Wasit Journal of Engineering Sciences
VOLUME: (7), NO. : (1) 2019

Optimization of Process Parameters of Friction Stir Welding by Taguchi Method

Azzam Sabah Albunduqee, Hussein R.Al-Bugharbee

Department of Mech. Eng., University of Wasit, Iraq
***Corresponding author* Dr.azzamaalkasy@gmail.com

Submitted: 23/1/2018
Accepted: 3/6/2018

Abstract. *Friction Stir Welding is one of the technologies of joining solid states, which still attracts the researchers' interest. In welded joints the mechanical properties are affected by a number of mechanical properties of the joined materials and by the process parameters as well. In the present study, the effect of a number of friction stir welding parameters on the tensile strength of the welded joint have been investigated using the Taguchi method and the analysis of variance (ANOVA). The study considers different levels of friction stir welding variables; namely, different rotational speeds of (2000, 1600, 1250 rpm), different welding speeds (12.5, 16, 20 mm / min), and different welding tilt angles (0, 1, 2 degrees). The optimum process parameters and their contribution rate were selected based on the Taguchi method for test design and by using the Minitab 16 program. In this study, the best results (i.e, higher tensile strength) were obtained at a rotational velocity of 1600 rpm, linear velocity of 16 mm / min, and welding angle, 1o. The highest tensile strength was obtained under these conditions.*

Keywords *:- Friction stir welding, Taguchi method, ANOVA, process parameters*

امثلية متغيرات عملية اللحام بالخلط الاحتكاكي باستخدام طريقة تاكوشي

عزام صباح البندقي، حسين رزاق صباح

الخلاصة:- يهدف البحث الى التحقق من تأثير متغيرات الخلط الاحتكاكي على مقاومة الشد لوصلات لحام سبائك الالمنيوم، تم اجراء اللحام عند عدة ظروف ومتغيرات حيث تم استخدام سرع دوران مختلفة لعدة اللحام (2000,1600,1250) دورة في الدقيقة وسرع خطية مختلفة لعدة اللحام(12,5 ، 16 ،20) مع تغيير زاوية اللحام(0 و1 و2) درجة. تم اظهار النتائج باستخدام طريقة تاكوشي لتصميم التجارب باستعمال برنامج(Minitab 16) لغرض تحديد الظروف المثلى لعوامل عملية اللحام المشار اليها في اعلاه ومعرفة تأثير قوة القص العظمى لوصلة اللحام ونسبة المساهمة لكل عامل.افضل النتائج التي تم الحصول عليها كانت عند السرعة الدورانية (1600 دروة / دقيقة) وسرعة خطية (16 ملم / دقيقة) وزاوية لحام (o1) حيث تم الحصول على اعلى مقاومة شد عند هذه الظروف

الكلمات المفتاحية:- لحام الخلط الاحتكاكي ، طريقة تاكوجي، تحليل معامل الاختلاف، اختبار الشد

1. Introduction

Friction stir welding (FSW) is a process of joining solid states, which was invented in the beginning of the 1990s, at the British Welding Institute [1]. In this process, the joined material does not melt during the welding operation. The FSW has been successfully and popularly used for joining parts made from aluminum alloys as the traditional welding methods shows poor performance.

The problems arising from joining aluminum alloys using the traditional melt welding methods encouraged the researchers to develop new joining methods. When joining aluminum alloys with the fusion–welding methods, the high input of heat may expose these materials to high thermal expansion and crack formation in the welding seam, due to the wide solidification intervals.

The study of the mechanical properties of the FSW joints are conducted in [2]. In that study, the joined material is made from an AA6013-T6 sheet of 3.6 mm thickness, using the FSW process. In this study, the FSW is carried out at 1200-rpm and 1 m/min welding linear speed. The results obtained in this study show that the base material and the welding zone have a homogenous distribution of Mg_2Si particles. The study in Ref. [3] investigated the mechanical properties and the microstructure of the welded zone using different tool pin profiles and diameters. The welded sample is made from AA2218-T72 aluminum alloy sheet of 3.8 mm thickness. It was deducted that the sample used in the experiment can be successfully welded using a threaded, cylindrical 5-mm diameter pin, at 900 rpm and a welding speed of 0.03 m/min. In Ref.[4] the hardness and strength of the FSW joint were investigated under different rotational and transverse tool speeds. In the experiment, the FSW was applied to join two pieces made of different aluminum alloys (i.e., AA 5383 and AA7075). The study showed that using 700 rpm as the rotational speed and 0.04 m/min as the transverse speed produced the best hardness and strength of materials of the welded region. The study in Ref.[5] compared the microstructure and mechanical specifications of the FSW aluminum base joints with those corresponding to conventional Tungsten inert gas (TIG) welding. The comparison showed that the joints produced by using FSW, with optimum process parameters, were more efficient than those produced by TIG welding, in terms of the ultimate tensile strength of the joint. In Ref. [6] the researchers investigated the impact of heat treatment of the welded zone on the efficiency (i.e., microstructure and mechanical properties) of the welded joint. It was found that post heat treatment affected the yield and ultimate stress of the joint negatively, whereas, it enhanced the elastic strain of the welded zone. The mechanical properties and the microstructure of the FSW of two different alloys under the post heat treatment effect were investigated in [7]. In that study, the effect of post heat treatment on the microstructure and mechanical properties was also investigated. In addition, the two joined materials were different, but had the same thickness. The results of that study highlighted the fact that aging treatment caused homogenous precipitation and consequently improved the ultimate tensile strength of the welded joint. Another recent study focused on the effect of pin geometry on the mechanical and structural properties of the FSW joint as in [8]. In reference [9], a study was performed on the effect of the plate position parameter on the tensile strength of the joint.

In FSW, a tool with a specific rotational speed is pressed onto the interface between two work pieces. This contact (between the tool and work piece) causes an increase of heat and consequently plastic deformation occurs. Many articles have aimed to optimize the FSW parameters, such as, the linear and angular speed of the tool. The optimum FSW parameters can be defined as those parameters that provide the best mechanical parameters in the FSW zone. Although numerous articles have been published, there are still gaps that need further investigation and analysis to control the FSW process and result in better mechanical properties. One example of these gaps is the investigation of the effect of the tool tilt angle that was not investigated sufficiently in literature. One of the main goals of the present article is to consider the effect of the tool tilt angle, besides other parameters, on tensile strength of the FSW joint.

The rest of the article is divided into: The second section describes the methodology used in the present study. Section three describes the experimental work that has been conducted to obtain the data for analysis. Results and their discussion are described in the fourth section. Finally, a number of conclusions are made in section 5.

2. METHODOLOGY

In this study the effect of three main parameters on tensile strength of the welded joint are investigated, namely, tool rotational speed, linear speed, and tool tilt angle. There are three levels for each parameter as shown in Table1.

Table 1 FSW parameters and design levels

Process parameters	Level 1	Level 2	Level 3
Total rotation Speed (RPM)	900	1300	1600
Welding Speed (mm/min)	40	60	80
Tilt angle (degrees)	0	1	2

In order to choose the least number of necessary experiments, the Taguchi method is adopted. The (3 x 3) orthogonal array is subjected to the Taguchi method using the Minitab software package, Minitab 16.

This section explains the FSW process used in the experimental part of the present study. A double jaws vice is used to clamp the samples during the FSW process.

The FSW starts with initiating a small hole where the tool pin is contacted. This hole helps to position the tool pin without the need for much load. Then with a specific rotational speed and transverse speed the tool is fed along the required path. The rotational and transverse speed of the cutting penetrating tool causes an increase in frictional heating due to the rubbing of the sample part which the tool contacts. With this increased heating, the tool stirs and deforms the heated sample part.

The S/N ratio can be described as the variation in the process. This ratio is utilized to indicate the key contributing factors that cause variation in tensile strength T.S has a “higher-the-better” type response and it is given by a logarithmic function based on the mean square deviation:

$$(S/N)_{HB} = -10\log (MSD)_{HB} \quad (3.1)$$

$$\text{where } MSD_{HB} = \frac{1}{y_i^2} \quad (3.2)$$

3. EXPERIMENTAL WORK.

In the present study, two 180 mm × 70 mm × 6 mm samples are used in the experiment, as shown in Figure .1. They are made of aluminum alloy where the chemical compositions are listed in Table 2.

Figure 1. Aluminum alloy samples before FSW process

The chemical composition percentages of the Al alloy are illustrated in the Table 2.

Table 2. Chemical composition of Al Alloy

Element	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Pb	Al
Wt. %	0.12	0.29	4.2	0.6	1.2	0.01	0.01	0.16	0.016	0.009	Bal

The FSW process is achieved by using a milling machine. The milling machine is supported with various clamps so that variable welding possibilities can be achieved (see Figure 2).

Fig 2. FSW machine, (1) machine vice, (2) supporting plate

The FSW tool, which is used for performing the FSW, was made of high carbon, high chromium steel, which is hardened by oil media to get 62 HRC steel in the shape of a cylinder, of a non-constant, cross-sectional area. The top part that will be holding the milling machine jaw has a 17-mm diameter. The bottom part that can also be called the shoulder has a 19-mm diameter. At the very end of the shoulder there will be a chamfered 6-mm pin that will be responsible for softening and mixing the substance of the work pieces during the FSW (see Figure 3).

Figure 3 FSW horn tool geometry

The FSW process starts by aligning the two work pieces together and gripping them with the help of some clamps. Next, the FSW tool is pressed at the edge of the plates contact line. The FSW tool is rotated at a certain speed and it is fed along the plates contact line with a certain linear speed. In the experiment, various rotational, linear speeds and various tool-tilting angles were considered. The plates were welded in a single pass. Figure 4 shows the two workspaces after the FSW process and the samples provided.

Figure 4.(Lef - aluminum plates after the FSW process; Right - cutting the plates to provide more samples

4. RESULTS AND DISCUSSION

A number of samples have been subjected to the tensile test. The ultimate tensile strength was recorded for all the samples used in the experiment. As mentioned above, these samples were produced under different FSW parameters. Figure 5 shows an example of broken samples after the application of tensile test.

Figure (5): - The FSW samples after tensile test

The tensile strength of the FSW joint was obtained experimentally for each of the pre-determined designed experimental parameters, as shown in Table 3

Table 3: Experimental results of the nine trials

NO	Rotation Speed (RPM)	Linear speed (mm/min)	Angle of Tool (Ɵ)	S/N Ratio	Tensile Strength (MPa)
1	1250	12.5	0	27.50595	23.73
2	1250	16	1	46.5484	212.53
3	1250	20	2	46.23792	205.067
4	1600	12.5	1	47.27976	231.2
5	1600	16	2	46.10991	202.067
6	1600	20	0	28.859	27.73
7	2000	12.5	2	26.68908	21.6
8	2000	16	0	28.43208	26.4
9	2000	20	1	43.19916	144.53

The results shown in the last two columns will be further analyzed by the ANOVA analysis. Table 4, shows the results of the ANOVA analysis.

Table 4: Analysis of Variance for Tensile Strength, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P	C%
Rotation speed	2	14929	14929	7465	2.22	0.311	20.8
Linear speed	2	4585	4585	2292	0.68	0.595	6.4
Angle	2	45452	45452	22726	6.75	0.129	63.4
Error	2	6735	6735	3368			9.4
Total	8	71701					100

S = 58.0303 R-Sq = 90.61% R-Sq(adj) = 62.43%

From the results shown in the last column of Table 4, it can be clearly seen that the total contribution of both tool rotational speed and linear speed are much less than the tool's angle contribution. Among the three parameters analyzed in this study, the tool angle has the greatest contribution, whereas, linear speed has the minimum. This is also confirmed by the output of the most recent study in [10].

Table 5 illustrates the S/N ratio of the three different levels of each FSW parameter. It can be seen that the difference between maximum and minimum values of the S/N ratio (i.e., delta) corresponding to the FSW parameters are shown in the fifth row of the table. The rank of the FSW effectiveness can be determined based on the delta values, as shown in the last row of the table. This means that the parameter that has the first rank is that parameter which has the highest delta value and vice versa. For the data shown in Table 5, it is found that the tool tilt angle has the greatest effect on the tensile strength, whereas, the linear speed has the last rank.

Table 5:- Response Table for Signal-to-Noise Ratios, Larger is better

Level	Rotation Speed	Linear Speed	Angle
1	40.10	33.82	28.27
2	40.75	40.36	45.68
3	32.77	39.43	39.68
Delta	7.98	6.54	17.41
Rank	2	3	1

Table 6 shows the rank of the FSW parameters based on the mean values of the tensile strength. Each of the FSW parameters considered in this analysis is also ranked based on the delta value. It can be clearly seen that the rank of the parameters is similar to the rank obtained based on the S/N ratio.

Table 6. Response Table for Means

Level	Rotation Speed	Linear Speed	Angle
1	147.11	92.18	25.95
2	153.67	147.00	196.09
3	64.18	125.78	142.91
Delta	89.49	54.82	170.13
Rank	2	3	1

Figure 3 shows the relation between the FSW parameters (i.e., rotational speed, linear speed, and tool angle) and the tensile strength. It can be seen that the maximum tensile strength of the welded joint can be obtained at 1600 rpm for tool rotational speed, 16 mm/min for transverse speed, and 1 degree for the tool angle.

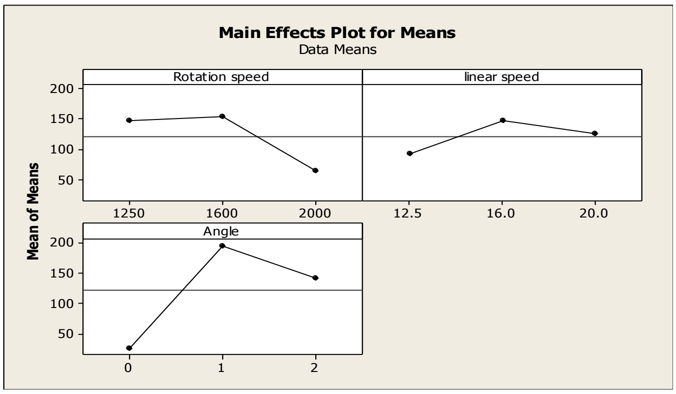

Figure 4:- Main effect plot for Tensile Strength

Figure 5 shows the relation between the FSW parameters (i.e., rotational speed, linear speed, and tool angle) and S/N ratio. It can be seen that the maximum tensile strength of the welded joint can be obtained at 1600 rpm for tool rotational speed, 16 mm/min for transverse speed, and 1 degree for tool angle.

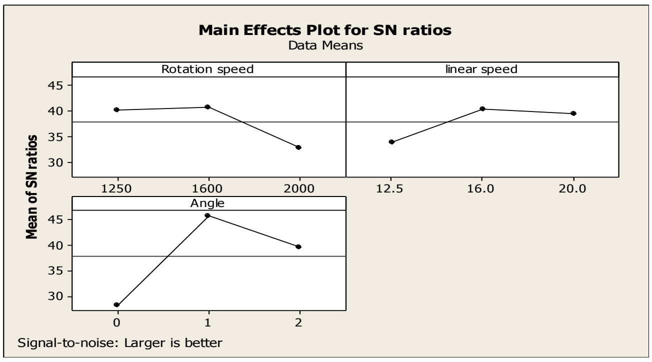

Figure 5:- Mean of S/N ratio effect plot for tensile strength

It is shown in the results that the rotational speed has a clear effect on tensile strength of the welded joints. The increase in rotational speed improves the tensile strength value to a certain point, and then increasing the rotation speed reduces the tensile strength. This can be interpreted as, increasing the rotational speed will increase the generated frictional heat that helps in softening the welded materials. However, excessive heat that might be generated from higher rotational speed can lead to the material starting to melt, which consequently affects the welding process and the microstructure of the welded joint.

For the linear speed effect, the results showed that higher linear speed results in lower tensile strength. This can be explained by the fact that applying higher feeding speed reduces the time of exposure to the generated frictional heat. This might consequently lead to the generation of defects in the welded joints.

The results also showed that compared to the other FSW parameters; the tool tilt angle has the greatest effect on the tensile strength of the welded joint. It is observed that the tensile strength increases with the increase of the tool tilt angle and then it decreases. This can be mainly explained by tilting the angle from 0 to 1 degree, which improves the mixing of the joint substance and consequently the tensile strength is improved. However, when the tilt angle increases to 2 degrees, possible defects might be formed and consequently the joint tensile strength decreases.

This is because the inclination of the tool means lifting the pin tip from the welded joint base and as a result insufficient quantity of material will flow and thus there will be unfilled regions.

5. CONFIRMATION EXPERIMENTS FOR OUTPUT FACTORS

The final step of the Taguchi method involves the confirmation experiments conducted for examining the quality characteristics. The confirmation experiments are performed to validate the conclusions of the above analysis. The results of the experimental confirmation using optimal parameters are shown in Table 7.

Table 7: Results of confirmation experiments

Response	Optimal condition	Predicted	Experiment	% Error
T.S	A2 B2 C2	142.59 MPa	150.5	5.26

CONCLUSIONS

In the present research, ANOVA and the Taguchi method are utilized for the purpose of optimization of FSW process parameters. The FSW is conducted to join two pieces of Aluminum alloy. For the data used in this analysis, the optimum parameters that provide the best mechanical properties are 120 m/min transverse speed, 1600 rpm rotational speed, and a tool angle of only one degree. Utilizing such process parameters results in a joint tensile strength of 142.59 MPa. The analysis also shows that the tool rotational speed has minimum significance on the joint of tensile strength, whereas, the tool angle has the maximum significance.

REFERENCES

1.W. THOMAS, E. NICHOLAS, J. C. NEEDHAM, M. MURCH, P. TEMPLESMITH, AND C. DAWES, "FRICTION STIR WELDING," INTERNATIONAL PATENT APPLICATION NO. PCT/GB92102203 AND GREAT BRITAIN PATENT APPLICATION, (1991).

2.H. KAFALI AND N. AY, "MECHANICAL PROPERTIES OF 6013-T6 ALUMINIUM ALLOY FRICTION STIR WELDED PLATE," IN 13TH INTERNATIONAL CONFERENCE, AEROSPACE SCIENCES & AVIATION TECHNOLOGY, 2009.

3.Q. DOOS AND S. MAHMOOD, "THE INFLUENCE OF TOOL GEOMETRY OF FRICTION STIR WELDS ON MECHANICAL PROPERTIES AND MICROSTRUCTURE OF 2218-T72 ALUMINUM ALLOY," J. ENG, VOL. 17, PP. 1242-1259, (2011).

4.G. R. A. D. A. S. SIVACHIDAMBARAM, "OPTIMIZING THE PARAMETERS FOR FRICTION STIR WELDING OF DISSIMILAR ALUMINIUM ALLOYS AA 5383/AA 7075," ARPN JOURNAL OF ENGINEERING AND APPLIED SCIENCES, VOL. 10, P. 4, (2015).

5.M. K. A. A. H. H. ABD, "A COMPARISON STUDY OF MECHANICAL PROPERTIES BETWEEN FRICTION STIR WELDING AND TIG WELDED JOINTS OF ALUMINUM ALLOY (AL 6061-T6," ENG. &TECH. JOURNAL, VOL. PART (A), PP. 2701-2715, (2013).

6.R. SINGH, C. SHARMA, D. DWIVEDI, N. MEHTA, AND P. KUMAR, "THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF FRICTION STIR WELDED AL–ZN–MG ALLOY IN AS WELDED AND HEAT TREATED CONDITIONS," MATERIALS & DESIGN, VOL. 32, PP. 682-687, (2011).

7.P. M. KRISHNA AND N. RAMANAIAH, "EFFECT OF POST-WELD HEAT TREATMENT ON THE MECHANICAL PROPERTIES OF FRICTION STIR WELDS OF DISSIMILAR ALUMINUM ALLOYS," IJEST, VOL. 3, PP. 5778-5785, (2011).

8.I. Z. RADISAVLJEVIĆ, A. B. ŽIVKOVIĆ, V. K. GRABULOV, AND N. A. RADOVIĆ, "INFLUENCE OF PIN GEOMETRY ON MECHANICAL AND STRUCTURAL PROPERTIES OF BUTT FRICTION STIR WELDED 2024-T351 ALUMINUM ALLOY," HEMIJSKA INDUSTRIJA, VOL. 69, P. 323, (2015).

9.S. BAYAZID, H. FARHANGI, AND A. GHAHRAMANI, "INVESTIGATION OF FRICTION STIR WELDING PARAMETERS OF 6063-7075 ALUMINUM ALLOYS BY TAGUCHI METHOD," PROCEDIA MATERIALS SCIENCE, VOL. 11, PP. 6-11, (2015).

10.K. K. D.DEVAIAH, P. LAXMINARAYANA, "PARAMETRIC OPTIMIZATION OF FRICTION STIR WELDING PARAMETERS USING TAGUCHI TECHNIQUE FOR DISSIMILAR ALUMINUM ALLOYS (AA5083 AND AA6061)," IOSR JOURNAL OF ENGINEERING, VOL. 3, PP. 44-49, (2017).