chemical compositions and mechanical properties of AA6082-T61 as provided by the supplier are shown in Tables 1 and 2 [11,19].

The dimensions of an aluminum sheet samples are (160×100×3) mm and were cut using an abrasive water jet machine.

The ultrasonic processor was utilized to obtain the required ultrasonic vibration. A vibrating tool head (sonotrode) is considering the critical component of the processor, which evaluates the maximum amplitude and output power of the device, An ultrasonic processor processed by (Hielscher ultrasonics GmbH) was utilized to obtain the required ultrasonic vibration. Ultrasonic vibration waves of amplitude from 20 μm up to 100 μm, frequency of 20 KHz, and a power of 85 Watt were employed [9]. The ultrasonic processor is attached to the head of a milling machine through a suitable attachment as shown in Figure 1. The tool head can move along the welding line ahead of the FSW tool by a distance of 25 mm and with an inclination angle of 60° to keep it away from the tool. Therefore, the ultrasonic vibration waves can be transmitted directly into the workpiece area without any loss in the transmitted energy [11].

TABLE 1. Mechanical properties of AA6082-T61

UTS (MPa)	YS (MPa)	Elongation (%)	Hardness (HV)
320	230	9	112

TABLE 2. Chemical composition of AA6082

Si	Fe	Cu	Mn	Mg	Cr	Ni	Ti	Al
0.9	0.5	0.1	0.7	0.6	0.25	0.2	0.1	REM



Figure 1. Experimental setup including the ultrasonic processor

2. 2. Process Parameters The experiments were carried out to study the effect of the main process parameters involved in UAFSW process (i.e. rotational speed, amplitude and traverse speed) on the joint efficiency besides determining the optimum condition to achieve the maximum joint efficiency using Taguchi technique.

3. DESIGN OF EXPERIMENTS

Taguchi technique is a powerful statistical tool that was utilized extensively in various fields. Taguchi technique is applied to investigate the impact ratio of the process parameters, in addition to, determining the optimum condition in UAFSW process. Taguchi technique with four levels and three factors was applied. The values of the three factors i.e. rotational speed, welding speed, and ultrasonic vibration amplitude are listed in Table 3.

3. 1. Tests and Measurements A tensile test was performed for the welded joints as the ultimate tensile strength was utilized as the output function in TAGUCHI model to express the joint efficiency and quality. The design and planning of the experiments according to TAGUCHI technique with total number of 16 experiments is given in Table 4.

4. RESULTS AND DISCUSSION

4. 1. Optimization of UAFSW Taguchi experimental design technique L_{16} orthogonal array was

TABLE 3. Process parameters and their levels

Process parameter	Range	Level 1	Level 2	Level 3	Level 4
Rotational speed (rpm)	630:1200	630	800	1000	1200
Traverse speed (mm/min)	40:160	40	80	120	160
Amplitude (μm)	20:80	20	40	60	80

TABLE 4. Design and planning of experiments according to Taguchi

	Rot. Speed	Trav. Speed	Amplitude
1	630	40	20
2	630	80	40
3	630	120	60
4	630	160	80
5	800	40	40
6	800	80	20
7	800	120	80
8	800	160	60
9	1000	40	60
10	1000	80	80
11	1000	120	20
12	1000	160	40
13	1200	40	80
14	1200	80	60
15	1200	120	40
16	1200	160	20

to evaluate the effect of the traverse speed, tool rotational speed and vibration amplitude at four levels as control factors, on the UTS of the welded joints resulting from UAFSW process as the response (quality characteristic). As well as determining the optimum condition of process parameters to achieve the best weld quality in terms of the UTS. This is carried out using two measures, namely, signal to noise ratio (S/N ratio) and the mean, which are calculated for each experimental trial. S/N ratio is chosen according to the objective function. In this analysis, the S/N ratio is chosen according to "larger is better" criteria, as the objective function is to maximize the response. In this case, the S/N ratio is estimated from Equation (1) [20]:

$$\eta = -10 \log(n^{-1} \sum Y^{-2}) \quad (1)$$

where, η is the S/N ratio, n is the number of experiments, and Y is the experimental value of the response. On the other hand, the mean for one level is estimated as the average of all responses that are related to that level. Minitab 18.1 software was utilized to perform this analysis. After the experiments were carried out according to Taguchi design of experiments, a tensile test was performed to measure the UTS for each sample. The values of process parameters and the corresponding UTS for each experimental trial are listed in Table 5. ANOVA was also applied to determine the contribution percentage of each process parameter.

4. 2. Taguchi Analysis After running the analysis using Minitab 18.1 software, the experimental data was transformed into S/N ratio values and average means for each control factor under different levels as shown in the response Table 6.

4. 2. 1. Optimum Condition As the better-quality characteristic i.e. UTS corresponds to the larger S/N ratio as observed from the response table. The optimal level of each process parameter can be determined based on the values of the S/N ratio which are provided in the response

TABLE 5. Design of experiment using Taguchi and the corresponding UTS

Test	Control factors			Response
	Rot. Speed (Rpm)	Trav. Speed (mm/min)	Vibr. Amplitude (μm)	UTS (MPa)
1	630	40	20	126
2	630	80	40	120
3	630	120	60	116
4	630	160	80	91
5	800	40	40	188
6	800	80	20	197
7	800	120	80	132
8	800	160	60	121
9	1000	40	60	143
10	1000	80	80	152
11	1000	120	20	137
12	1000	160	40	125
13	1200	40	80	132
14	1200	80	60	154
15	1200	120	40	118
16	1200	160	20	130

TABLE 6. S/N ratios and means for each process parameter at different levels

Level	S/N ratios (dB)			Means (MPa)		
	Rot. Speed	Trav. Speed	Vibr. Amp.	Rot. Speed	Trav. Speed	Vibr. Amp.
1	39.98	42.76	42.71	100.8	140.0	140.0
2	43.5	43.23	42.05	154.5	148.3	130.3
3	42.22	41.03	41.57	129.5	113.3	121.3
4	41.79	40.47	41.17	123.5	106.8	116.8
Delta	3.52	2.76	1.54	53.8	41.5	23.3
Rank	1	2	3	1	2	3

table. It is clear from the results that, rotational speed at level 2 (800 rpm), traverse speed at level 2 (80 mm/min), and vibration amplitude at level 1 (20 μm) are the optimum process parameters condition to obtain the largest UTS. The same result can be realized from the main effect plots for both, the S/N ratios and means as shown in Figures 2 and 3, respectively.

4. 3. Determining the Most Significant Parameter

The response table can be used also to determine the most significant factor, as each factor has its rank. It is clear from the results that, the rotational speed is the most influential factor because it has a higher rank, followed by the traverse speed then followed by the vibration amplitude.

4. 4. Effects of Process Parameters on The Response

The effects of the different process parameters on the response (UTS) can be investigated through discussing and explaining the main effects plots obtained from Taguchi analysis as follows.

4. 4. 1. Effect of Rotational Speed

Figure 3 shows the UTS at various rotational speeds. The lowest value of UTS is at a rotational speed of 630 rpm. This may be attributed to the lower heat input due to using low rotational speed. Low heat input causes inadequate material softening, leading to improper material flow. Thus, the weld joint is incomplete and different defects such as tunnel defects are encountered. The UTS reaches its maximum value at a rotational speed of 800 rpm. On the further increase of the rotational speed, the UTS decrease. This reduction can be explained by the coarsening of grain structures at the weld zone due to the excessive heating resulting from high rotational speeds.

4. 4. 2. Effect of Traverse Speed

The effect of the traverse speed on the UTS is shown in Figure 2. As

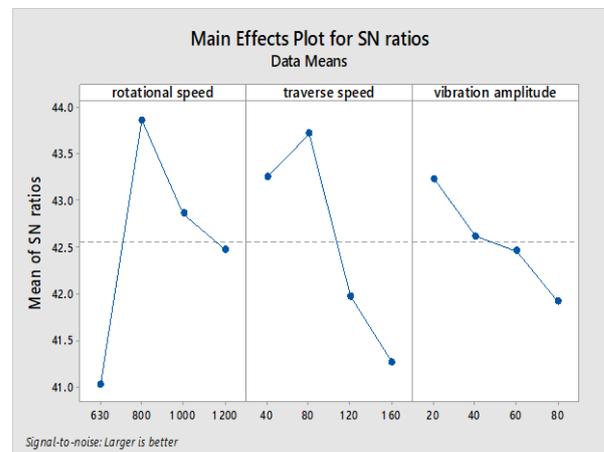


Figure 2. A plot for S/N ratios

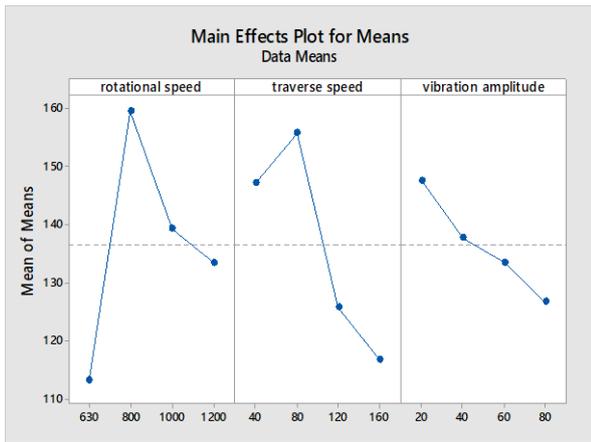


Figure 3. A plot for means

shown from the figure, the optimum value of UTS is at a traverse speed of 80 mm/min. By increasing the traverse speed to 120 mm/min a considerable reduction in the UTS is recorded due to the low heat input and insufficient material plasticization. The worst value of UTS was recorded when a traverse speed of 160 mm/min was applied, where the very low heat input causes insufficient softening leading to significant defects at the weld zone that deteriorate the mechanical properties.

4. 4. 3. Effect of Vibration Amplitude As shown in Figure 3, the maximum value of the UTS is at a vibration amplitude of 20 μm then, the value decreases until reaches its lowest value at a vibration amplitude of 80 μm . From the previous findings, it can be stated that increasing the amplitude of the ultrasonic vibration may cause acoustic hardening leading to a negative effect on the materials flow and subsequently on the UTS of the joints.

4. 5. The Maximum Value of Response at the Optimum Condition One of the powerful tools in Taguchi approach is the ability to predict the value of the response at any experimental condition if even it was not performed. The value of the optimum condition was predicted and a value of 290 MPa was obtained.

4. 6. ANOVA Analysis ANOVA test was conducted using Minitab software to evaluate the process parameters significance which affect the ultimate tensile strength of FSW joints by calculating the contribution percentage for each process parameter. ANOVA results are indicated in Table 7. As shown from the results, the rotational speed is the most prominent factor with a contributing factor of 41.09 % on the UTS of FSW joints, followed by the traverse speed which has a contribution percentage of 37.52 %. The lowest effective parameter is the vibration amplitude with a contribution percentage of 8.57 %. Another type of data that can be obtained from

ANOVA is the interaction plot which is used mainly to show how the relationship between a process parameter depends on the other process parameters, as shown in Figure 4. As shown from the figure, the lines are not parallel and there are intersections between them. This indicates that the relation between one process parameter and the UTS depends on the values of the other parameters. For instance, at a rotational speed of 800 rpm, the value of the UTS is highly affected by the value of the traverse speed and reaches its maximum value at a traverse speed of 80 mm/min and the vibration amplitude of 20 μm .

4. 7. Confirmation Test The final step has to verify the predicted value of the UTS at the optimum condition. An experimental trial was performed at the optimum condition, a rotational speed at level 2 (800 rpm), a traverse speed at level 2 (80 mm/min), and a vibration amplitude at level 1 (20 μm). The tensile test was conducted on the friction stir welded joint which was welded at the optimum condition and UTS of 290 MPa was recorded. While the actual value of the experiment was 297 MPa, here an error of 3.5%, as the percentage of error was realized.

TABLE 7. ANOVA analysis

Source	DF	SS	MS	F-Value	P-Value	% Contribution
RS	3	4344.2	1448.1	6.41	0.027	41.09%
TS	3	3966.8	1322.3	5.86	0.032	37.52%
VA	3	906.3	302.1	1.34	0.347	8.57%
Error	6	1354.5	225.7			12.81%
Total	15	10571.8				100.00%

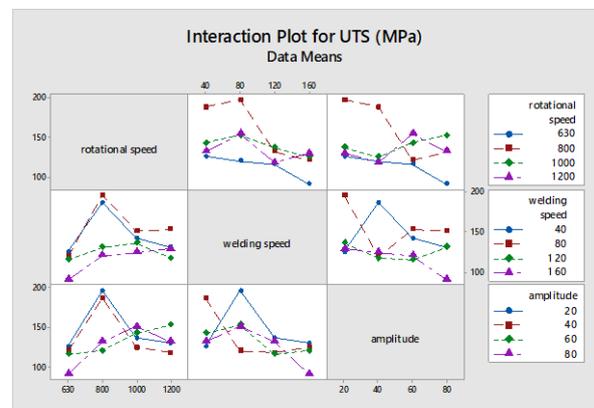


Figure 4. Interaction plots for means of UTS

5. CONCLUSIONS

The Ultrasonic-assisted FSW process was optimized using Taguchi technique to evaluate the optimum condition of process parameters and analyzing the process parameters effect on the joint quality using the UTS as the objective function. The results showed that a vibration amplitude of 20 μm , a traverse speed of 80 mm/min and a rotational speed of 800 rpm are the optimum condition to achieve the highest UTS. The predicted value of the UTS at the optimum condition is 290 MPa which is in a good agreement with the actual value of 297 MPa with 3.5% error. Rotational speed was found to be the most effective parameter. The effect of each process parameter was investigated. A reduction in the UTS value was realized by reducing the rotational speed and increasing the traverse speed and this can be attributed to the fall in the heat input which results in inadequate softening and improper material flow. Increasing the vibration amplitude larger than 20 μm can cause acoustic hardening rather than acoustic softening leading to a decrease in the UTS.

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Persian Abstract

چکیده

فرآیند جوشکاری اصطکاکی اغتشاشی یکی از روش های جوشکاری حالت جامد است. از سوی دیگر، فرآیند FSW دارای محدودیت هایی مانند سرعت کم و گشتاور بالا است که بهره وری و کاربرد فرآیند را محدود می کند. برای غلبه بر این محدودیت ها، چندین منبع انرژی ثانویه با فرآیند FSW ادغام شدند. در مقاله حاضر، FSW توسط انرژی ارتعاشی اولتراسونیک در فرآیندی به نام جوشکاری اغتشاشی اصطکاکی به کمک اولتراسونیک (UAFSW) عمل می کند. هدف این مقاله بهینه سازی پارامترهای فرآیند اصلی فرآیند UAFSW با استفاده از 4 سطح برای هر پارامتر با مجموع 16 آزمایش تجربی با استفاده از تکنیک تاگوچی است تا به جوشکاران کمک کند تا پارامترهای مناسب را برای دستیابی به بالاترین راندمان اتصال از نظر نهایی انتخاب کنند. استحکام کششی (UTS) پارامترهایی که باید بهینه شوند عبارتند از دامنه ارتعاش (20-80 میکرومتر)، سرعت تراورس (40-160 میلی متر در دقیقه) و سرعت چرخش ابزار (630-1200 دور در دقیقه). علاوه بر این، تجزیه و تحلیل ANOVA برای تعیین درصد مشارکت هر پارامتر فرآیند استفاده گردد. تأثیر هر پارامتر فرآیند بر UTS نیز مورد بررسی و تجزیه و تحلیل قرار گرفت. نتایج نشان داد که شرایط بهینه 20 میکرومتر، 80 میلی متر در دقیقه و 800 دور در دقیقه است. تجزیه و تحلیل ANOVA نشان داد که سرعت چرخش مهم ترین پارامتر است. UTS 290 مگاپاسکال توسط مدل پیش بینی می شود که در آن مقدار واقعی 297 مگاپاسکال با درصد خطای 3.5 درصد است.