

Modeling and Optimizing Robotic MIG Welding of AA6061 Butt Joints

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Abstract

In this work, Taguchi approach was successfully applied to model and optimize robotic MIG welding process of AA6061 butt joints. The effect of robotic MIG welding parameters viz arc voltage, welding current and welding speed was analyzed in terms of maximizing fatigue life. Mathematical model was developed to describe the influence of the selected parameters on fatigue life, to predict its value within the limits of the study. Results of signal to noise (S/N) ratio and ANOVA analysis indicated that welding speed has a strong significant effect on fatigue life, arc voltage and welding current also have a significant effect on fatigue life, and the developed model can adequately predict fatigue life satisfactorily.

Keywords: MIG welding; fatigue life; Taguchi approach; modeling; optimization.

نمذجة وأمثلة لحام MIG الآلي للوصلات التناكبية لسبيكة AA6061 الومنيوم

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الملخص

تم في هذا البحث تطبيق طريقة تاقوشي بنجاح لنمذجة وأمثلة لحام MIG الآلي للوصلات التناكبية لسبيكة AA6061. وقد تم تحليل تأثير متغيرات لحام MIG الآلي (جهد القوس وتيار اللحام وسرعة اللحام) بهدف الحصول على أقصى عمر للكلل. وتم تطوير نموذج رياضي لوصف تأثير المتغيرات المختارة على عمر الكلل، وللتنبؤ بقيم عمر الكلل في حدود نطاق الدراسة. وقد بينت نتائج نسبة (S/N) ونتائج تحليل التباين أن سرعة اللحام لها أقوى تأثير مهم على عمر الكلل وأن جهد القوس وتيار اللحام لهما أيضا تأثير مهم على عمر الكلل. وأن النموذج الرياضي المطور يمكنه التنبؤ بعمر الكلل بشكل ملائم ومرضي.

1. Introduction

In today's industrial sector, it is important to have good quality welding to obtain a high quality product. In the field of welding; weld quality is affected by the type of welding process, its parameters and the mechanical properties of the weld metal and heat affected zone (HAZ). Gas Metal Arc Welding (GMAW) is an adaptable process that can be used to weld a wide range of ferrous and nonferrous metals; to weld sheet metal or relatively heavy sections, and can be used for manual, semiautomatic or automatic welding using robots. Robotic GMAW welding process is more advantageous than manual GMAW welding process in the quality and productivity. However, setting up the process parameters of a robotic GMAW welding process must be done manually. Setting up the process parameters correctly is essential to ensure the precision and the quality of the welded joints [1]. Taguchi method utilizes a signal-to-noise (S/N) ratio to calculate the deviation between the experimental value and the desired value. There are Usually three categories of the quality characteristic in the analysis of the S/N ratio, namely; lower-the-better, higher-the-better and the nominal-the-better, depending on the goal of the design. The S/N ratio for each level of the process parameters is computed based on the S/N analysis. Furthermore, performing a statistical analysis of variance (ANOVA) to see which process parameters are statistically significant and to predict the optimal combination of the process parameters. Finally, a verification has to be performed to confirm the optimization results [2].

2. Literature Review

Several efforts have been made to optimize and model the effect of GMAW process parameters on the welded joints. These efforts utilized empirical methods and statistical approaches to derive mathematical models from the obtained experimental results. These models can be used to predict the response and to optimize the process input/output variables. Jaimea et al. [3] studied the effect of robotic GMAW process parameters on bead area geometry. The investigated GMAW parameters were welding voltage, torch travel speed and Wire feed speed. A three level factorial design of experiments was used for the training of the neural network of a radial basis function (RBF) neural network, which is used for the prediction of the cross sectional area of the welding bead.

Ambekar et al. [4] investigated the effect of GMAW parameters on the penetration for Martensitic stainless steel AISI 410 using Taguchi approach. They optimized GMAW parameters viz welding speed, welding current and wire diameter. ANOVA and signal to noise ratio were utilized to identify the significant factors and to predicted optimal parameter setting. They confirmed the results and found that Taguchi method was successfully implemented.

Malhi and singh [5] investigated the effect of GMAW welding parameters viz. welding voltage, welding current and welding speed on ultimate tensile strength of AISI 1030 mild steel. Taguchi technique was used in the experimental design. An orthogonal array, signal to noise ratio and analysis of variance were utilized in the study of the welding characteristics of the material and in optimizing the process parameters. Sivasakthivel et al. [6] studied the welding process parameters in MIG welding of Titanium alloy plates by using Taguchi technique. They investigated the effect of three main parameters of MIG welding viz., current, voltage, and travel

speed on tensile strength. Based on the results of S/N ratio and ANOVA analysis, the process parameters were found significantly affect the tensile strength and the optimal solution was found out.

3. Experimental design and procedure

The work of this paper is based on the results obtained by Ghazvinloo et. al [7], where they investigated the effect of robotic MIG welding parameters; namely arc voltage, welding current and welding speed on fatigue life of AA6061 butt joints. The filler metal was ER5356 (AWS A5.10-92 classification) wire electrode having a chemical composition as given in Table 1, and the MIG welding process parameters were set up as shown in Table 2.

Table 1: Chemical composition of the filler metal (ER5356) [7]

Elements	Al	Mn	Si	Fe	Mg	Cr	Ti	Zn	Cu
Wt (%)	Balance	0.125	0.25	0.4	5	0.125	0.13	0.1	0.1

Table 2: Welding process parameters set up [7]

Cylinder pressure (bar)	145
Cylinder outlet pressure (l/min)	14
Nozzle opening (mm)	10
Electrode stick out (mm)	19.2
Arc length (mm)	3
Nozzle-to-work distance (mm)	20.2
Contact tip-to-work distance (mm)	22.2
Arc voltage (V)	20, 23, 26
Welding current (A)	110,130, 150
Welding speed (mm/min)	500, 600, 700
Wire feeding rate (m/min)	8
Torch angle (degree)	5
Droplet transfer	Spray transfer mode
Polarity	DCEP
Shielding gas	100% Argon
wire electrode diameter (mm)	1

Modeling and optimization of the process were carried out utilizing Taguchi approach, L9 orthogonal array was applied which composed of three columns and nine rows, which mean that three welding parameters with three levels each and nine experiments, the three welding parameters are: arc voltage, welding current and welding speed. Table 3 shows the experimental input variables and their levels. The Taguchi method was applied to the experimental data using statistical softwares “Design-expert 9” and “MINITAB 17”. The S/N ratio for each level of process parameters is computed based on the S/N analysis.

Furthermore, a statistical analysis of variance (ANOVA) was performed to see which process parameters are statistically significant. The optimal combination of the process parameters can then be predicted. Assigned nine experiments and their responses are presented in Table 4.

Table 3: Process parameters and design levels used

Variables	Code	Unit	Level 1	Level 2	Level 3
Current	I	Amp	110	130	150
Volt	V	Volt	20	23	26
Welding Speed	S	cm/min	50	60	70

Table 4: Taguchi design matrix in actual values of the studied parameters and their measured responses

Std	I, Amp	V, Volt	S, cm/min	Fatigue Life, (No. of cycles to failure)
1	110	20	50	221
2	110	23	60	331
3	110	26	70	429
4	130	20	60	325
5	130	23	70	408
6	130	26	50	101
7	150	20	70	390
8	150	23	50	98
9	150	26	60	246

4. Results and discussion

Fatigue test was performed at room temperature in order to evaluate the fatigue life of the weldments obtained in the different welding conditions. The specimens were tested at the 180 MPa stress range only with stress ratio of 0.1 in order to investigate the effect of the MIG parameters on the fatigue life of weld metals[7]. Table 5 shows the measured responses. Design expert 9 software was utilized for analyzing the measured responses. The fit summary output indicates that the developed linear model is statistically significant for the prediction of the response, therefore it will be used for further analyses. It has been seen that the fatigue life is controlled by the rate of heat input, which is a function of arc voltage, welding current and welding speed. But the welding speed parameter is mostly affecting the fatigue life.

4.1 The signal-to-noise (S/N) ratio analysis

To evaluate the influence of each selected factor on the response: The signal-to-noise ratios S/N for each control factor were calculated. The signals have indicated that the effect on the average responses and the noises were measured by the influence on the deviations from the average responses, which would indicate the sensitiveness of the experiment output to the noise factors. The appropriate S/N ratio must be chosen to depend on the goal of the design. In this study, the S/N ratio was chosen to accord to the criterion the-larger-the-better, in order to maximize the response. The S/N ratio for the-larger-the-better target for all the responses was calculated as follows:

$$S/N = -10 \log [(\Sigma 1/Y^2)/n]$$

where y is the average measured fatigue life, n the repetitions, in this study = 9. Using the above-presented data with the selected above formula for calculating S/N, the Taguchi experiment results are summarized in Table 5 and presented in Fig. 1, which were obtained by means of MINITAB 17 statistical software. It can be noticed from this figure, the S/N plot, that the welding speed is the most important factor affecting the responses; the maximum value of response is at the highest level of welding speed. Welding current has a lower relevant effect. While the arc voltage show the lowest effect among these factors. Main effects plot for S/N ratios suggest that these levels of variables would maximize the fatigue life, also were robust against variability due to noises as presented in Fig.1.

Table 5: Response for signal-to-noise ratio (S/N)

level	1	2	3	Delta	Rank
Current	49.98	47.51	46.49	3.49	2
Voltage	49.65	47.48	46.85	2.80	3
Welding Speed	42.27	49.48	52.23	9.96	1

4.2 Analysis of variance

The purpose of the ANOVA is to investigate which factor is significantly affect the quality characteristic. This is accomplished by separating the total variability of the S/N ratios, which is measured by the sum of the squared deviations from the total mean of the S/N ratio, into contributions by each factor and the error [8]. Design Expert 9 software was utilized to test the significance of the developed linear model, the significance of the individual model coefficients and the lack-of-fit. ANOVA for the developed model is exhibited in Table 6.

Fig. 1 Main effects plot for S/N ratio

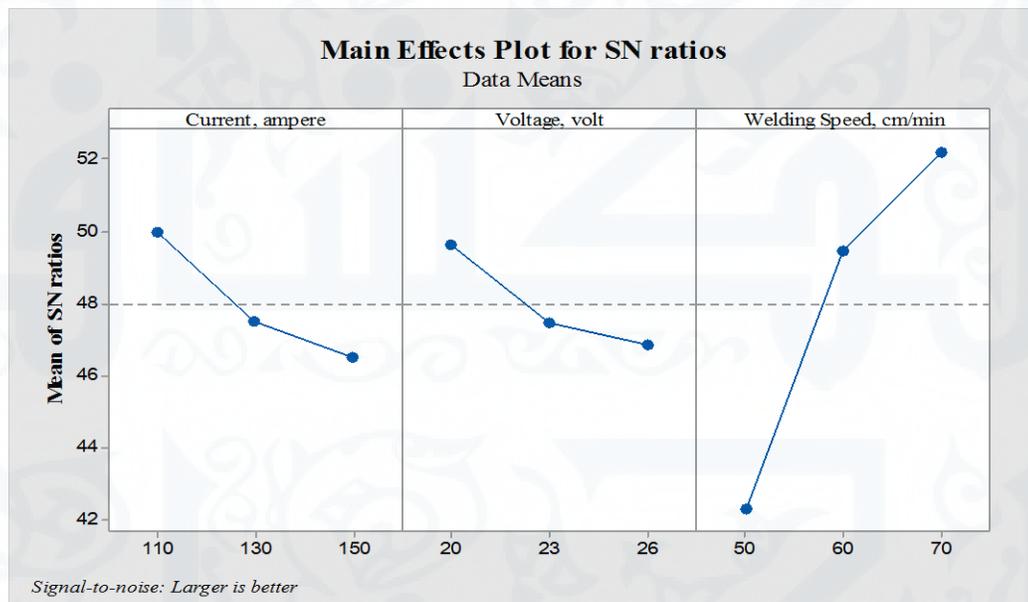


Table 6: ANOVA Table for fatigue life model

Source	Sum of Squares	d f	Mean Square	F-Value	P-value	
Model	1.230E+005	3	40992.11	100.31	< 0.0001	significant
I	10168.17	1	10168.17	24.88	0.0041	
V	4266.67	1	4266.67	10.44	0.0232	
S	1.085E+005	1	108500	265.61	< 0.0001	
Residual	2043.22	5	408.64			
Cor. Total	1.250E+005	8				
R-Squared = 0.9837			Adeq Precision = 24.091			
Adj. R-Squared = 0.9739						
Pre. R-Squared = 0.9454						

4.2.1 ANOVA outputs

The ANOVA indicates that the three studied parameters significantly affect fatigue life, High F value for a parameter means that the effect of the parameter on the fatigue life is large. The results show that the highest value of F is at welding speed of about 265.61, and at arc voltage and welding current equal to 10.44 and 24.88 respectively. This means that arc voltage and welding current parameters have less effect on the fatigue life. The same Table shows the other adequacy measures R², Adjusted R² and Predicted R². All the adequacy measures indicate an adequate linear model. The adequate precision is 24.091, indicating adequate model discrimination. The developed linear model in terms of actual factors as determined by design expert software are shown below.

$$\text{Fatigue Life} = -51.75 - 2.058 * I - 8.889 * V + 13.45 * S$$

4.3 Validation of the model

Fig. 2 exhibited a plot of the actual values versus predicted values for fatigue life. It indicates that the developed model is adequate since the residuals in prediction of the fatigue life are negligible, where the residuals tend to be close to the diagonal line. Furthermore, to verify the satisfactoriness of the developed model, three confirmation experiments were selected within the studied range of the parameters to confirm the model validation. Table 7 shows the actual and predicted values of fatigue life and the percentage of absolute error in the prediction.

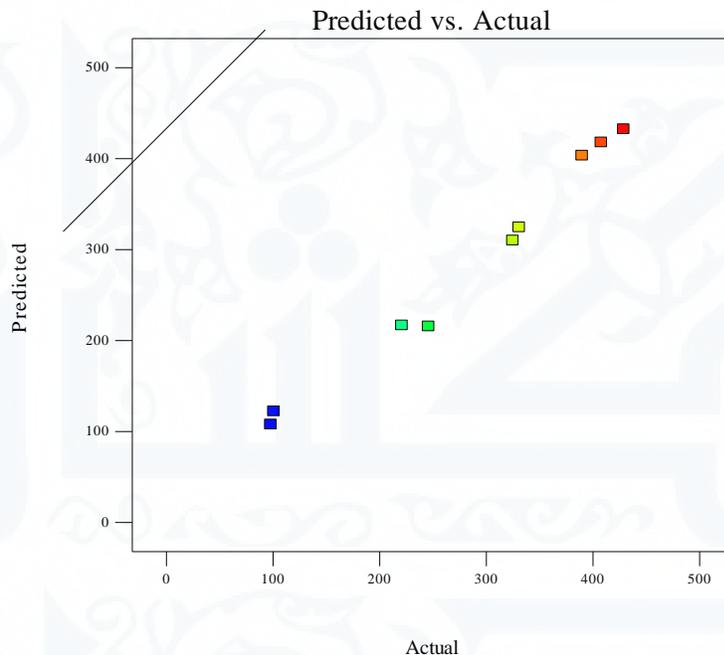


Fig. 2 Predicted values of fatigue life vs. actual measured values

Table 7: Confirmation experiments of the fatigue life

Std	I, Amp	V, Volt	S, cm/min	fatigue life		E %
				Act.	Pred.	
1	110	20	70	476	485	2
2	110	26	50	161	163	1
3	150	23	70	366	376	3

4.4 Model Optimization

The developed model was utilized to optimize the welding input/output parameters. Achieved results were based on the criteria presented in Table 8. Selected importance for each factor is presented in the same table. The selected importance greatly affects the result and it is essential to select it correctly. The numerical optimization results are presented in Table 9.

Table 8: The optimization criteria for input/output welding parameters

Parameter	Current	Voltage	Speed	fatigue life
Criteria	min	min	max	max
Importance	+++	+++	+++	+++ ++

Table 9: The numerical optimization results

Current	Voltage	Speed	fatigue life	Desirability
110	20	70	485	1

5 Effect of the parameters on the response

The results indicated that the welding speed is the most significant factor affecting fatigue life, as shown in Fig. 1 and table 6. It is clear that as welding speed increases fatigue life increase, the fatigue life has the highest value at welding speed of 70 cm/min. It is also evident from the results that arc voltage and welding current also have a significant effect on fatigue life of the welded joints. Fig. 3 is a contour graph shows the effect of S and I on fatigue life at V = 20 volts. While Fig. 4 is a 3D plot to present the effect of S and I on fatigue life at V = 20 volts.

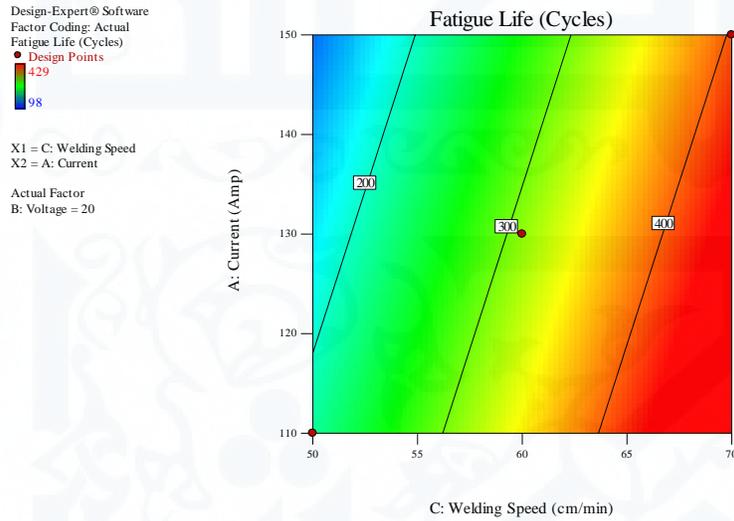


Fig. 3 Contour graphs exhibiting the effect of S and I on fatigue life at V = 20 V.

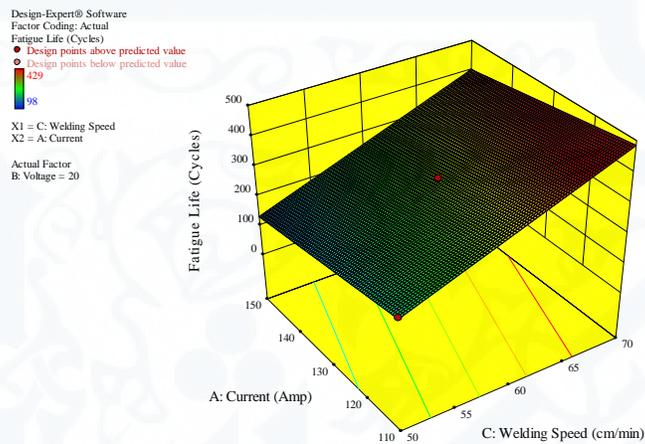


Fig. 4 3D graph shows the effect of S and I on fatigue life at V = 20.

6. Conclusion

The following points were concluded from this study:

- (i) Based on S/N ratio and ANOVA welding speed has a strong significant effect on fatigue life, changing welding speed value will dramatically change fatigue life, so welding speed should be carefully selected. Arc voltage and welding current also have a significant effect on fatigue life.
- (ii) The developed model can be adequately used in predicting fatigue life within the applied limits of process parameters.

- (iii) Optimum value of fatigue life can be obtained by the optimal parameter setting (i.e. welding current=110 Amp, arc voltage = 20 V and welding current = 70 cm/min).
- (iv) Taguchi approach can be efficiently utilized to model and optimize MIG welding processes.

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