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Influence of SAW Welding Parameters on Microhardness of Steel A516-Gr60

Abstract- *Submerged Arc Welding (SAW) process is generally used for industries, such as petroleum storage tanks, pressure vessels, and structural components. Good mechanical properties of welded joint lead to crack-free strong joints. In this research, included angle, current, welding travel speed and arc voltage were utilized as welding parameters to weld ASTM A516 Grade 60 (low carbon steel). The experiments were carried out according to a design matrix that established by DOE (Version10) with RSM technique. Microhardness of welded samples was measured by a Digital Microhardness Tester, and then RSM technique was used to model and optimize the microhardness based on the welding parameters. The results showed that the including angle and welding current have a great effect on the microhardness. The optimum solution for minimum microhardness was found at 450 Amp welding current, 38 cpm welding speed, 34-volt arc voltage and included angle of 60 ^{o}. The optimum value of microhardness was (186.7 HV). Eventually, the experimental and predicted results of microhardness were found in good agreement with 4.6%. maximum error.*

Keywords- *SAW, Microhardness, Welding parameters, DOE, RSM*

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1. Introduction

SAW is a welding process that uses the arc between the materials and the uncoated welding wire. Both the weld pool and the arc are shielded by the flux. Such operation is generally used by big industries parts, like petroleum storage tanks, pressure vessels, and structural components [1]. Good mechanical properties of welded joint lead to crack-free strong joints. Microhardness of weld bead decreased with the voltage or current increase. The microhardness decrease with the current or voltage increase might be resulted due to slow cooling of the molten metal of weld because of greater heat produced at a high current level [2]. The welding current, voltage and electrode stick-out have remarkable effects on the weld hardness and HAZ hardness [3]. Type of flux and welding current were the most important factors influencing on the microhardness, where it possess a large increasing with the welding current increase [4]. Microhardness of the heat affected zone and weld metal dropped when the heat input was increased. For increasing the heat input, graphite and pearlite percentage reduced and ferrite increased, which led to better mechanical properties [5]. The speed of welding, nozzle space from the workpiece, arc voltage, current intensity, and oxide nanoparticles thickness of magnesium had the greatest influence on the hardness of melted zone [6]. The high cooling rate and low heat input caused the higher hardness, where the cooling rate was directly affected by the process parameters [7]. The microhardness increased with the increase in groove angle [8]. Considerable numbers of researchers in the area of submerged arc welding operation have tried to evolve its mathematical models using different computer programs, like factorial design, Taguchi method and finite FEA via ANSYS to investigate influence of welding parameters on the mechanical characteristics of SAW joint [9-11]. A few works have regarded the utilization of included angle during SAW operation. In addition to that, a few studies have considered the use of RSM method by design of experiment. In addition, response surface methodology is defined as a mathematical pluse statistical methods combination utilized to model analyze the problem and optimize a response based on input parameters. Thus, the objective of the present research is to study the effect of the process parameters (included angle, travelling speed, current, and voltage) on the microhardness produced during the SAW operation. After that, an empirical mathematical model for microhardness of the SAW joint will be built by the design of experiment software with response surface methodology technique. Additionally, an optimization process by using RSM technique

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will be carried out to find the optimum welding input factors.

2. The Experimental Procedure

I. Utilized Materials

The basic utilized alloys in this investigation include plates of Low Carbon Steel (ASTM A516 Grade 60) having 10 mm thickness, normally utilized for producing pressure vessels, tanks and boilers for petroleum industries. A flux type AWS F60-EM12K (with basicity index = 0.8) and AWS EM12K wire (4 mm diameter) were used for welding these plates. The chemical analyses of nominal and utilized plates are depicted in Table 1. The mechanical properties of these plates are shown in Table 2 to check the conformity of the used material with the nominal and also for the purpose of comparison. The nominal composition of AWS EM12K is depicted in Table 3 [13].

II. Conditions of SAW

In order to investigate the effect of the process parameters on the microhardness produced by submerged arc welding operation, the used parameters (voltage, included angle, travelling speed and current) were utilized as individual parameters in 2 levels, as given in Table 4. These levels were chosen depending on the previous practice plus the investigated results recorded in previous research. These levels are listed by (-1 and +1) codes according to the RSM input requirement.

Table 1: The composition of ASTM A516 Grade 60 plate steels (used and nominal plate)

Material (wt %)	%C	%Mn	%Si	%P Max.	%S Max.
Used	0.17	0.9	0.19	0.03	0.03
Nominal (For t ≤ 12.5 mm) [12]	0.21 Max.	0.60 to 0.90	0.15 to 0.40	0.035	0.03

Table 2: The mechanical properties of ASTM A516 Grade 60 steels (used and nominal)

Material	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
Used	430	295	31
Nominal [12]	415 - 550	220 Min.	25 Min.

Table 3: The composition of EM12K wire [13]

%C	%Mn	%Si	%S	%P	%Cu
0.05 - 0.15	0.80 - 1.25	0.10 - 0.35	0.030	0.030	0.35

Table 4: Levels of used parameters

Input parameters	Levels	
	-1	+ 1
Welding current (Ampere)	350	450
Arc voltage (volt)	30	34
Traveling Speed (cpm)	35	45
The included Angle	54°	66°

III. Procedure of Welding

Sand blasting was used to remove the contaminations and oxides and clean the surfaces of pieces, which were cut from the plate. 60 pieces were used in this study with dimensions (300x150x10 mm). Included angles were made by a milling cuter. The included angles were 72°, 66°, 60°, 54° and 48°. The design matrix (Table 5) was used to conduct the experiments which created by (DOE) program with the selected levels to determine the influence of welding factors on microhardness produced in SAW process. A sample of welded pieces is shown in Figure 1. Figure 2 views the welding machine which was used in the experiments.

Table 5: Matrix of design for the input parameters and the response (Microhardness)

Std. No.	Run No.	Current (Amp.)	Voltage (volt)	Welding speed (cpm)	Included angle (deg.)	Micro hardness HV
1	4	350	30	35	54	200
2	16	450	30	35	54	188.06
3	14	350	34	35	54	204
4	30	450	34	35	54	196.2
5	2	350	30	45	54	193.65
6	22	450	30	45	54	190
7	28	350	34	45	54	205
8	21	450	34	45	54	201.3
9	1	350	30	35	66	240.45
10	11	450	30	35	66	191.8
11	18	350	34	35	66	244.9
12	8	450	34	35	66	195
13	5	350	30	45	66	223
14	20	450	30	45	66	180.7
15	24	350	34	45	66	228
16	10	450	34	45	66	185.9
17	26	300	32	40	60	210
18	29	500	32	40	60	163
19	7	400	28	40	60	199
20	6	400	36	40	60	216.66
21	17	400	32	30	60	205.85
22	13	400	32	50	60	190
23	27	400	32	40	48	210.63
24	15	400	32	40	72	236
25	19	400	32	40	60	192.7
26	3	400	32	40	60	192
27	12	400	32	40	60	193
28	23	400	32	40	60	191
29	9	400	32	40	60	192
30	25	400	32	40	60	193

Figure 1: Welded plate sample at input welding factors of run No. 1

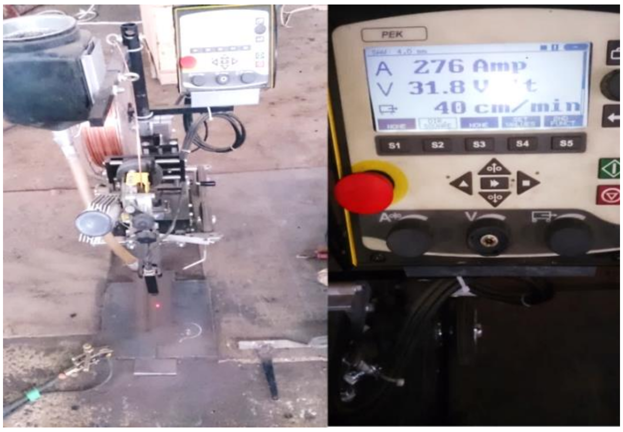

Figure 2: A view of EsabA2 Multitrack welding machine with the A2-A6 process controller PEK

IV. Microhrdness Test

The microhardness test was carried out by using a Digital Microhardness Tester, which was conducted in the department of Materials Engineering at University of Technology/ Baghdad, shown in Figure 3. Microhardness measurements were taken in central axes of welding using pyramid indenter with a load of 1 kg and a loading time of 15 seconds according to ASTM-E384. Three readings of microhardness were recorded for each specimen and the average value was taken.

V. Design of Experiments

In this research, the experiments were carried out according to the design matrix that found by design of experiment (DOE) software (DESIGN EXPERT10) with the technique of RSM, which utilized to establish a model according to the results of experiments. The curvature was modeled by the quadratic functions of response surface. The total experiments were 30 runs carried out according to the matrix of experimental design. The runs were carried out based on the order of run that presented in Table 5. Each parameter used levels was coded between -2 and +2. The design matrix was utilized for the obtained microhardness values with the input parameters, as shown in Table 5. Prediction model has 95% confidence level.

Figure 3: Digital microhardness tester

3. Results and Discussion

I. Microhardness modeling

Quadratic response surface model for microhardness was built by utilizing the experimental data given in Table 5. From Table 6, The F-value 345.54 of model indicates the significance of the model. Prob. > F values lower than 0.05 mean the model terms are significant. In this model, the terms A, B, C, D, AC, AD, BC, BD, CD, A^2, B^2, C^2 and D^2 are highly important. Therefore, such model implies that all welding parameters had a great impact on the microhardness of the welded joint. The final predicted empirical quadratic model developed for microhardness, which induced in SAW of A516 Grade 60 steel, is stated as follows:

$$\text{Microhardness} = +973.44833 + 1.87322A - 59.27208B - 3.64333C - 4.43167D + 6.63500AC - 0.032471AD + 0.081625BC - 0.088229BD - 0.11717CD - 5.5466A^2 + 0.98646B^2 + 0.058783C^2 + 0.21714D^2$$

Where,
A: Current
B: Voltage
C: Welding speed
D: Included angle

Checking adequacy of the model was carried out by using the analysis of residual, and the data presented in both Figures 4 and 5. The normal probability is presented in Figure 4, where from this figure it can be noted that the residuals exist on a straight line. Figure 5 shows that the residuals are distributed in both positive and negative directions without any explicit unusual style. This implies that this model is adequate. Figure 6 appears that the predicted microhardness values are close to the measured ones in the experiments, indicating a proper fitting between experimental and predicted data. The microhardness perturbation in such model is depicted in Figure 7. Also, this figure reveals that the included angle (D) highly increased the microhardness along the used levels (54° – 66°), this influence is considered most probably due to increase the volume of filler metal deposited and the strength of joint increased with the increase of groove angle (included angle). Also, it can be observed that the arc voltage (B) increased slightly the microhardness along the chosen levels (30–34 Volt), such result could be possibly due to that increasing the voltage increased the consumption of flux that has caused many alloying elements enter the weld metal. Therefore, the voltage affects the composition of weld metal and then increased the microhardness of weld metal. While, the welding current (A) possesses an opposite influence, the value of microhardness highly reduced at the higher level (450 Amp.), such result is likely to be caused by heat input increase which associated with the reduction in cooling rate, and this leads to coarse grains then decrease the microhardness. However, the welding speed (C) had a slight influence on the microhardness at all levels. This result also becomes certain with two-dimensional and three-dimensional surface plots manifested in the Figures 8 and 9, respectively in relation with current and arc voltage at (60°) included angle and (40 cpm) welding speed, where a similar behavior was observed when varying the welding speed and the included angle over the ranges (35-45 cpm) and (54-66°), respectively.

Table 6: ANOVA variance for output Surface Reduced Squared Model (for Microhardness)

Source	Sum of Squares	df	Mean squares	F-value	Prob > F
Model	9493.09	13	730.24	345.54	< 0.0001 significant
A-Current	3851.68	1	3851.68	1822.57	<0.0001
B - Voltage	322.37	1	322.37	152.54	< 0.0001
C - Welding speed	297.93	1	297.93	140.98	< 0.0001
D-Included angle	1097.28	1	1097.28	519.22	<0.0001
AC	44.02	1	44.02	20.83	0.0003
AD	1518.27	1	1518.27	718.43	<0.0001
BC	10.66	1	10.66	5.04	0.0392
BD	17.94	1	17.94	8.49	0.0102
CD	197.68	1	197.68	93.54	<0.0001
A^2	52.74	1	52.74	24.96	0.0001
B2	427.05	1	427.05	202.08	<0.0001
C^2	59.24	1	59.24	28.03	<0.0001
D^2	1676.07	1	1676.07	793.10	<0.0001
Residual	33.81	16	2.11		
Lack of Fit	30.80	11	2.80	4.65	0.0511 not significant
Pure Error	3.01	5	0.60		
Cor Total	9526.91	29			

Std. Dev.	1.45	R-Squared	0.9965
Mean	201.76	Adj R-Squared	0.9936
C.V.%	0.72	Pred R-Squared	0.9833
PRESS	159.07	Adeq Precision	82.961

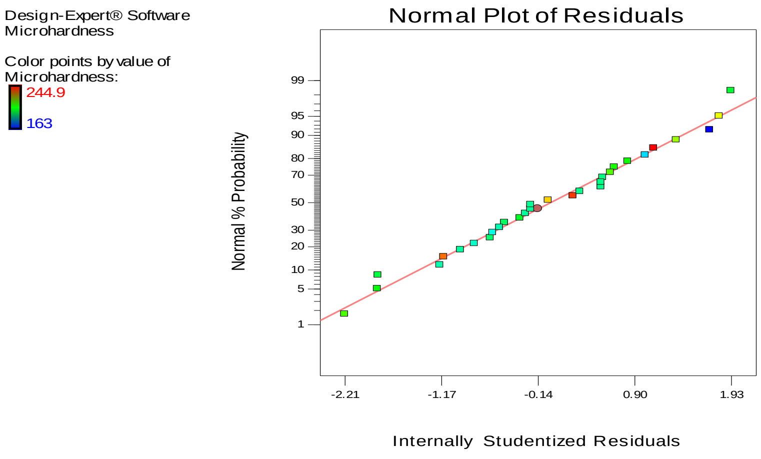

Figure 4: The normal probability of microhardness data

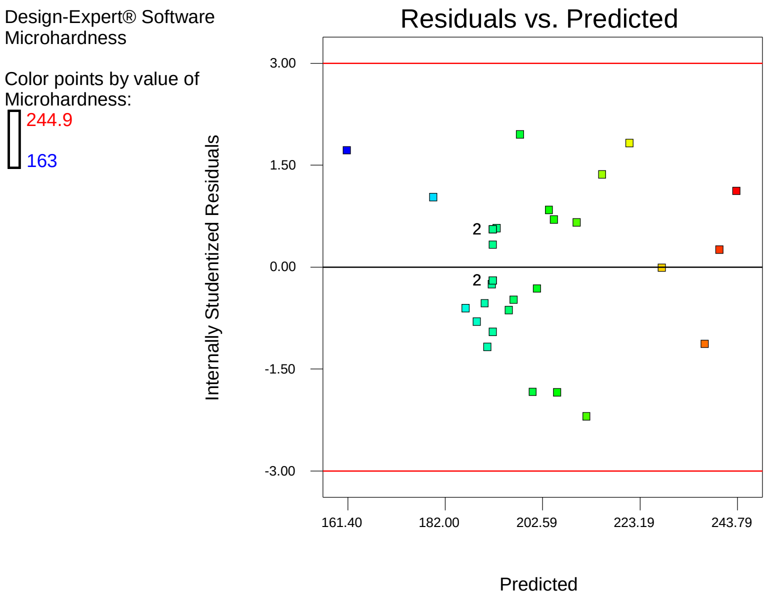

Figure 5: The residual against the predicted outputs for microhardness data.

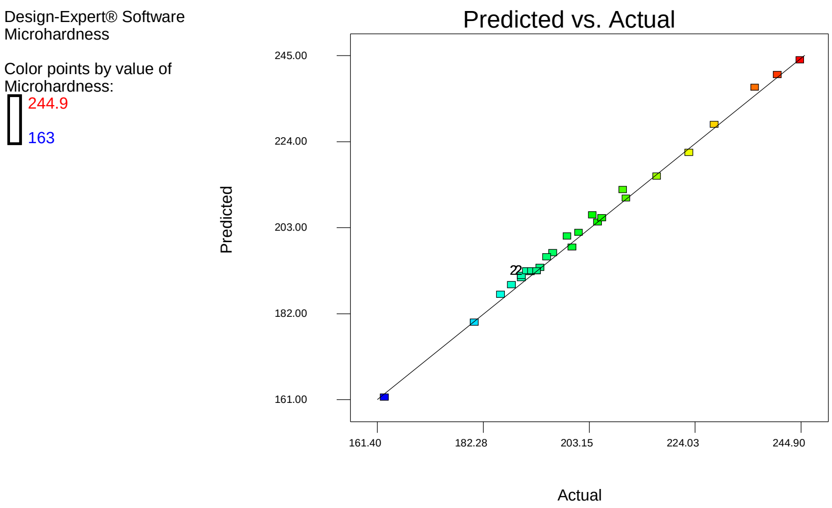

Figure 6: Predicted vs. actual microhardness results for comparison.

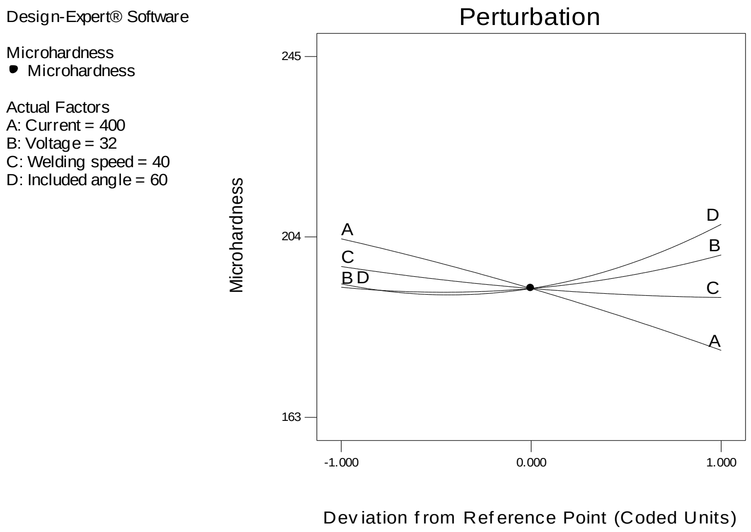

Figure 7: The microhardness perturbation depicting influence of every input factor along the chosen range.

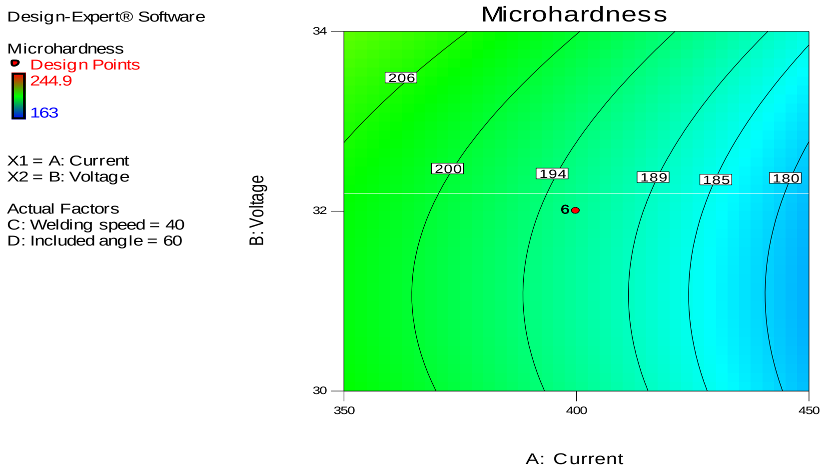

Figure 8: Two-dimensional plot of microhardness in terms of voltage and current at the center level ((60°) included angle and (40 cpm) welding speed).

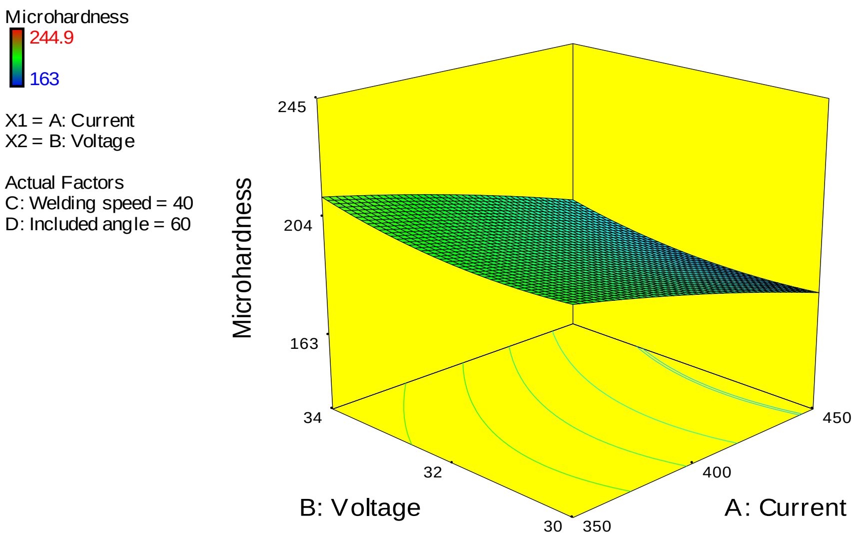

Figure 9: Three-dimensional plot of microhardness in terms of voltage and current at the center level ((60°) included angle and (40 cpm) welding speed).

II. Optimization of Microhardness

The numerical optimization was carried out by the DOE program to find out the factors optimum combinations in order to obtain the desired needs. Thus, this program was utilized for this optimization aim depending on the predictive model results of one output, microhardness, in terms of the input parameters: arc voltage, included angle, welding current, and welding speed. To develop a noval predictive model, the objective function, called desirability that permits to combine suitably the whole goals, was evaluted. This objective function must be maximized by the numerical optimization, it has a value between 0 and 1 at the goal. Modifying the importance and weight might change the features of goal, and the purpose of optimization is for obtaining a good set of conditions that meets the whole goals. Normally, the weights are employed for developing the estimation of the importance of goal's 3D through the maximization of the desirability function. In the present research, the weights weren't altered, because the microhardness (output) possesses the principal significance. The principal objective of optimization was to find the minimum output that satisfies the factor characteristics with maximum desirability value. Table 7 presents The constrains of optimization of every factor to optimize the microhardness. By considering such table, one test satisfied those constrains for determining the minimum microhardness value, as shown in the Table 8 indicating that the value (0.781) is the maximum chosen desirability. The optimum value of minimum microhardness (186.7 HV) in 2D and 3D plots is illustrated in both Figures 10 and 11, respectively.

Table 7: Constraints of the optimization of microhardness

Name	Goal	Lower Limit	Upper Limit	Lower Weight	UpperW eight	Importance
A:welding current	is in range	350	450	1	1	3
B:arc voltage	is in range	30	34	1	1	3
C:welding speed	is in range	35	45	1	1	3
D:included angle	is in range	54	66	1	1	3
Microhardness	minimize	163	244.9	1	1	3

Table 8: Optimum input factors for the lowest value of microhardness

Current (Amp.)	Voltage (volt)	Travelling speed (cm/min)	Included angle (deg.)	Microhardness (HV)	Desirability
450	34	38	60	186.7	0.781 Selected

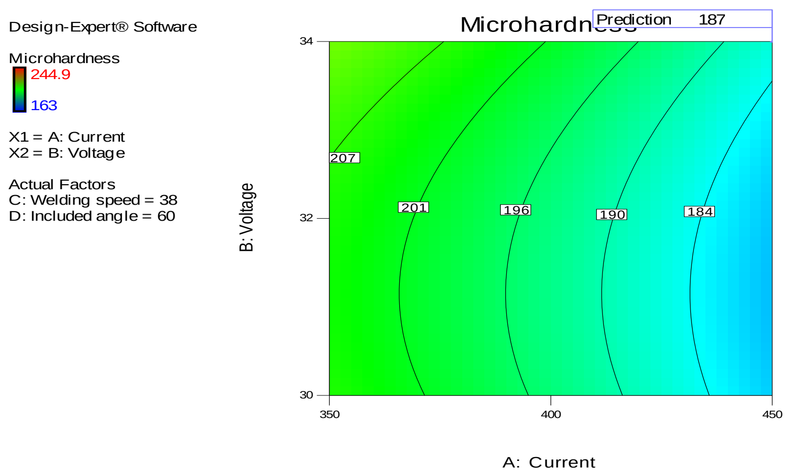

Figure 10: The lowest value of microhardness at the optimal conditions (included angle of 60°, welding speed of 38 cpm, current of 450 amp, and voltage of 34 v)

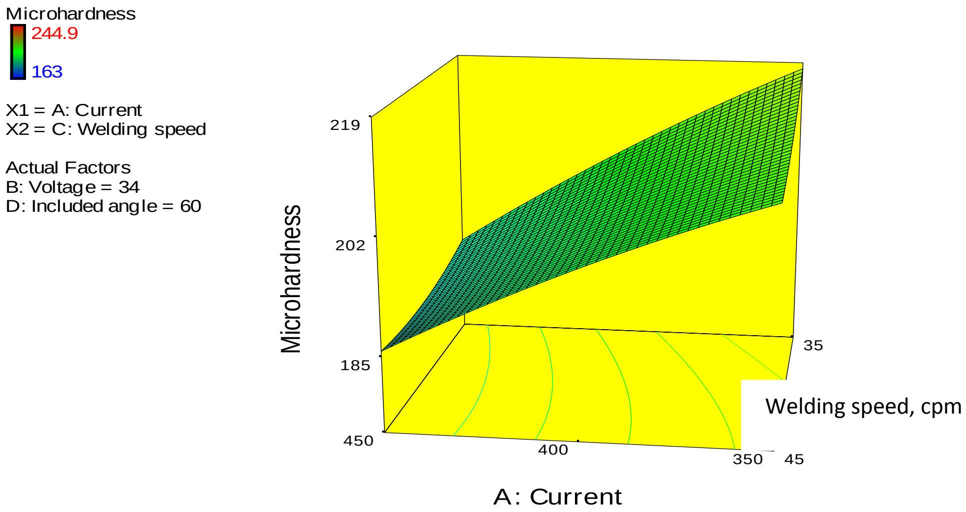

Figure 11: Minimum microhardness value at the optimum onditions (included angle of 60°, welding speed of 38 cpm, current of 450 amp, and voltage of 34 v)

4. Confirmation Test

For checking the model validity, confirmation tests were conducted experimentally using the predicted optimum results of the welding input factors determined in this model for measuring the microhardness. The experimental result of microhardness measurement is listed together with the predicted one in the Table (9) for comparison purpose. Such table reveals that the predicted and experimental results are in good agreement with 4.6 %. maximum error.

Table 9: Comparison between the predicted and experimental microhardness

Current (Amp.)	Voltage (volt)	Travelling speed (cm/min)	Included angle (deg.)	Microhardness (HV)		
				Predict	Exp.	Max. error (%)
450	**34**	**38**	**60**	**186.7**	**178**	**4.6**

5. Conclusions

1- Welding current and included angle have a great impact on microhardness. Where, the included angle highly increased the microhardness along the chosen input range (54° – 66°). While, the welding current has an opposite influence, and the microhardness reduced greately at high level (450 Amp.).

2- Depending on the DOE and RMS technique, the minimum value of microhardness (186.7 HV) was found at the optimum welding parameters: 38 cpm welding speed, 60° included angle, 34 volt arc voltage, and 450 Amp welding current.

3- Relying on the determined experimental results, the SAW operation of steel (516 Gr. 60) increased slightly the microhardness from (170 HV) for base metal to (178 HV) for the welded joint, with 4.4% increase.

4- A proper fitting was found between experimental and predicted results of microhardness which has a maximum error of 4.6%.

5- DOE and RSM technique are found good tools for predicting the microhardness for the used levels of input factors in submerged arc welding operation.

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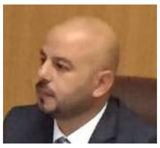

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