Experimental Study of Mechanical Properties and Hardness in Gas Metal Arc Welding on SUH 310S Steel Using Response Surface Methodology

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Abstract

Due to technological advances and the growing need to repair parts at low cost, the gas metal arc welding (GMAW) method has become increasingly popular among industrialists. The response surface methodology (RSM) and model validity were measured with standard statistical measures. In this research, the input parameters including; welding speed (mm/min), voltage (V), and wire feed rate (cm/min), have been selected as input parameters. Mini-tab software was utilized to carry out modeling and optimization using RSM. On heat resistance steel (SUH 310S) using the RSM method, 17 experimental experiments were designed with three center points. According to the signal-to-noise ratio (S/N), the effective parameters of mechanical properties and hardness are wire feed rate, voltage, and welding speed, respectively. The results showed that the analysis of variance (ANOVA) with the desirability model obtained 0.953. Optimum levels for each input variable were analyzed in terms of mechanical properties and welding hardness. Finally, the optimum levels obtained are welding speed of 250 mm/min, wire feed rate of 210 cm/min, and voltage of 17 volts.

Keywords: Gas Metal Arc Welding, Response surface methodology, SUH 310S steel, Mechanical properties, Optimization.

1. Introduction

Among many austenitic stainless steel materials, because SUH 310S stainless steel sheet has higher chromium and nickel content than ordinary 18-8 austenitic SUH 310S, its heat resistance and corrosion resistance are relatively better, and it can be used at temperatures as high as 1090 ℃ [1,2]. SUH 310S continuous used at high temperature [3]. SUH 310S plate should be forged at a temperature of about 1175 °C, and the forging temperature should not be lower than 980 °C [4,5]. After forging, rapid air cooling or direct water quenching of small forgings is required [6]. For optimum corrosion resistance, it should also be annealed after forging [7]. SUH 310S sheet can be used to produce furnace components, furnace plates, high temperature vessels and welding wire [8,9]. The material can also be used further in many applications by taking advantage of its thermal properties.

Gas metal arc welding (GMAW) is one of the welding methods in the industry, such as special structures of Power stations [10]. High flexibility, possibility of welding in different thicknesses, increased production capability and possibility of automatic implementation of reasons distinguish this method from other welding methods [11]. This process is widely used in various industries, including pipelines, petrochemicals, buildings, automobiles, and ships [12]. In this process, the continuity of the consumed electrode, welding discontinuity, lack of slag, and low thermal hazard in the base metal are considered the advantages of this method, in which the continuity of the consumed electrode is an essential advantage that increases the productivity

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rate [13]. In large industries, the cost is high, and this factor is entirely dependent on the determination of the welding variables in the welding process with gas protection and the equation between the existing parameters and how to achieve the desired state [14,15]. Among all techniques, one common method is GMAW welding with neutral gas [16].

J. Vora et al. [17] studied the wire arc additive manufacturing (WAAM) method based on GMAW welding to fabricate multilayer structures with optimized process parameters on SS316L using SS316L metal wires. The microstructure, macrostructure, and mechanical properties (tensile test, impact test, microhardness, and fractography) of the multilayer structure were examined. The results of all tensile properties of high, medium, and low surface tests developed by the WAAM process are within the range of SS 316L values. The UTS, YS, and elongation of the used SS316L were 485 MPa, 220 MPa, and 45%, respectively. The average number of specimens of UTS, the upper, middle, and lower zone and height of YS were 512.53 MPa, 256.57 MPa and 49.35%, respectively. Therefore, it can be concluded that the experimentally measured UTS, YS, and elongation of the WAAM process developed parts are within the limits of the SS 316L grade values used. Chen et al. [18] studied the fabrication of SS316L alloys by the GMAW process. The main objective of this study was to determine the effect of heat treatment on strength and corrosion behavior. The results showed that high temperature and time of treatment heat caused SS 316L to deteriorate. The ultimate tensile strength and yield strength were changed by the heat treatment carried out at 1000 °C. Also, the maximum strength of the AM components was found to be similar to SS 316L. Ahsan et al. [19] have developed a bimetallic additively manufactured structure of SS 316 L, and low alloy carbon steel to produce a WAAM structure of two different materials using the GMAW process. Two separate layers of low-carbon and stainless steel were shown on the welded area in the microstructure definition, and no defect was seen in the specified area. In the microhardness test, the hardness value was more significant in the stainless steel region due to Cr. However, the hardness value was observed at the lower part of the low-carbon steel. So the standard design failed from that point of view and that part of the carbon steel had less strength. Another study by Ji et al. [20] used the WAAM process to fabricate SS 304L. He studied mechanical properties through complex testing and micro-structures through metallographic research. The result is that when the components are placed in another place, the temperature increases, the dendrite's thickness increases, and the microstructure remains the same. In the presence of dendrites, the stiffness will be different in the vertical and horizontal directions, which will affect the mechanical properties. Their findings revealed that the presence of dendrites changed the strength of the boundary between longitudinal and lateral pathways. This resulted in anisotropy of mechanical properties.

In the present study, wire feed rate, welding speed, and voltage have been considered as effective input parameters of the process and according to the necessities of research, the parameters of mechanical properties and hardness are output parameters. RSM modeling was used to establish the interaction between process input and output parameters. The purpose of this research is to model the output parameters based on the input parameters and also to optimize the mechanical properties and hardness. Finally, the optimized part is examined regarding hardness and mechanical properties.

2. Materials and methods

The purpose of this research is to optimization mechanical properties and hardness to investigate the influence of effective parameters in neutral gas welding. For this purpose, as shown in Fig. 1, GMAW process devices Including the carry MIG 501 wire feed system and FP4M machine were used. Referring to the above, in this research, 17 experiments were carried out on heat resistance steel (SUH 310S) with 10×30×50 mm^3, as the base metal in GMAW welding. Failure to control the consumable electrode on the workpiece will lead to deviation from the welding center or false joining of the welding point. The reason for using the milling machine is to move in the direction of the X, Y, and Z-axis and to automate the GMAW process. The SUH 310S (base metal) and stainless steel 743 (wire electrode) chemical composition and mechanical properties are shown in Tables 1 and 2. Due to the use of GMAW welding, the feeding wire electrode is a consumable material in the form of welding electrodes the material is stainless steel 743, the diameter of the electrodes is 1 mm and produced by AMA company. Carbon dioxide (CO_2) gas was used as a shielding gas.

Table 1. Chemical composition of SUH 310S steel.

Metal	Fe	C	Mn	P	Si	Cr	Ni	Cu
SUH 310S steel	Bal	0.10	2.00	0.05	2.50	25.00	21.00	--
Stainless steel SS743	Bal	0.03	1.50	0.01	0.65	21.00	12.00	0.70

Table 2. Mechanical properties of SUH 310S steel.

Mechanical properties	UTS	YS	Elongation	Hardness
Unit	(MPa)	(MPa)	(%)	(HB)
Value	524	217	40	225

Fig. 1. GMAW process devices.

In this research, the input parameters including welding speed (mm/min), voltage (V), and wire feed rate (cm/min) have been selected as input parameters. Mini-tab software was utilized to carry out modeling and optimization using RSM. On heat resistance steel (SUH 310S) using the RSM method, 17 experimental experiments were designed with three center points. Properties sample welding that was measured directly from the tensile test. A standard tensile test was performed to evaluate the mechanical properties of the optimized part. In this test, sample is prepared according to the ASTM-E8 standard. It should be noted that the test was performed at room temperature at a speed of 10 mm/min.

3. Response Surface Methodology

The design of experiments (DoE) is a scientific solution that provides targeted changes to the factors affecting a process or product and then examines the resulting changes in output, which provide extensive information and understanding of the process, development, and how these factors affect the response. In designing an experiment, the first step is to determine the response variables. Then the parameters affecting the problem must be identified and the variable levels must be determined. Then, according to the parameters and levels considered for each parameter, experiments were performed. In this research, the aim is to the effect of material and process parameters on the mechanical properties and hardness of welded samples using the GMAW process. One of the essential mechanical properties can be mentioned tensile strength, which determines the amount of tolerable stress by the part under tensile loads, which is considered the response variable. The structure of boiling points of samples produced in different process conditions was also investigated. After identifying the response variables and parameters affecting the problem, the next step is determining the number of levels studied for the parameters and their range. According to the studies, the usual welding speeds of 200, 300, and 400 mm/min, the voltage of 17, 27, and 32 volts, and wire feed rates of 210, 231, and 253 cm/min were selected. The purpose of choosing the minimum welding speed, equal to 200 mm/min, was that the possibility of performing a welding process lower than this speed in the method used was impossible and a connection between the electrode and sample was not accepted. Also, the reason for choosing the welding speed of 400 mm/min as the maximum welding speed was the limitation of the machine used for welding. Therefore, it is necessary to use a suitable test design to reduce the number of tests. In this research, wire feeding speed (electrode), welding voltage, and welding speed as effective input parameters have been placed on the welding cross-section. The data and intervals of each process variable can be seen in Table 3. The experiments were performed in the same laboratory conditions based on RSM with different parameters. The DoE methods such as the RSM method are an effective way to reduce the number of experiments. The parameters and levels tested for each parameter in the present study are in Table 4. The experiments of the said research were designed as a table using the Minitab software.

Table 3. Input parameters of GMAWed process.

GMAW parameter	Voltage (V)			Wire feed rate (cm/min)			Welding speed (mm/min)		
Unit	low	medium	high	low	medium	high	low	medium	high
Code	-1	0	+1	-1	0	+1	-1	0	+1
Range	17	27	32	210	231	253	200	300	400

Table 4. Input and output parameter.

	Coded			Actual values			Responses	
No.	Welding speed	Voltage	Wire feed rate	Welding speed	Voltage	Wire feed rate	Mechanical properties	Hardness
#1	1	-1	1	400	17	253	674	88
#2	0	0	0	300	27	231	643	85
#3	-1	-1	-1	200	17	210	611	86
#4	0	0	1	300	27	253	635	85
#5	-1	1	-1	200	32	210	655	89
#6	-1	1	1	200	32	253	639	86
#7	0	0	0	300	27	231	643	85
#8	-1	0	0	200	27	231	623	83
#9	1	0	0	400	27	231	634	86
#10	0	1	0	300	32	231	655	87
#11	1	1	1	400	32	253	623	86
#12	1	1	-1	400	32	210	641	89
#13	0	0	-1	300	27	210	678	91
#14	1	-1	-1	400	17	210	612	84
#15	0	-1	0	300	17	231	594	82
#16	-1	-1	1	200	17	253	612	87
#17	0	0	0	300	27	231	643	85

The RSM approach is a method to determine the interaction between different process parameters with varying criteria of welding and investigate the effect of these process parameters on related responses. RSM is a set of mathematical and statistical techniques that are useful for modeling and analyzing problems in which the desired answers are affected by several variables. The RSM method is a strategy for building experimental and optimization models. By performing experiments and using regression analysis, a response model to some independent input variables is obtained. In the surface response method, independent parameters can be shown based on Eq 1.

$$y = f[x_1 . x_2 . x_3 \dots \dots \dots x_n] \quad \text{Eq. (1)}$$

When Y is the answer, F is the function's answer, X is an experimental error, and X_1, X_2, …., X_n are independent parameters. By plotting the expected response Y, a level known as the RSM is obtained. The shape of the F function is unknown and can be very complex. Therefore, the RSM method intends to compare the F-value with a lower-order polynomial in some independent process variables. If the response is well modeled by a linear function of the independent variable, Eq 1 can be equated with Eq 2:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \cdots \dots \dots + \beta_n x_n \quad \text{Eq. (2)}$$

However, if a curvature appears in the system, higher-order polynomials, such as the Quadratic equation model can be used according to Eq 3:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum\sum_{i<j} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} {x_i}^2 + \varepsilon \quad \text{Eq. (3)}$$

Regression analysis is performed when the dependent set related to the experimental orientations is collected. Then, an appropriate statistical analysis such as ANOVA analysis, is performed to identify the effects of factors on dependents as well as the interactions between factors. Then, the developed model is justified by a validation test.

4. Results and discussion

4.1. Tensile test

Improving mechanical properties has always been one of the most important challenges. In this research, the tensile test at room temperature was used to check the mechanical properties. Fig 2 shows the tensile test sample after the GMAWed process in SUH 310S Steel. The tensile test of the samples showed that all the samples behave close to each other in the tensile stress. This same behavior shows the significant potential of the base metal. The range of low changes in tensile stress indicates the quality of welding, the compatibility of the used electrode with the BM, and the low residual stress of the welding site. After the tensile test, the prepared test samples were all broken from the base metal or HAZ area and based on the results, the fracture occurred in a part of the triple HAZ area, which has the lowest strength due to the grain size.

Fig. 2. Tensile test samples.

4.2. Responses optimization of RSM mothed

The data output was obtained by entering the results of the tensile test in Minitab software and analyzing it by the Ryan-Joyner method. The P-value in the obtained diagram is greater than the risk probability value of 0.05. It's concluded that the results related to the tensile strength of the welded sample follow the normal distribution. Due to the normal distribution of the data, the ANOVA of the data obtained from the tensile test is checked. One of the essential topics in analyzing the results of experimental tests is to study the interaction effects of parameters on the response variable. The two-parameter interactions that had the most significant effect on the tensile strength of welded sample have been investigated from the S/N table. The deal of tensile strength has increased with increasing speed welding. This is due to the decrease in melt strength, which increases the adhesion and improves the weld strength. The obtained interactions for modeling and predicting the outputs of the welding process are shown in Eqs 4 and 5.

Eq. (4)

Mechanical properties = 643.18 + 3.77 welding speed + 11.10 voltage - 3.17 wire feed rate - 5.73 welding speed*welding speed - 7.15 voltage*voltage + 4.17 wire feed rate*wire feed rate - 11.62 welding speed*-voltage + 7.38 welding speed*wire feed rate - 12.13 voltage*wire feed rate

Eq. (5)

Hardness = 84.925 + 0.296 welding speed + 0.982 voltage - 0.812 wire feed rate + 0.083 welding speed*welding speed + 0.083 voltage*voltage + 1.320 wire feed rate*wire feed rate + 0.125 welding speed*voltage + 0.375 welding speed*wire feed rate - 1.375 voltage* wire feed rate

ANOVA was used to check the accuracy of the obtained modeling interactions. If the obtained P-value is less than 0.05, the accepted model has 95% confidence. Tables 5 and 6 show the results of ANOVA of the proposed models.

Due to the appropriateness of the modeling equations, the interaction of the input parameters with the output parameters is reported separately below. Fig 3 shows the 3D surface plot of the wire speed and voltage parameters related to the mechanical properties. By increasing the voltage and wire feed rate, the width of the mechanical properties increases. The modeling results performed in Minitab software were reviewed separately in this section.

Table 5. ANOVA for the mechanical properties model.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	6101.92	677.99	2.51	0.019
Linear	3	2014.22	671.41	2.48	0.025
welding speed	1	194.20	194.20	0.72	0.025
voltage	1	1682.62	1682.62	6.22	0.041
wire feed rate	1	137.39	137.39	0.51	0.099
Square	3	1395.33	465.11	1.72	0.049
welding speed * welding speed	1	370.49	370.49	1.37	0.080
voltage * voltage	1	575.84	575.84	2.13	0.088
wire feed rate * wire feed rate	1	195.73	195.73	0.72	0.023
2-Way Interaction	3	2692.37	897.46	3.32	0.087
welding speed * voltage	1	1081.13	1081.13	4.00	0.086
welding speed * wire feed rate	1	435.13	435.13	1.61	0.045
voltage * wire feed rate	1	1176.12	1176.12	4.35	0.075
Error	7	1892.55	270.36	3.55	0.634
Lack-of-Fit	5	1892.55	378.51	3.24	
Pure Error	2	1873.32	412.11		
Total	16	7994.47			
		$R^2 = 0.89$	$R^2_{adj} = 0.81$	$R^2_{predict} = 0.93$	

Table 6. ANOVA for hardness model.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	61.2878	6.8098	2.33	0.039
Linear	3	23.3707	7.7902	2.66	0.029
welding speed	1	1.1983	1.1983	0.41	0.043
voltage	1	13.1656	13.1656	4.50	0.072
wire feed rate	1	9.0068	9.0068	3.08	0.023
Square	3	21.5421	7.1807	2.45	0.048
welding speed * welding speed	1	0.0767	0.0767	0.03	0.076
voltage * voltage	1	0.0767	0.0767	0.03	0.076
wire feed rate * wire feed rate	1	19.6410	19.6410	1.71	0.036
2-Way Interaction	3	16.3750	5.4583	1.87	0.024
welding speed * voltage	1	0.1250	0.1250	0.04	0.051
welding speed * wire feed rate	1	1.1250	1.1250	0.38	0.055
voltage * wire feed rate	1	15.1250	15.1250	1.17	0.057
Error	7	20.4770	2.9253	1.11	0.636
Lack-of-Fit	5	20.4770	4.0954	1.37	
Pure Error	2	21.3281	4.9917		
Total	16	81.7647			
	$R^2 = 0.88$		$R^2_{adj} = 0.92$	$R^2_{predict} = 0.98$	

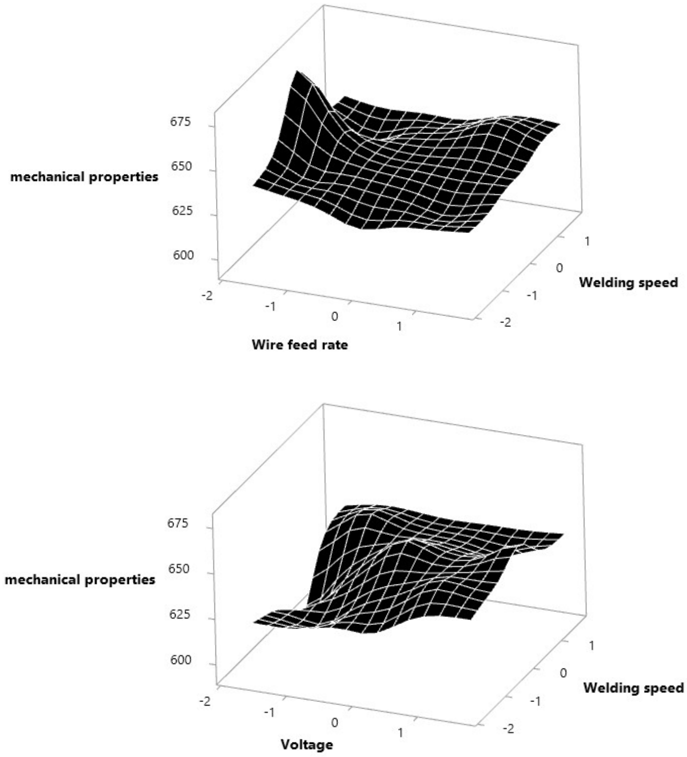

Fig. 3. 3D surface plot for mechanical properties.

The interactions mean of mechanical properties in Fig 4 show that the three primary parameters in the DoE are chosen correctly and they affect each other a lot. The results shown in each parameters are as follows: welding speed and voltage have an extreme point, but the opposite has been done in the wire feeding rate.

For better grain growth and optimal bonding, the maximum weld penetration depth in the SUH 310S steel is required. Therefore, the interaction of three-factors on the mechanical properties and hardness was investigated. Fig 5 shows the 3D plots of the objective response to different variables. The experimental results show that the three design variables have a significant impact on actual performance. As shown in Fig 5, when mechanical properties are constant, the objective function voltage first decreases and then increases with the increase of voltage and wire feed rate.

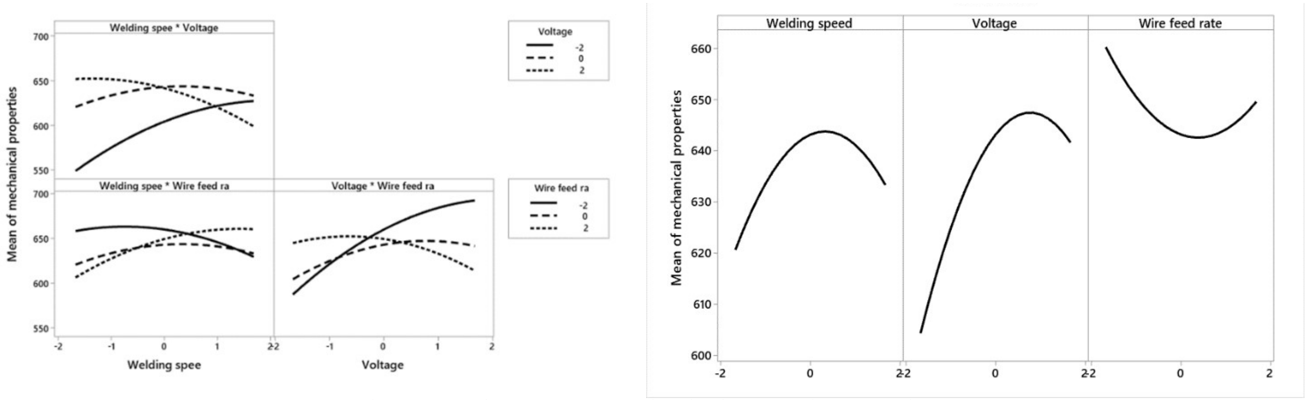

Fig. 4. Results mean of mechanical properties of optimization in RSM method.

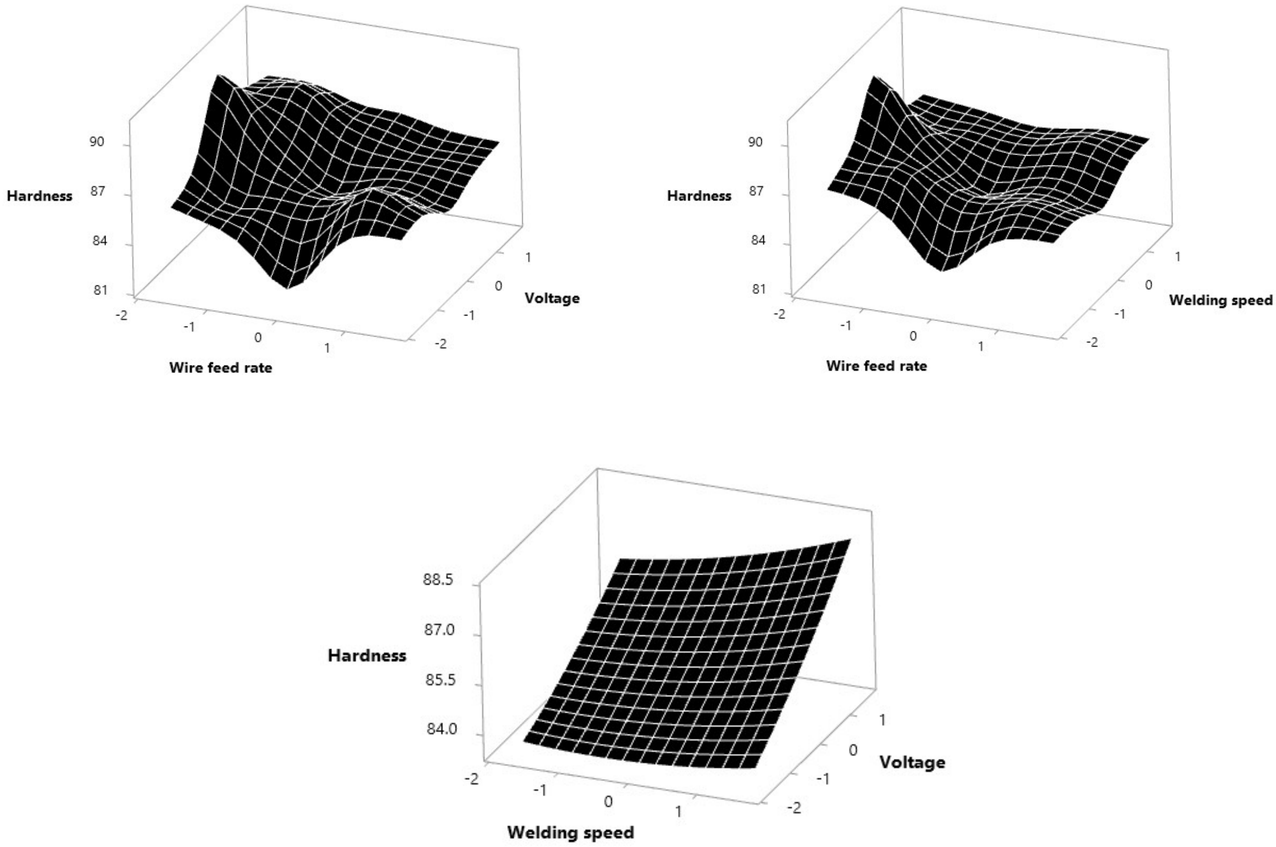

Fig. 5. 3D surface plot for hardness.

The interactions mean of hardness in Fig 6 shows that the three main parameters in the DoE are chosen correctly and they affect each other a lot. The results shown in each parameters are as follows: welding speed and voltage have a linear effect.

In this research, in addition to modeling the output parameters, optimization of the parameters of voltage, welding speed and wire feed rate concerning max model the mechanical properties and hardness with the Minitab software and RSM method are obtained. Table 7 shows the results of optimizing the input parameters. Voltage values of 17 volts, wire feed rate of 210 cm/min and welding speed of 250 mm/min. The desirability model value of 0.953 optimization result. The error rate is reported to be less than 0.1% and indicates that the optimization parameters are acceptable.

5. Conclusions

In this research, mechanical properties and hardness were investigated according to the parameters of the gas metal arc welding (GMAW) process. Input parameters including; voltage, welding speed, and wire feeding rate are modeled using response surface methodology (RSM) methods and the model's accuracy is measured by standard statistical measures.

- According to the P-value value in the analysis of variance (S/N) tables, we find that modeling by the RSM method has desirability.
- According to the validation test of the optimization, we find that the optimization has a level of reliability response.
- ANOVA results for the mechanical properties model are: R^2 = 0.89, R^2 (adj) = 0.81, and R^2 (predict) = 0.93, respectively.
- ANOVA results for the hardness model are: R^2 = 0.88, R^2 (adj) = 0.92, and R^2 (predict) = 0.98, respectively.
- The results of optimizing the input parameters are voltage values of 17 volts, wire feed rate of 210 cm/min, and welding speed of 250 mm/min. The desirability model is equal to 0.953.

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7. Conflict of Interest

The authors declared no potential conflicts of interest for the research, authorship, and publication of this article.

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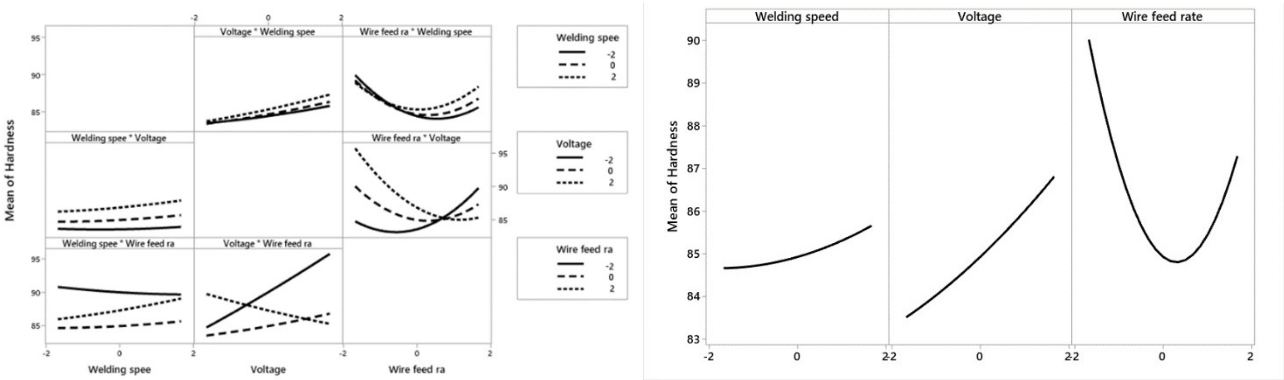

Fig. 6. Results mean of hardness of optimization in RSM method.

Table 7. Optimization of influential factors with the accuracy of the proposed model.

	Welding speed	Voltage	Wire feed rate	Mechanical properties	Hardness
Importance	*****	***	*	***	***
Real-Predict	250	17	210	676.331	88.9902

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