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Optimization of Friction Stir Welding Process Parameters to joint 7075-T6 Aluminium Alloy by Utilizing Taguchi Technique

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ABSTRACT

In this study, a 3 mm thickness 7075-T6 aluminium alloy sheet was used in the friction stir welding process. Using the design of experiment to reduce the number of experiments and to obtain the optimum friction stir welding parameters by utilizing Taguchi technique based on the ultimate tensile test results. Orthogonal array of L9 (3^3) was used based on three numbers of the parameters and three levels for each parameter, where shoulder-workpiece interference depth (0.20, 0.25, and 0.3) mm, pin geometry (cylindrical thread flat end, cylindrical thread with 3 flat round end, cylindrical thread round end), and thread pitch (0.8, 1, and 1.2) mm) this technique executed by Minitab 17 software. The results showed that the optimum friction stir welding parameters were 0.25 mm shoulder-workpiece interference depth, cylindrical thread flat end pin shape, 1.2 mm thread pitch depending on the S/ N ratio and ANOVA analysis and the welding efficiency was 93.3% based on the ultimate tensile stress.

Key words: friction stir welding, AA7075, Taguchi technique, design of experiment, tool shape

امثليه عوامل عملية اللحام بالاحتكاك والخلط لربط لسبائك الألمنيوم (7075-T6) باستخدام تقنية تاكوجي

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الخلاصة

في هذه الدراسة، تم استخدام صفائح من سبائك الألومنيوم بسمك ٣ ملم ٧٠٧٥-T6 في عملية اللحام بالاحتكاك والخلط. تم استخدام طريقة تصميم التجارب لتقليل عدد التجارب وللحصول على القيم المثلى لمتغيرات عملية اللحام بالاحتكاك والخلط باستخدام تقنية (Taguchi) وبالاعتماد على نتائج مقاومة الشد القصوى للملحومات، حيث تم استخدام المصفوفة المتعامدة (L9) اعتماداً على ثلاثة قيم من متغيرات العملية وثلاثة مستويات لكل متغير حيث كان مقدار عمق التداخل هو (٠,٢، ٠,٢٥، ٠,٣) مليميتر وشكل النتوء هو(اسطواني مسنن ذات نهاية مستوية، اسطواني مسنن ذات نهاية مدورة، و اسطواني مسنن مع ٣ شقوق مستوية ذات نهاية مستديرة) وخطوة التسنين للنتوء هي (٠,٨، ١، و ١,٢) مليميتر، تم تنفيذ هذه التقنية باستخدام برنامج (Minitab 17). أوضحت

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النتائج ومن خلال استخدام تقنية (نسبة الإشارة إلى الضوضاء signal to noise ratio) وإجراء تحليل التباين (ANOVA) إن القيم المثلى لمتغيرات عملية اللحام هي (٠,٢٥) مليميتر لعمق التداخل، (أسطواني مسنن ذو نهاية مستوية) لشكل النتوء، و (١,٢) مليميتر لخطوة تسنين النتوء. وتم الحصول على كفاءة اللحام (٩٣,٣%) اعتماداً على مقاومة الشد القصوى للمنطقة اللحام عند تطبيق هذه الظروف.

الكلمات الرئيسية: لحام الاحتكاك والخلط، 7075، تقنية تاكوجي، تصميم التجارب، شكل العدة.

1. INTRODUCTION

Friction stir welding (FSW) was conceived at the welding institute (TWI) of the United Kingdom in 1991 as a solid-state joining process, **Mishra and Mahoney, 2007**, that produce a weld joint between two (or more) workpiece (WP) by the friction heat and plastic material displacement created by a high rotating tool that traverses along the weld joint. Even though the FSW technique was initially used to weld the aluminum alloys, and it developed for joining other metals, including magnesium, copper, zinc, bronze, titanium, lead, and steels, as well as polymers and composites, **Kumar and Ramana, 2014**. The FSW is useful to weld the butt, lap, T, and others joints configuration in an enormous range of metals thickness and length**, Schwartz, 2011**. It was used to weld dissimilar materials combinations, specifically those with close melting temperatures and comparable behavior like hot workability, **Cam, 2011**. Many alloys cannot be welded by fusion welding but can be welded through friction stir welding process.

The FSW process including four main stages: plunging stage, dwelling stage, welding stage and cooling stage (pull out), as shown in the **Fig. 1**.

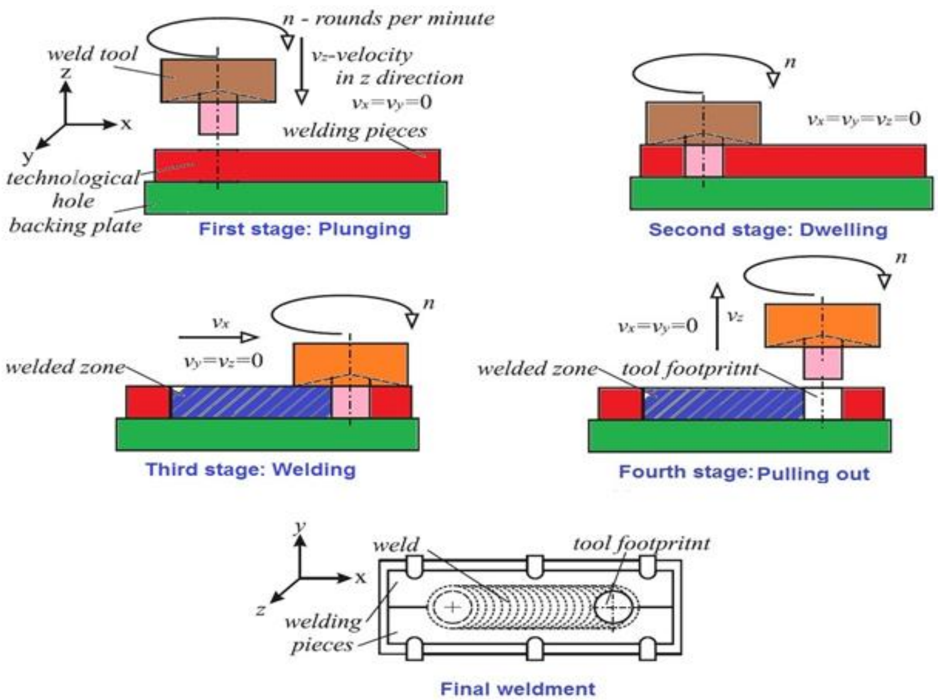


Figure 1. Main stages of the FSW process, **Đurđanović, et al., 2009**.

The FSW process is performed by inserting the rotating pin that has been specially designed into the WPs and then moving it along the welding line. The tool is recognized by a small tilting angle to restrict the contact between the tool shoulder and the WP to about half of the surface of the shoulder. When the pin is immersed in the WP, the material around pin reach the soft state without melting because of heat resulting from friction and deformation and the reverse extrusion process of the plasticised material leading to raise it to the shoulder cavity, then forged by the trailing edge of the shoulder. As the material had been softened, the FSW tool is easily moved along the welding line and kept the pin tool from breaking or damaging. The tool rotation speed and welding speed, axial force, shoulder-workpiece interference (SWI) depth, and others FSW parameters are responsible for the heat generation of the material attributed to the friction forces and material deformation.
Many researchers were studied the optimization of FSW process parameters by applying design of experiment (DOE) by utilizing Taguchi technique where, **Bhadoria, et al., 2015,** investigated an effective method for optimization the FSW process parameters of AA 6101 that has 6mm thickness. Process parameters have been taken into consideration were tool rotation speed TRS and the welding speed WS. Analysis of these parameters was done and optimize results were obtained by using Taguchi method at the 1250 rpm TRS & 20 mm/min WS. It is noticed that the highest contribution to the impact on tensile strength was 23% to TRS and the lowest was 16% to WS. **Gopi and Manonmani, 2012**, studied the impact of shoulder shape and shoulder plunge on the joints strength of FSW AA6082. Experiments are executed for different combinations of TRS, WS, pin profile, shoulder shape, shoulder plunge at five levels in Taguchi's orthogonal array. The highest tensile strength was obtained when using 1300 rpm TRS, 3.2 mm/sec WS, hexagonal pin shape, 0.08 mm shoulder plunge, and convex 5° shoulder. From the ANOVA found that the more influential parameters of the process are TRS and the lowest is shoulder shape.

2. DESIGN OF EXPERIMENT (DOE)

Design of experiment (DOE) is a concatenation of test in which make significant changes to the variables that input into the process and measured the impact on the response variables. The DOE is an efficient path to maximizing the volume of information obtained as well as minimizing the volume of data to be gathered with a reducing the number of tests, **Telford, 2007**.

3. TAGUCHI TECHNIQUE

Taguchi technique is an orderly and functional path for performing experiments and define nigh optimum settings of the parameters design for performance and cost. In this technique was used the orthogonal arrays to studied a great number of variables with a little number of experiments. Dr. Genichi Taguchi who advanced a technique for DOE to studied how different parameters impact on the mean and variance of a process characteristic which determines the quality of the process. Much of the Taguchi technique was traditional where orthogonal arrays are 2-level, 3-level, and mixed-level fractional-factorial designs**, Hvalec, et al., 2004**. The unrivaled sides of his approach are utilized of signal and noise factors, inner and outer arrays, and signal-to-noise ratios. The essential aim of the Taguchi technique is to design a strong system that is efficacious under uncontrollable conditions. The purpose of this technique was to determine the parameters of design recognized as control factors to their optimal levels so that the system response is powerful and insensitive to noise factors that were difficult to control. The advantage of this technique was that it confirms the value of the mean was close to the target value rather than a value within nominated specification limits, thus enhancing the product quality, also can be used to readily narrow the area of a research plan or to recognize problems in a manufacturing process from data previously in subsistence. The main disadvantage of the Taguchi technique was that the results gained are only relative and do not nicely indicate what parameter has a big influence on the performance characteristic value, **Karna, et al., 2012**.

To study the effect of the shoulder-workpiece interference (SWI) depth, pin geometry, and threaded pitch of the pin on the welding efficiency by using DOE and Taguchi technique to obtain the optimum FSW parameters and reduce the number of experiments and thus reduce the cost and time.

4. SIGNAL-TO-NOISE RATIO (S/N)

The S/N ratio was used to take care of the sensitivity of quality characteristic which is tested in controlled ways. The expression signal illustrates the desirable effect the mean for the output feature and the expression noise illustrate the undesirable effect for the output feature which affects the outcome since the factors were outer called noise factors. Typically, there are three types of the quality features were used in the S/N ratio including, the nominal-the-better, the larger-the-better, and the lower-the-better, **Kamaruddin, et al., 2010**.

5. ANALYSIS OF VARIANCE (ANOVA)

The ANOVA is a statistical processing, which can be beneficial for determining the impact of specific input parameters from a series of EXPs results by DOE for the process. It is used to calculate some quantities such as degrees of freedom (DOF), mean squares (V), the sum of squares (S), etc. and regulated them on a standard table format. The effect of individual parameters on the entire process cannot be determined when using Taguchi method while can determine the proportion of the contribution of these parameters using ANOVA, **Stephanie, et al., 2006**.

6. EXPERIMENTAL WORK

6.1 Material Selection

A 3mm sheet thickness high strength aluminium alloy AA7075-T6 was utilized in this work, the chemical composition is listed in **Table 1** and the mechanical properties are mentioned in **Table 2**. The specimens to be welded were cut and machined to the final dimensions (200×100×3) mm, considering the rolling direction is perpendicular to the welding direction.

Table 1. Chemical compositions of AA7075-T6.

Element%	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other	Al
Measured	0.101	0.332	1.73	0.075	2.44	0.213	5.68	0.031	0.056	Bal.
Standard	≤ 0.4	≤ 0.5	1.2-2.0	≤ 0.30	2.1-2.9	0.18-0.28	5.1-6.1	0.2	0.056	Bal.

Table 2. Mechanical properties of AA7075-T6.

	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Vickers Hardness (HV)
Measured	496	525	170
Standard	470 min	510 min	165 min

The composite tool consists of two separate parts shoulder and pin (probe). A concave surface shoulder of 6 º, made of ASTM H13 tool steel with 15mm diameter, the pin material is Cobalt-based superalloys MP159, 5mm diameter, and 2.7mm length.

The FSW was executed on a CNC vertical milling machine type MITSUBISHI M70V. For the reason of a fixed spindle head, a special designed and manufactured adjustable-angle fixture was designed and manufactured included a backing plate. It can be tilted by a range of inclinations included but not limited to 2º. As shown in **Fig. 2**.

Figure 2. The backing plate and fixture tilted in 2° set up on the table of the machine.

6.2 Determining the Welding Parameters and their Levels

The FSW parameters were selected in this study implicate the SWI depth of 0.20, 0.25, and 0.30 mm, pin shapes of cylindrical thread flat end (CTFE), cylindrical thread round end (CTRE), and cylindrical thread with 3 flats round end (CTRFE), and threaded pitch of 0.8, 1, 1.2 mm these parameters are collected in the **Table 3**., and other parameters remained constant. After determining the FSW parameters and levels should be calculated the degree of freedom (DOF) because of the Taguchi design used it to determine the number of EXP runs. DOF refers to the number of ways that system can independently vary when a constraint is imposed. The total number of EXP runs equal to (1+(Sum. of DOF)) as shown in **Table 4**. So the orthogonal array should be greater than the total number of DOF. By using Minitab 17 Software, orthogonal-array (L9) was selected as shown in **Table 5**. This array has nine EXP runs as shown in **Table 6.**

Table 3. Parameters and their levels of FSW process.

Parameters	Level 1	Level 2	Level 3
SWI Depth (mm)	0.20	0.25	0.30
Pin shape	CTFE	CTRE	CTFRE
Threaded Pitch (mm)	0.8	1	1.2

Table 4. DOF and total numbers of EXP.

Parameters	Level	DOF = (Level-1)
SWI depth (mm)	3	2
Pin shape	3	2
Threaded pitch (mm)	3	2
Total DOF		6
Total no. of EXP runs = (1+∑ DOF)		7

Table 5. (L9) orthogonal array Taguchi technique.

Experiment No.	SWI depth (mm)	Pin Shape	Threaded Pitch (mm)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 6. DOE - (L9) Taguchi technique.

Experiment no.	SWI depth (mm)	Pin Shape	Threaded Pitch (mm)
1	0.20	CTRE	0.8
2	0.20	CTFE	1.0
3	0.20	CTFRE	1.2
4	0.25	CTRE	1.0
5	0.25	CTFE	1.2
6	0.25	CTFRE	0.8
7	0.30	CTRE	1.2
8	0.30	CTFE	0.8
9	0.30	CTFRE	1.0

After accomplish FSW process as shown in **Fig. 3**, all experiments (nine experiments), specimens for the tensile test were performed by using CNC wire Electrical Discharge Machine perpendicular to the welding direction in dimensions as shown in the **Fig. 4.**

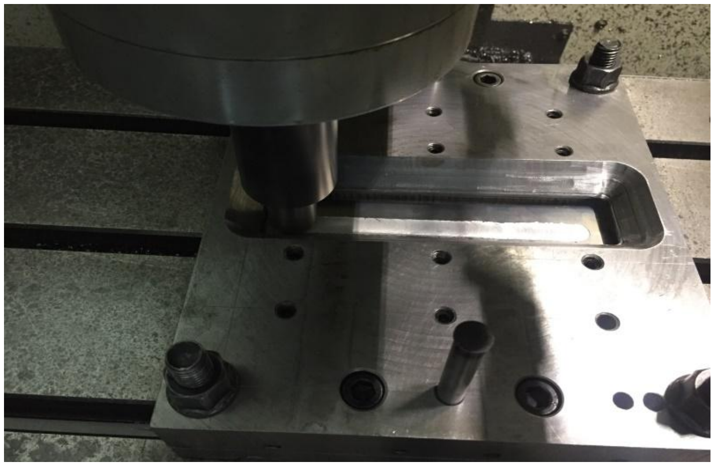
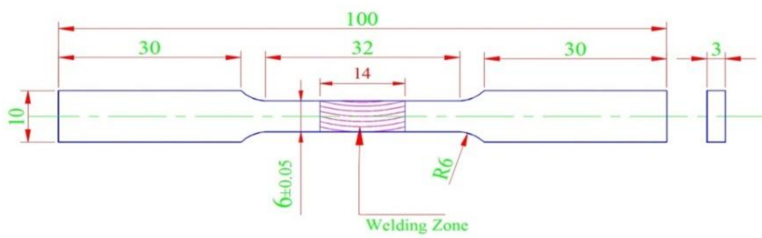
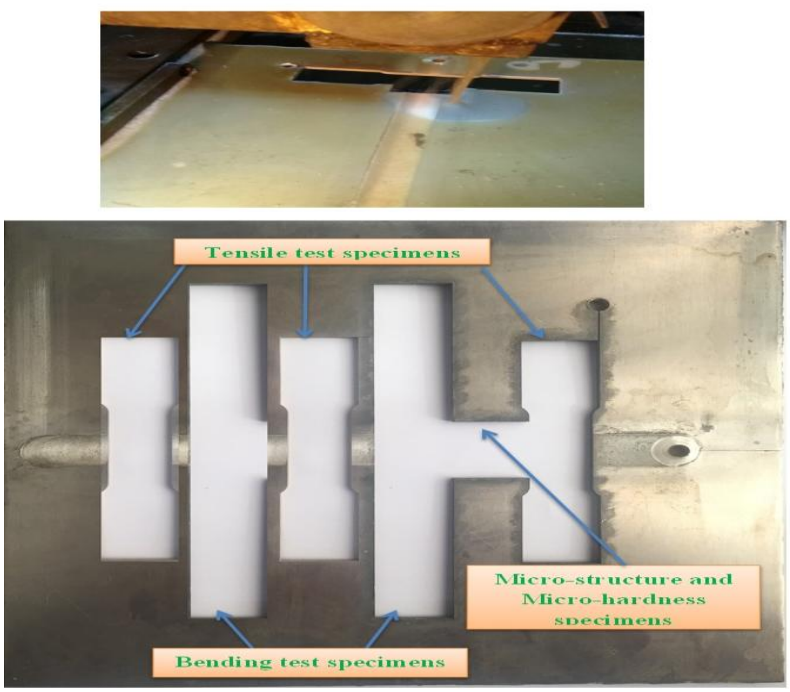


Figure 3. After completed FSW process.



(a)



(b)

Figure 4. a) dimensions of tensile test specimens according to ASTM (E8/E8M-09) , b) Tensile test specimens during preparing.

7. RESULTS AND DISCUSSION

7.1 Microstructure evaluation

Microstructure test result is shown in **Fig. 5** for specimen 5 which has the highest UTS and compared it with the base metals as shown in **Fig. 6**. The result showed that an oval-shaped area at the center of the weld appeared. Moreover fully re-crystallized at the weld center. Equiaxed grain in smaller size shown in the microstructure of the nugget zone (NZ) comparing with the base material, in the thermal mechanical affected zone (TMAZ) the grain has been no dynamic recrystallization, and instead, the grains are elongated and typically of a different orientation than those in the base metal. in additional to note the region no significant change in grain size or orientation when compared with the base metal called heat affect zone (HAZ).

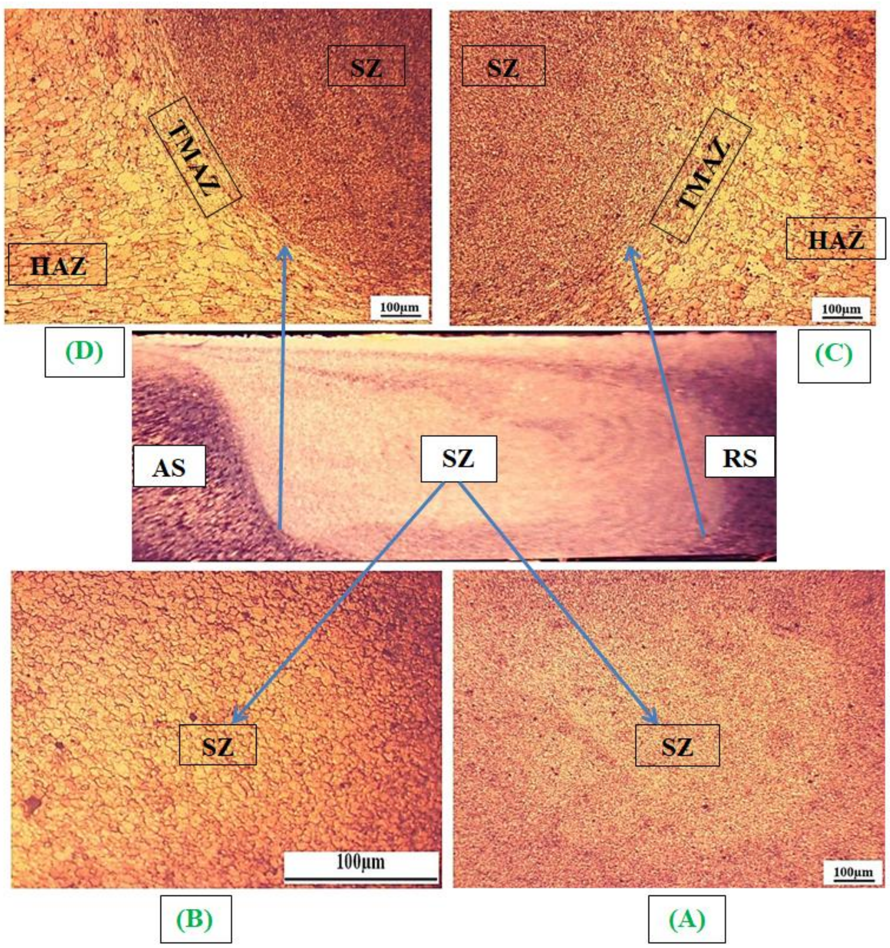


Figure 5. Microstructure of specimen no.5 A) center of SZ, B) high magnaficationof the cinter SZ, C) SZ+TMAZ+HAZ in RS, and D) SZ+TMAZ+HAZ in AS

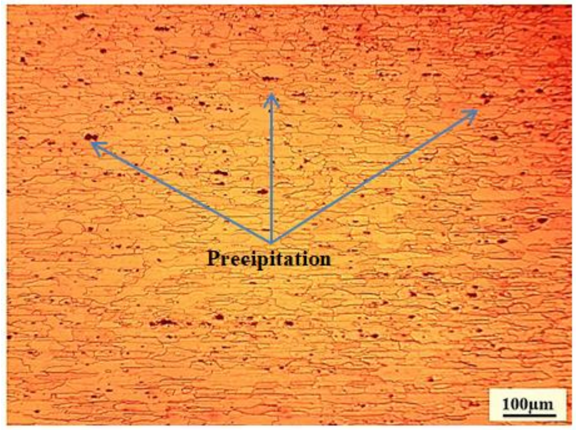


Figure 6. Microstructure image for base metal AA7075-T6

7.2 Optimized FSW Process Parameters for Ultimate Tensile Strength

One of the most significant mechanical properties is a tensile strength, the tensile test for BM and nine EXPs were performed in Universal Testing Machine, and the results are shown in **Fig. 7** and Fig. 8. The data were analyzed to determine the optimal levels of parameters that have a significant role in deciding the welding quality. After selecting FSW process parameters, the mean values of the ultimate tensile strength were obtained. The results are collected in **Table 7**.

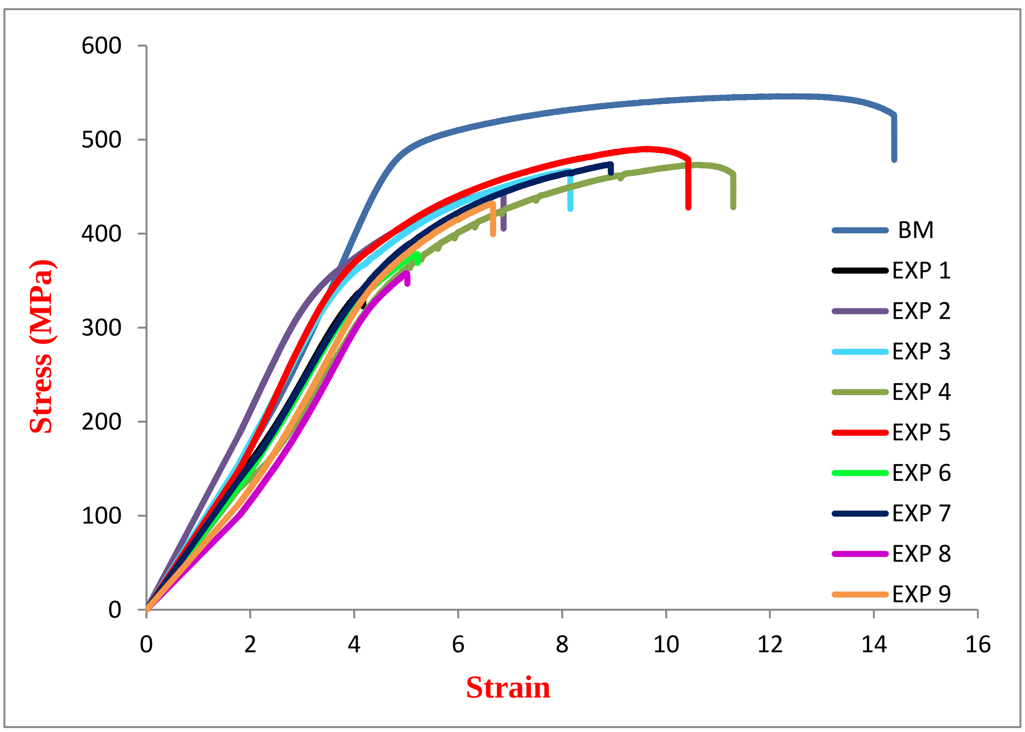


Figure 7. Strain-Stress curve for BM and nine EXPs.

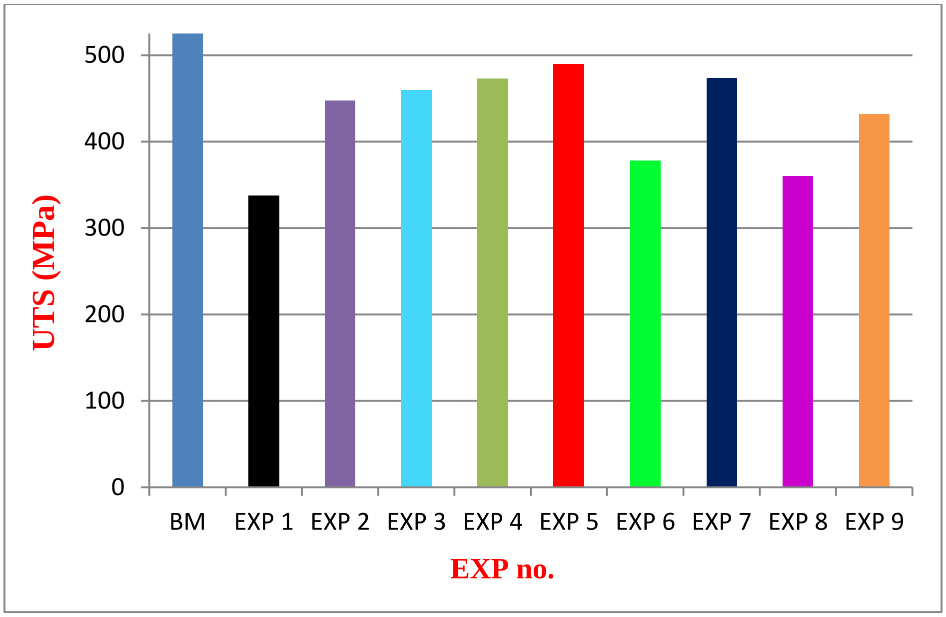


Figure 8. The UTS of BM and nine experiments.

Table 7. The mean values for tensile strength.

Experiment No.	SWI depth (mm)	Pin Shape	Thread Pitch (mm)	Mean UTS (MPa)
1	0.20	CTRE	0.8	337.5
2	0.20	CTFE	1.0	447.8
3	0.20	CTFRE	1.2	460.0
4	0.25	CTRE	1.0	473.0
5	0.25	CTFE	1.2	490.0
6	0.25	CTFRE	0.8	378.0
7	0.30	CTRE	1.2	473.5
8	0.30	CTFE	0.8	360.0
9	0.30	CTFRE	1.0	432.0

7.3 The (S/N) Ratio Analysis

The S\N ratio for the large-the better was calculated by Eq. (1) for each experiment to analyze the experimental data. S/N ratio results are listed in **Table 8**.

$$S/N = -\log((\sum 1/Y^2)/n) \quad \text{(1)}$$

Devaiah, et al., 2018,

Where

S/N: the ratio of the mean (S) to the standard deviation (N).

Y: the average observed data for each test.

N: the number of tests conducted.

Table 8. The (S/N) ratio results of tensile strength.

EXP. No.	SWI depth (mm)	Pin Shape	Pitch (mm)	UTS (MPa)	S/N Ratio
1	0.20	CTRE	0.8	337.5	50.5655
2	0.20	CTFE	1.0	447.8	53.0217
3	0.20	CTFRE	1.2	460.0	53.2552
4	0.25	CTRE	1.0	473.0	53.4972
5	0.25	CTFE	1.2	490.0	53.8039
6	0.25	CTFRE	0.8	378.0	51.5498
7	0.30	CTRE	1.2	473.5	53.5064
8	0.30	CTFE	0.8	360.0	51.1261
9	0.30	CTFRE	1.0	432.0	52.7097

Analyzing the S/N ratio for different FSW parameters appeared the higher S/N ratio corresponding to the best quality characteristics; the optimal level of the FSW parameters corresponding to the higher S/N ratio and the UTS can be identified from the plots as shown in **Fig. 9** and **Fig. 10** respectively.

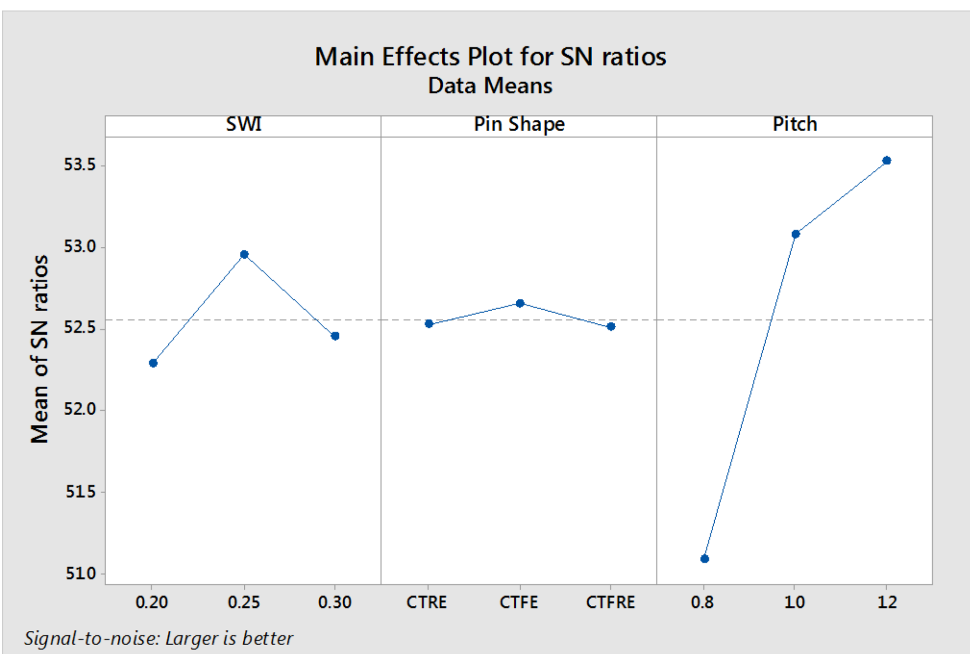


Figure 9. Main effect plot for S/N ratios.

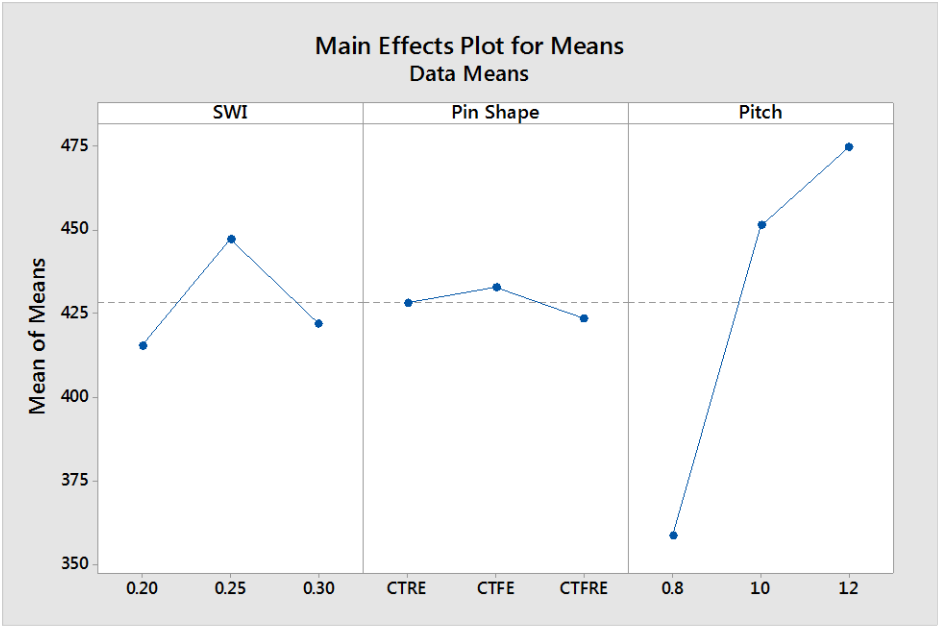


Figure 10. Main effect plot for mean tensile strength.

The main effect plot for S/N ratios and means suggests that these levels of parameters can reduce the FSW defects. The best parameters set for the FSW joints are listed in **Table 9**.

Table 9. Best setting of combination parameters.

Factors	Parameters	Level
Threaded Pitch (mm)	1.2	3
SWI Depth (mm)	0.25	2
Pin shape	CTFE	2

7.4 Analysis of Variance (ANOVA)

ANOVA carried out to inspect the significant of the parameters of FSW process which impact on the UTS of the weld joints. The F-test named after Fisher can also be used to identify which parameter has the largest effect on UTS. Typically, the alteration of the FSW parameters has the important impact on quality characteristics of UTS for FSW joints when F is large. ANOVA results are shown in **Table 10** and **Fig. 11**. ANOVA showed that the thread pitch is more influential on the ultimate tensile stress followed by the SWI depth and finally the pin shape.

Table 10. ANOVA for FSW process parameters.

Source		DOF	Adj SS	Adj MS	F-Value	P % Contribution
SWI depth (mm)		2	1696.3	848.2	5.56	6.87
Pin Shape		2	128.8	64.4	0.42	0.52
Thread Pitch (mm)		2	22555.3	11277.7	73.93	91.37
Error		2	305.1	152.6		1.24
Total		8	24685.5			100

DOF= Degree of freedom, Adj SS= Adjusted Sum of the square, Adj MS= Adjusted Pure mean for the sum of square, F= fisher ratio, P% = Percentage contribution

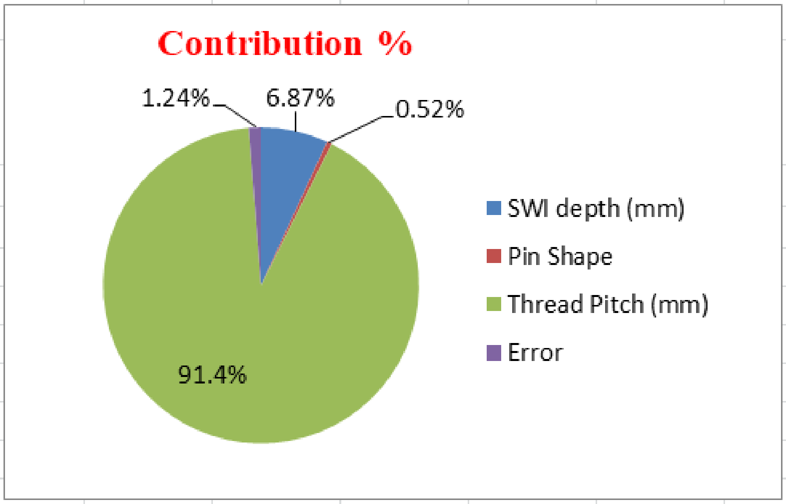


Figure 11. Contribution % of FSW parameters.

7.5 Predict of Optimum Performance Characteristics

To predict the optimum value of (UTS) after the significant process parameters and their levels have selected as SWI depth (level 2) = 0.25 mm, pin shape (level 2) = CTFE, and threaded pitch (level 3) =1.2 mm. The mean of response from applied Eq (2) as shown

UTS (predicted) = A2 + B2 + C3 - (2*T) (2) **Devaiah, et al., 2018**

where

T = The overall mean of UTS = 427.98 MPa.

A2 = The average UTS at the second level of SWI depth (0.25) mm = 447 MPa.

B2 = The average UTS at the second level of pin shape (CTFE) = 432.6 MPa.

C3 = The average UTS at the third level of thread pitch of pin (1.2) mm = 474.5 MPa.

UTS (predicted) = A2 + B2 + C3 - (2*T)

UTS (predicted) = 447 + 432.6 + 474.5 - (2*427.98) = 498.14 MPa.

UTS predicted was (498.13) MPa while the actual value was (490) MPa. The welding efficiency was 93.3% based on UTS.

8. CONCLUSIONS

using DOE method and by Taguchi technique to reduce the number of the experiment from (27 to 9) and study the impact SWI depth, Pin shape, and thread pitch of pin in the welding quality based on UTS results. the important conclusions from this study are described in the following:

1. The optimal welding parameters that obtained from applied signal to noise ratio (S/N) were 0.25 mm SWI depth, CTFE pin geometry, and 1.2 mm thread pitch based on UTS.
2. By using ANOVA the results showed that the most important factors affecting the process were thread pitch with a contribution percentage (91.37%) followed SWI depth of (6.87%) and pin geometry of (0.52%).
3. The predict the optimum value of (UTS) from ANOVA was (498.13) MPa while the actual value was (490) MPa.
4. Welding efficiency was 93.3% when using CTFE pin, 1.2 mm thread pitch, and 0.25 mm SWI depth based on UTS.
5. Fully re-crystallized in the weld center and equiaxed grain in smaller size, and in the TMAZ there is no dynamic recrystallization, and instead, the grains were elongated and typically of a different orientation than those in the base metal, while there is no significant change in grain size or orientation in the HAZ when compared to BM .

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