Friction Stir Welded 6063- Aluminium Joint Mechanical Characteristics Prediction Methodology Based on Monte Carlo Simulation

Ibrahim Sabry, Noah E. El-Zathry, A.M. Hewidy

Benha University Benha, Egypt, ibrahim.sabry@bhit.bu.edu.eg, nouh.elsayed@bhit.bu.edu.eg, ahmed.hewidy@ bhit.bu.edu.eg

***Abstract*— The aluminum alloy plate Al–6063 was butt-welded employing friction stir welding in the current investigation. Using Taguchi L9 orthogonal design of experiments, the process parameters of tool rotational speed, tool traverse speed, and shoulder diameter were optimized. The optimal process parameters were calculated based on the weld's ultimate tensile strength(UTS). A validation run utilizing the optimum settings confirmed the projected ideal value of UTS. The maximum important elements contributing to weld strength, according to the analysis of variance, were tool rotation speed (RS) tool traverse speed(TS) and axial forces(AF). utilizing the full factorial analysis, the maximum critical parameters were discovered. RS, SD , and their interacting impact were revealed to be the maximum critical parameters using full factorial analysis. According to the Anderson-Darling test, UTS follows a normal distribution.**

Keywords—FSW, plate joint, microstructure, mechanical properties.

I. Introduction

Friction welding is a versatile method that may be used to manufacture a wide range of components in a variety of industries, including light and heavy automotive, electrical, chemical, and civil engineering[1][2] [3]. Aluminium alloys, and titanium are among the materials that can be friction stir welded [4] [5][6]. Their study was based on FSW of Al alloys to improve the mechanical characteristic of the joint [7]. Due to the narrowing of the precipitate free zone, the HAZ hardness can be increased using the FSW process[8] [9][10] [11][12] [13]. The FSW of plates has been studied in [20][21] and the FSW of pipe has been studied in [14] within the same rotational speed scale. Many studies have been carried out in order to improve the FSW operation[15][16].

The most prevalent approach published on the forecasting of FSW processes is mechanical models, which range from simple analytical models based on Sabry et al. [17] to prediction models by A.M.Kassas et al. [18] and Khourshid et al. [19]. Conventionally the forecasting models are either transient Ibrahim [20] or A.M. Kassas [21]. The first type allows ANN model to be used and the UTS and hardness to be studied. The latter type has the RSM of utilizing a mathematic models to the tensile strength [22]. For this process, the completely linked full factorial analysis and Taguchi techniques have only lately been investigated. he forecasting models of the FSW process can be utilized to analyse various mechanical, metallurgical aspects of the weld, depending on the study's objectives. A time- involved model for evaluating the 'VH' of a 6082-T6 aluminium alloy next an spot T.H. like, welding, is described in a paper by Myhr & Grong [23]. By improving process settings and employing appropriate instruments, faults can be reduced. The welding of 6063 by FSW, on the other hand, necessitates the use of the proper process parameters. The link between welding parameters and mechanical qualities is the most pressing issue, and it necessitates a thorough investigation. As a result, the focus of this study is on determining the best process parameters for improving the target material's hardness and tensile strength.

II. Experimental work

2.1 Setting up the Materials and the Experiment:

For butt joints, Al 6063 plate with a 5 mm thickness, 150 mm length, and 70 mm width was used. The work pieces were mounted on a customised mild steel fixture. To determine the operational range of process parameters, such as RS and TS, preliminary experiments were conducted. The RS from 1000 to 1800 rpm; the TS was 4 to 10 mm/min; and the AF from 1 KN to 2 KN. In this investigation, Taguchi L9 OA is employed. The process parameters at each level are shown in Table 1. The chemical composition and mechanical properties of the foundation materials are shown in Tables 2. The mechanical qualities were assessed using tensile strength testing. The tensile strength test specimens were cut from the weld region and were 15 mm wide and 120 mm long. Following the Taguchi analysis, a full factorial DOE was used to discover the ffarthest critical parameters from the chosen parameters. The UTS is predicted via Monte Carlo simulation. The tensile test is used to determine whether the response variable 'UTS' is normal

TABLE I. THE CHEMICAL STRUCTURE OF THE PLATE AND PIPE'S COMPONENT AL 6063.

Wt. %	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn
	Bal	0.4	0.67	0.15	0.15	0.9	0.104	0.25

TABLE II. AA6063-T6 MECHANICAL CHARACTERISTICS

Alloy	UTS (MPa)	YS	E%	VHD
Al 6082 alloy	185	340	15	100

Fig. 1. Experimental setup for

2.2. Machine

As in [24], a vertical milling machine (VMM) was prepared and fitted for the FSW for pipe procedure. A fixture design that can tolerate a rotating motion for the pipe is frequently used to prepare the machine. Figure 1 shows how the rotating motion of the pipes works as the travel speed (TS) to allow the tool to advance over the weld line.

2.4. Tool Design

Welding aluminium pipes requires special, non-consumable tools made of 6 mm pin diameter K18 tool steel. With a root diameter of 5 mm, a tip diameter of 1 mm, and a pin length of 4 mm, the pin profile was tapered. A shoulder with an oval 10 mm 9 mm shape and a height of 5 mm linked the pin to the main tool body. Figure 2 shows the instrument (which has been rotated by 90 degrees) [25].

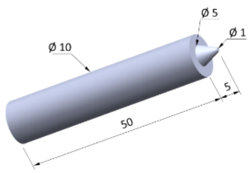

Fig. 2. Tool shape

2.5 Variables in the FSW process

Based on early experiments and prior studies, the independent process parameters controlling the UTS, VHN, and SR were characterised as (RS), (AF), and (TS). Table 3 shows the friction-stir welding settings.

TABLE III. VALUES AND LEVELS OF PROCESS PARAMETERS

Parameter	Value
Tool rotation [rpm]	1000, 1400, 1800
Axial force [KN]	1, 1.5, 2
Transverse speed [mm/min]	4, 8, 10

By adjusting only one parameter at a time, trial runs continued to test the maximum and lower limits of Al 6063 process parameters. A parameter set was calibrated in such a way that visual screening in the finished welded joint revealed no faults. The upper limit was assigned a value of 1 while the lower limit was assigned a value of -1. Equation was used to calculate the coded intermediate values (1).

$$X_i = 2X - \frac{X_{max}+X_{min}}{X_{max}-X_{min}} \quad (1)$$

where X_i, X, X_{max} and X_{min} are the desired coded value, the variable's value, the variable's lower limit, and the variable's upper limit, respectively [26]. Table 3 lists the process parameters that were considered, along with their associated borders, units, and notations.

TABLE IV. METHOD PARAMETERS AND THEIR LEVELS IN FSW

Process Parameters	Unit	Levels		
		-1	0	1
Tool rotation (RS)	[rpm]	1000	1400	1800
Axial force (AF)	[mm]	2	3	4
Travel speed (TS)	[mm/min]	4	8	10

Figure 3 shows how specimens of the proper size were cut from the welded plate to conduct metallurgical studies (a). Figure 3 shows FSW samples that were welded at 10 mm/min and 1800 rpm (b).

(a)

(b)

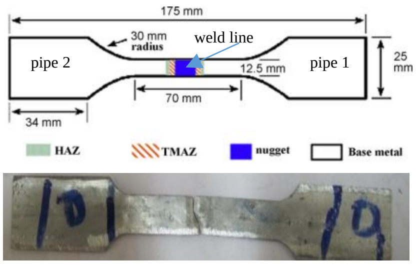

Fig. 3. (a) Sample geometry of tensile test (b) A welded FSW sample

The milling machine was used for the experimentation. The UTS of the welded sample was tested in accordance with ASTM D638-14 [27] [28]. ANOVA was used to identify relevant variables. The primary impact plots and their interaction plots were produced to analyse the parametric impacts on the features of the response using a statistical analysis technique at all phases. All of the findings were assessed using the "Minitab 18" statistical tool (Table 3).

III. RESULTS AND DISCUSSION

3.1. Taguchi Method

The S/N ratio is used in the Taguchi process to measure the characteristics of good quality divergence from the desired value. The properties of the S/ N ratio can be divided into three modes: nominal is best, smaller is better, and larger is better. The goal of this study is to maximise UTS,VHN and SR minimum using the best FSW process settings, with the greater is better principle used. To understand the influence of the FSW process parameters, the UTS,SR and VHN of the welded joints is investigated. The MINITAB 18 programmer [27] [32]. is used to do the analysis. The mean S/N ratio for each level of welding settings is shown in Table 4. The higher the S/N ratio, the better the quality qualities. To comprehend the influence of the FSW process parameters, the UTS, VHN, and SR of the welded joints are examined. The MINITAB 18 programme is used to do the analysis. The mean S/N ratio for each level of welding settings is shown in Table 4. The higher the S/N ratio, the better the quality qualities.

The ideal level setting was attained at 1800 rpm RS, 4 mm/min TS, and 2 KN AF based on S/N ratio values. Tables 5 and 6 show the response tables for mean influence and S/N ratio, respectively. Figures 1 and 2 show the major influence plots for means and S/N ratios, respectively.

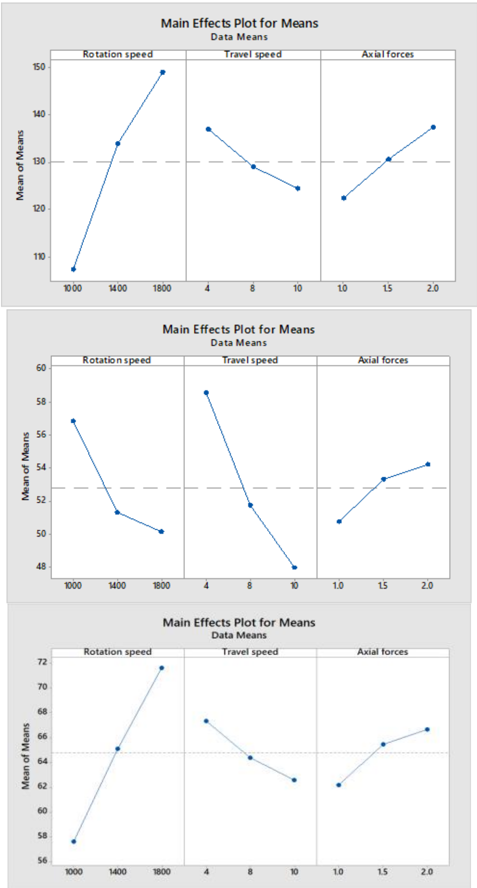

Fig. 4. Means main impacts plot (a) UTS (b) VHN (c) SR

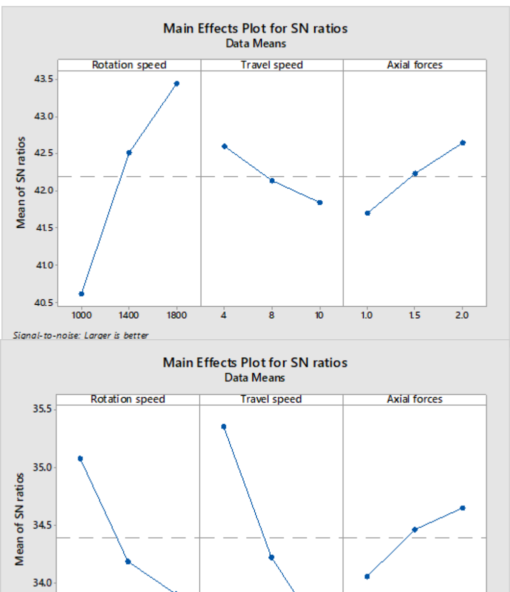

Fig. 5. For SN ratios, the main effects graphic (a) UTS (b) VHN (c) SR

The ideal level setting was attained at a rotating speed of 1800 rpm (RS), a traverse speed of 4 mm/min (TS), and a axial forces (AF) of mm based on S/N ratio values . Tables 5 and 6 show the response tables for mean effect and S/N ratio, respectively. Figures 1 and 2 depict the main influence plots for means and S/N ratios, respectively. The influence of process factors on UTS, SR and VHN is evaluated using analysis of variance. Tables 7 and 8 show the findings of ANOVA [27] of means and ANOVA of signal to noise ratios, respectively. The TS and AF were shown to be the most significant factors affecting weld strength in this study.

According to the experiments, the best level settings are RS, TS, and AF. Table 5 shows the average values of the components at their various levels. and the maximum UTS,VHN and SR is presented below as a prediction

UTS = 49.89 + 0.05204 Rotation speed - 2.065 Travel speed + 15.03 Axial forces

VHN = 72.29 - 0.00842 Rotation speed - 1.763 Travel speed + 3.47 Axial forces

SR = -4.29 + 0.00893 Rotation speed + 1.467 Travel speed - 5.07 Axial forces

Test for confirmation

The ideal level of design parameters is used to verify the improvement of the quality feature. At 1800 rpm, 4mm/min, and 2 mm, respectively, the tool rotational speed, traversal speed, and axial forces were measured. The friction stir welded Al 6063 joint's average UTS, VHN, and SR values were 162.5 MPa, 60.8VH, and 7.134, respectively.

3.2 Factorial analysis in its entirety

The complete factorial DOE was used to discover the most critical parameter among the parameters that were chosen for further study. For the three parameters, the full factorial DOE revealed eight different possibilities[29] [30] [31]. A normal plot of influence, main effect plot, Pareto chart, and interaction plot are used to calculate and assess the UTS,VHN, and SR for each combination. The TS, RS, and their interaction have a significant influence on UTS, VHN, and SR at the 95% confidence interval, as shown by the normal influence plot and the Pareto chart. Figures 3., 4., and 5. show the normal influence plot, the main plot of the influences, and the Pareto chart of the influences, respectively. The primary influence plot revealed that greater TS and RS values result in a higher UTS. The influences of AF variation on UTS, VHN, and SR were minor.

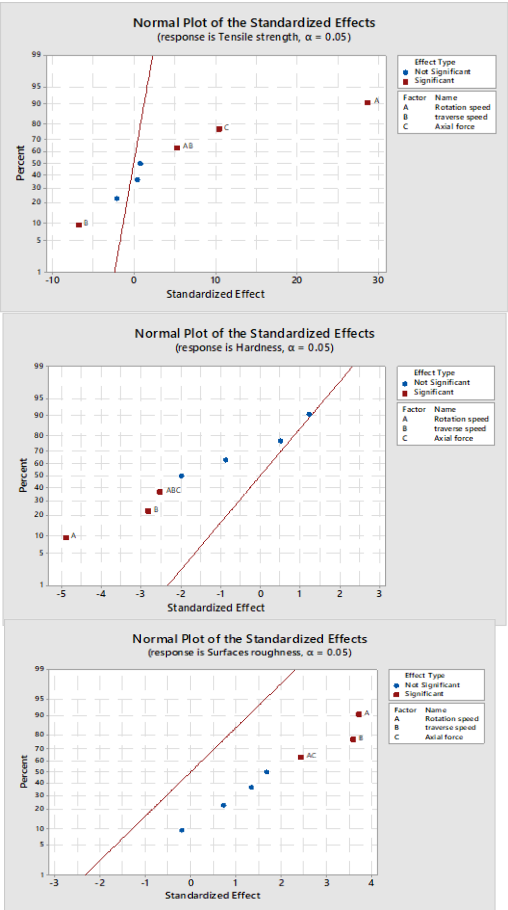

Fig. 6. Normal plot of the effects (a) surfaces roughness (b)UTS (c) hardness

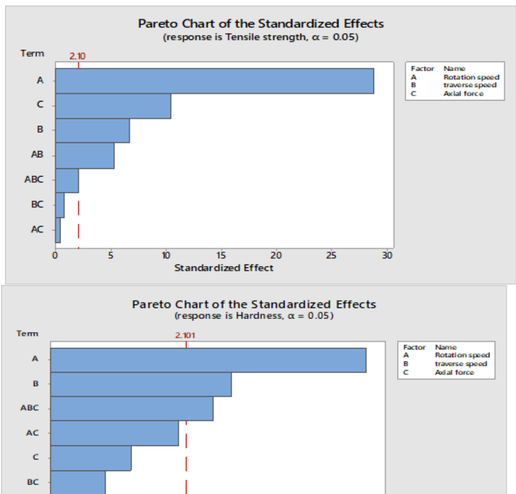

Fig. 7. Pareto chart of the effects (a)UTS (b) hardness (c) surfaces roughness

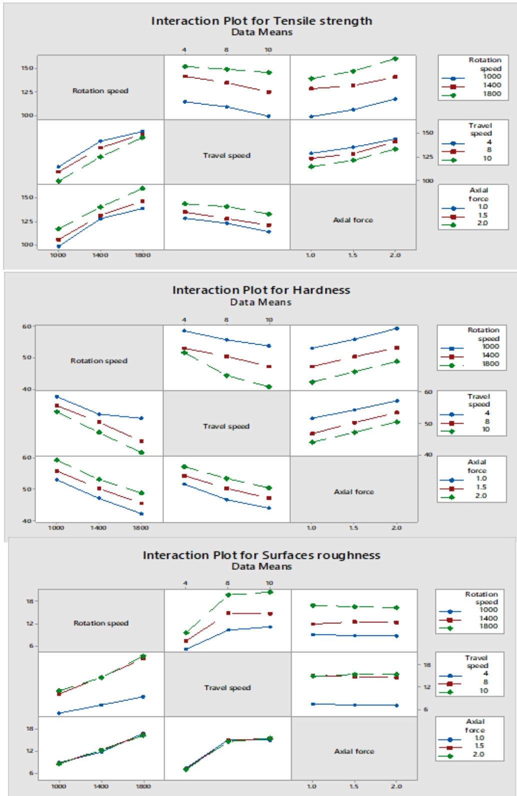

Fig. 8. Effects interaction diagram (a)UTS (b) hardness (c) surfaces roughness Visual inspection

Figure 6 depicts the interaction among any two chosen parameters by respect to UTS, SR, and VHN in an interaction plot. Between AF and RS, there is no discernible interaction. Between RS and AF, there is a moderate interaction. Between RS and TS, there is a strong beneficial interaction. To forecast the UTS, VHN, and SR, a functional equation was devised and illustrated below.

$$UTS = 122.0 + 0.0003\ RS - 12.44\ TS - 15.3\ AF + 0.00726\ RS*TS + 0.02014\ RS*AF + 4.05\ TS*AF$$

- 0.00261 RS*TS*AF + 3.81 Ct Pt (8)

VHN = 98.7 - 0.0346 RS - 7.40 TS - 16.2 AF + 0.00524 RS*TS + 0.01515 RS*AF + 4.13 TS*AF - 0.00327 RS*TS*AF - 2.48 Ct Pt (9)

SR = 3.6 + 0.0034 RS + 1.80 TS - 5.5 AF - 0.00136 RS*TS + 0.00251 RS*AF - 0.55 TS*AF + 0.00083 RS*TS*AF + 3.78 Ct Pt (10)

3.3 Analysis of results

The impacts of various process parameters on the mechanical properties of FSW welded aluminium alloy 6063 are estimated from mathematical models utilising experimental findings in Figure 9, which shows the typical patterns between cause and effect. Figure 9 depicts the UTS, VHN, and SR contour graphs for FSW.

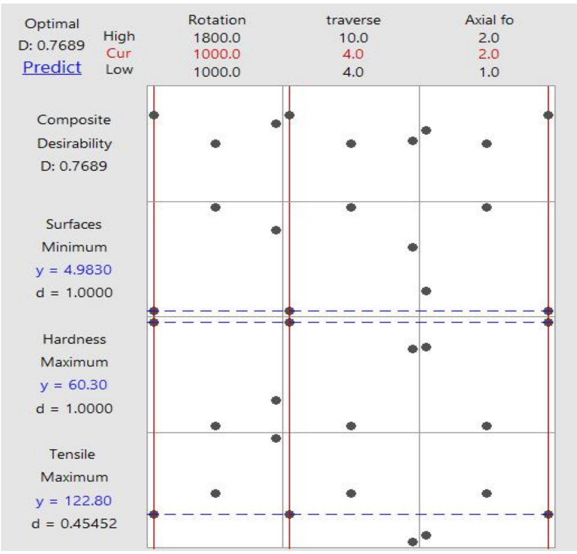

Fig. 9. The overall desirability rating of 0.679 for the combined desirability value is shown in a bar chart.

3.4 Simulation with Monte Carlo

Utilizing the equation generated from the full factorial analysis, Monte Carlo simulation is utilizing to determine the UTS SR and VHN. The normal distribution was used to produce the random data, which consisted of around 1000 datum for each of the three parameters. The simulation was run to calculate the performance utilized the UTS SR and VHN equations. Based on around 1000 samples, the mean UTS, SR, and VHN are 149.49, 46.5, and 9.49, respectively. 105, 17, and 4 are the minimum UTS, SR, and VHN, respectively. UTS, SR, and VHN have maximum values of 192, 77, and 19 respectively, with standard deviations of 22.6, 14.7, and 2.5 for UTS, SR, and VHN, respectively. Figures 10 (a,b,c) show the probability plot and summary report for UTS, SR, and VHN, respectively.

Figure 10 displays the response optimizer's optimised parameters (RS, TS, and AF) and the related response values (UTS,SR, and VHN) in ANOVA. The optimal combination of parameters for a single response or a group of responses can be determined using a response optimizer. After optimising several responses for the three input variables, an optimization plot was obtained in this scenario. 1800 rpm, 4 mm /min, and 2 KN were the optimal RS, TS, and AF, respectively.

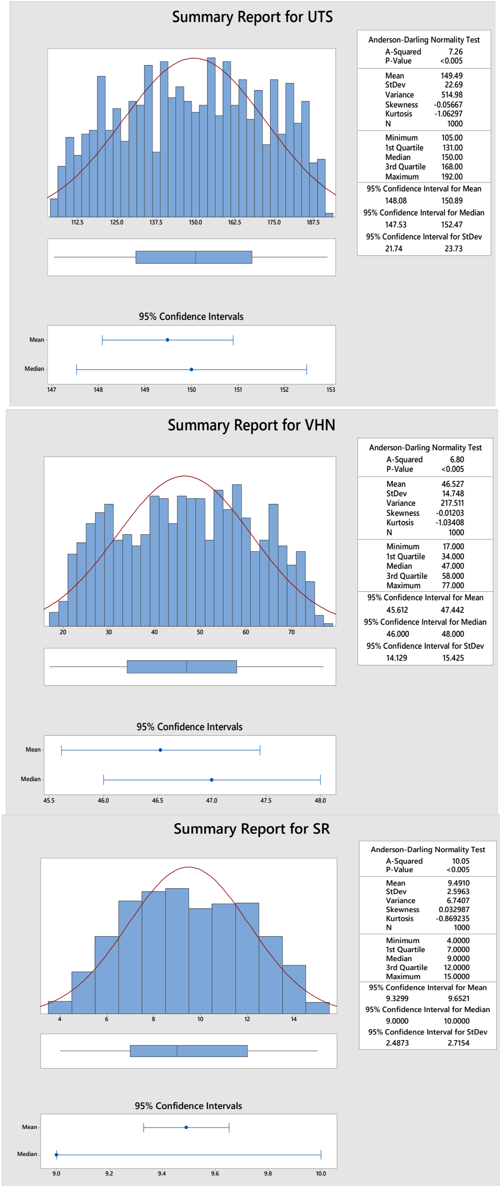

Fig. 10. Probability plot for (a)UTS (b) VHN (c) SR

IV. CONCLUSIONS

To butt weld the Al 6063 plate, FSW experiments were carried out. We came to the following conclusions:

1. The best RS, TS, and AF settings are 1800 rpm, 4 mm/min, and 02 KN, respectively.
2. The RS, TS, and AF are found to contribute 25.3 percent, 59 percent, and 11.4 percent of the UTS, SR, and VHN of welded joints, respectively.
3. According to the factorial study, RS, TS, and their interaction had the greatest influence on UTS, SR, and VHN.
4. The range of UTS observed by Monte Carlo simulation ranges from 135 MPa to 162. MPa, with

a mean value of 151 MPa, and the range of SR observed by Monte Carlo simulation ranges from 7.19 MPa to 20.6 MPa, with a mean value of 13.

5. The normal distribution is followed by the UTS, SR, and VHN.

REFERENCES

[1] B. H. a. J. F. Hinrichs 2007 Friction Stir Welding (FSW) of Littoral Combat Ship Deckhouse Structure," J. of Ship Prod. **23 pp.**161-16.

[2] H. S. P. a. N. Soman 2010 Experimental study on the effect of welding speed and tool pin profiles on AA6082-O aluminium friction stir welded butt joints Int. J. of Eng., Sci. and Tech. **2** pp.268-275 .

[3] A.-H. I. M. D. T. T. Ibrahim Sabry 2020 Comparison of Mechanical Characteristics of Conventional and Underwater Friction Stir Welding of AA 6063 Pipe Joints Int. Rev. of Aeros. Eng. 14 .

[4] N. G. M. A. G. a. M. A.-M. Ibrahim Sabry 2020 Optimization of Process Parameters to Maximize Ultimate Tensile Strength and Hardness of Underwater Friction Stir Welded Aluminium Alloys using Fuzzy Logic Modern Conce. in Mater. Scien. **3** pp.73–78.

[5] C. G. M. K. A. M. S. K. P. Raju P. Mahto 2019 Weldability of AA6061-T6 and AISI 304 by underwater friction stir welding J. of Manuf. Proc. **38** pp.370–386.

[6] R. V. B. a. M. H. Kh. Bijanrostami 2017 Effect of Traverse and Rotational Speeds on the Tensile Behavior of the Underwater Dissimilar Friction Stir Welded Aluminum Alloys," J. of Mater. Engi. and Perfor. **26** pp.909–920 .

[7] B. G. S. R. FRATINI L 2008 In-process heat treatments to improve FS-welded butt joints," Int. J. of Mach. Tools and Manuf. **10** pp.42-53.

[8] A.-H. I. M. . D. T. T. Ibrahim Sabry 2020 Optimization of metal inert gas welded aluminium 6061 pipe parameters using analysis of variance and grey relational analysis SN Applied Scien. **2** .

[9] I. S. A.M.El-Kassas 2018 Comparative Study on Different Tool Geometrics in Friction Stirred Aluminum Welds Using Response Surface Methodology," in 4th Int. Conf. on Weld. and Fail. Analy. of Eng. Mater. Aswan, Egypt 19-22 .

[10] A. M. E.-K. a. A. K. Ibrahim Sabry 2017 Comparison of RSM and RA with ANN in Predicting Mechanical Properties of Friction Stir Welded Aluminum Alloy Pipes Eng. and Techn. in India **8** pp. 1-14.

[11] A. M. E.-K. a. A. K. Ibrahim Sabry 2015 Integration between Artificial Neural Network and Responses Surface Methodology for Modeling of Friction Stir Welding Int. J. of Adv. Eng. Resea. and Scie. **1** pp.67-73 .

[12] K. N. P. R. K. Saurabh Kumar Gupta 2017 Experimental modelling and genetic algorithm-based optimisation of friction stir welding process parameters for joining of dissimilar AA5083-O and AA6063-T6 aluminium alloys," Int. J. of Mater. and Product Techn. **56** pp.253-270 .

[13] S. K. S. K. v. Mr.Shashi K. Jaiswal 2017 Study and Optimization of Friction Stir Welding (FSW) Process Using the Genetic Algorithms (GA) Int. J. for Scien. Res. & Develp. **5** pp.555-560.

[14] F. B. N. K. S. M. N. G. M. F. M. M. Nabi Mehri khansari 2018 Development of an optimal process for friction stir welding based on GA-RSM hybrid algorithm Frattura ed Integrità Strutturale 12 106-122.

[15] N. M. Khansari 2018 Development of an optimal process for friction stir welding based on GA-RSM hybrid algorithm Fratturaed Integrità Struttural 44 106-122 .

[16] K. P. P. S. A. N. H. S. S. P. M. &. C. V. S. M. K. Kamal Babu 2018 Parameter optimization of friction stir welding of cryorolled AA2219 alloy using artificial neural network modeling with genetic algorithm The Int. J. of Adv. Manuf. Techno. 94 3117–3129 .

[17] I. S. Ahmed M. El-Kassas 2019 Optimization of the Underwater Friction Stir Welding of Pipes Using Hybrid RSM-Fuzzy Approach Int. J. of App. Eng. Rese. 14 4562-4572.

[18] I. S. Ahmed M. El-Kassas 2019 Using Multi Criteria Decision Making in Optimizing the Friction Stir Welding Process of Pipes: A Tool Pin Diameter Int. J. of App. Eng. Rese. 14 3668-3677.

[19] A. M. E.-K. a. A. K. Ibrahim Sabry 2015 Integration between Artificial Neural Network and Responses Surface Methodology for Modeling of Friction Stir Welding Int. J. of Adv. Eng. Rese. and Sci. 1 67-73.

[20] I. S., N. G. and M. Abu-Okail 2020 Optimization of friction stir welding parameters using response surface methodology, IOP Conf. Series: Mater. Scie.e and Eng. 973 . 012017 IOP Publishing doi:10.1088/1757-899X/973/1/012017

[21] A. M. El-K.I. S., A.M. K. and H. M. Hindawy 2017 Development of Mathematical Model to Predict the Mechanical Properties of Friction Stir Welded Aluminum Pipe, Int. J. of App. Scien. and Techn. 6 .

[22] I. S., A. M. El-K. and A.M. Khourshid 2016 optimization of Friction Stir Welding Parameters for Jining Aluminum Pipes using Regression Analysis Int. J. of Civil, Mecha. and Ener. Scien. 2 .

[23] O. R. Myhr and Ø Grong 1991 Process Modelling Applied to 6082-T6 Aluminium Weldments-I. Reaction Kinetics A. Metall. et Mater. 39 2693-2702.

[24] A.M El.-K. A. Ibrahim Sabry 2019 An appraisal of characteristic mechanical properties and microstructure

of friction stir welding for Aluminium 6061 alloy – Silicon Carbide (SiCp) metal matrix composite.," J. of Mech. Eng. and Sci. 13 5804–5817.

[25] I. Sabry 2020 Six sigma methodology using to improve the mechanical properties for Friction Stir Welding of Aluminum pipes Manag.t and Prod. Eng. Rev. 11 73–78.

[26] I. S. and M.A. Gh. N. Gadallah 2019 A Summarized Review on Friction Stir Welding for Aluminum Alloys in 3rd Int. Conf. Arch., Eng. and tech. (AET), Cairo, Egypt.

[27] I. S. A. H.Idrisi, A.-H. Ismail Mourad 2021 Friction stir welding process parameters optimization through hybrid multi-criteria decision-making approach, Int. Rev. on Mod. and Simul, 14 32-43.

[28] I. S., M. A.l Gh., A.-H.d I. M. and Amir Hussain Idrisi 2020 Stir casted SiC-Gr/Al6061 hybrid composite tribological and mechanical properties SN Appli. Scien. 2 .

[29] I. S., Ahmed M. El-K., A.-H. I. Moura, D. Th. and Jaber Abu Qudeiri 2019 Friction Stir Welding of T-Joints: Experimental and Statistical Analysis J. of Manuf. and Mater. Proce. 3 .

[30] Ibrahim Sabry, N E El-Zathry, N Gadallah and M Abdel Ghafaar" Implementation of hybrid RSM-GA optimization techniques in underwater friction stir welding," Journal of Physics: Conference Series, Vol. 2299,No. 1, 20th International Conference on Applied Mechanics and Mechanical Engineering (AMME-20), 28/03/2021 - 31/03/2022, Military Technical College, Cairo, Egypt.

[31] N E El-Zathry, A I Hassan, A A El-Betar and Ibrahim Sabry, "Optimization of friction stir welding AA6082-T6 parameters using analysis of variance and grey relational analysis," Journal of Physics: Conference Series, Vol. 2299,No. 1, 20th International Conference on Applied Mechanics and Mechanical Engineering (AMME-20), 28/03/2021 - 31/03/2022, Military Technical College, Cairo, Egypt.

[32] Ibrahim Sabry, A.M. Hewid "Underwater friction-stir welding of a stir-cast AA6061-SiC metal matrix composite: optimization of the process parameters, microstructural characterization, and mechanical properties," Materials Science-Poland, Vol. 40, no. 1, PP. 101-115,2022.

TABLE V. UTS, VHN, AND SR, S/N RESPONSES

No.	RS	SD	TS	UTS	VHN	SR	(S/N) Ratio	Mean	St. Dev

1	1000	4	1.0	107.3	58.7	5.124	19.9433	57.6044	50.0228
2	1000	8	1.5	106.0	59.8	10.010	24.4756	57.8876	48.5785
3	1000	10	2.0	109.0	52.1	10.400	24.0284	57.3193	50.0079
4	1400	4	1.5	141.1	56.3	7.198	20.9580	68.3520	68.2525
5	1400	8	2.0	140.9	49.8	7.340	23.0030	66.5764	67.1548
6	1400	10	1.0	119.9	47.9	15.310	27.8377	60.3209	54.0905
7	1800	4	2.0	162.5	60.8	7.134	21.6235	76.0956	79.4832
8	1800	8	1.0	140.1	45.7	19.640	28.9506	68.6327	63.8917
9	1800	10	1.5	144.6	43.9	20.180	30.9905	70.1231	64.9745

TABLE VI. MEANS TABLE OF RESPONSES (A) UTS (B) VHN (C) SR

	a			b				c			
Level	RS	TS	AF	Level	RS	TS	AF	Level	RS	TS	AF
1	40.62	42.61	41.71	1	35.08	35.35	34.06	1	18.18	16.13	21.25
2	42.52	42.14	42.23	2	34.19	34.23	34.46	2	19.39	21.06	21.08
3	43.45	41.84	42.65	3	33.91	33.60	34.65	3	23.01	23.38	18.24
Delta	2.83	0.76	0.94	Delta	1.17	1.76	0.59	Delta	4.83	7.25	3.01
Rank	1	3	2	Rank	2	1	3	Rank	2	1	3

TABLE VII. SIGNAL-TO-NOISE RATIO RESPONSE TABLE: THE HIGHER THE NUMBER, THE BETTER (A) UTS (B) VHN (C) SR

	a			b				c			
Level	RS	TS	AF	Level	RS	TS	AF	Level	RS	TS	AF
1	107.4	137.0	122.4	1	56.87	58.60	50.77	1	8.511	6.485	13.358
2	134.0	129.0	130.6	2	51.33	51.77	53.33	2	9.949	12.330	12.463
3	149.1	124.5	137.5	3	50.13	47.97	54.23	3	15.651	15.297	8.291
Delta	41.6	12.5	15.0	Delta	6.73	10.63	3.47	Delta	7.140	8.811	5.067
Rank	1	3	2	Rank	2	1	3	Rank	2	1	3

TABLE VIII. . ANALYSIS OF VARIANCE BY MEANS (A) UTS (B) VHN (C) SR

a

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Rotation speed	2	2665.36	2665.36	1332.68	817.04	0.001
Travel speed	2	239.14	239.14	119.57	73.30	0.013
Axial forces	2	339.76	339.76	169.88	104.15	0.010
Residual Error	2	3.26	3.26	1.63		
Total	8	3247.52				
S = 1.277			R-Sq = 99.9%		R-Sq(adj) = 99.6%	

b

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Rotation speed	2	77.40	77.40	38.698	1.48	0.403
Travel speed	2	174.20	174.20	87.101	3.34	0.230
Axial forces	2	19.42	19.42	9.708	0.37	0.729
Residual Error	2	52.16	52.16	26.081		
Total	8	323.18				
S = 1.277			R-Sq = 99.9%		R-Sq(adj) = 99.6%	

c

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Rotation speed	2	85.560	42.780	17.49	0.054
Travel speed	2	120.601	60.300	24.65	0.039
Axial forces	2	43.873	21.936	8.97	0.100
Error	2	4.892	2.446		
Total	8	254.926			
S = 1.564		R-Sq = 98.1%		R-Sq(adj) = 92.3%	

TABLE IX. SIGNAL-TO-NOISE RATIOS: ANALYSIS OF VARIANCE

a

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Rotation speed	2	12.4513	12.4513	6.22566	283.36	0.004
Travel speed	2	0.8901	0.8901	0.44507	20.26	0.047
Axial forces	2	1.3381	1.3381	0.66904	30.45	0.032
Residual Error	2	0.0439	0.0439	0.02197		
Total	8	14.7235				
S=0.1482			R-Sq = 99.7%		R-Sq(adj) = 98.8%	

b

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Rotation speed	2	12.4513	12.4513	6.22566	283.36	0.004
Travel speed	2	0.8901	0.8901	0.44507	20.26	0.047
Axial forces	2	1.3381	1.3381	0.66904	30.45	0.032
Residual Error	2	0.0439	0.0439	0.02197		
Total	8	14.7235				
S = 0.1482			R-Sq = 99.7%		R-Sq(adj) = 98.8%	

c

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Rotation speed	2	37.899	37.899	18.950	6.87	0.127
Travel speed	2	82.144	82.144	41.072	14.89	0.063
Axial forces	2	17.180	17.180	8.590	3.11	0.243
Residual Error	2	5.517	5.517	2.759		
Total	8	142.740				
S = 1.661			R-Sq = 96.1%		R-Sq(adj) = 84.5%	