Al-Khwarizmi Engineering Journal

Al-Khwarizmi Engineering Journal, Vol. 10, No. 4, P.P. 64- 80 (2014)

Determination of Welding Velocity and Arc Energy for Fusion MAG Welding Joint

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(Received 22 April 2014; accepted 27 September 2014)

Abstract

This paper is an experimental work to determinate the effect of welding velocity and formed arc energy for CO2-MAG fusion weld pool. The input parameters (arc voltage, wire feed speed and gas flow rate) were investigated to find their effects on the weld joint efficiency. Design of experiment with response surface methodology technique was used to build empirical mathematical models for welding velocity and arc energy in term of the input welding parameters. The predicted quadratic models were statistically checked for adequacy purpose by ANOVA analysis. Additionally, numerical optimization was conducted to obtain the optimum values for welding velocity and arc energy. A good agreement was found between experimental and predicted results.

Keywords: *Welding Velocity, Arc Energy, Mathematical Modeling, Numerical Optimization, Joint Efficiency.*

1. Introduction

Carbon Dioxide, as inert gas is normally considered effective in MAG welding process, since the heat of the arc breaks down the CO2 into carbon monoxide and free oxygen. The oxygen will combine with elements transferring across the arc to form the oxides which are released from the weld pool in the form of slag and scale. Although CO2 is an active gas and produces an oxidizing effect, efficient joint welds are achieved almost free of porosity and weld defects. CO2 is widely used for welding mostly for low carbon steel due to its common availability, quality weld efficiency and low cost [1].

CO2 -MAG is an electric arc welding process which joins metals by heating them with an arc established between the electrode and the work. Industrially, CO2-MAG welding is one of the most important processes for welding sheet metal engineering applications, such as automobiles, structures and marine parts. CO2-MAG welding is versatile, gives very little loss of alloying elements and can be operated as semi as well as fully automated. Many commercial metals can be welded by the CO2- MAG process, including carbon steels, stainless steels, Aluminum, copper and nickel alloys [2].

The recommended arc energy (rate of heat input) results in good mechanical properties in the heat affected zone. The rate of heat input supplied by the welding process affects the efficiency of the welded joint. This is described by the arc energy that can be calculated taking in account arc voltage, welding current and speed of welding [3].

Arc energy is one of the most important process parameters in controlling weld response. It can be referred to as an electrical energy supplied by the welding arc to the weldment. In practice, however, arc energy can approximately (i.e., if the arc efficiency is not taken into consideration) be characterized as the ratio of the arc power supplied to the electrode to the arc travel speed [4].

The welding speed has a major influence on the arc energy formed during CO2-MAG welding, since a high welding speed will provide a lower energy input per unit of length of a welded joint

[5]. And, this will result in insufficient melting of the base metal.

Many researchers have been previously carried out by using CO2-MAG welding processes considering mainly the effect of process parameters on the structure and mechanical properties, but there is little works have focused on studying the influence of these parameters on the welding velocity and arc energy using the Design of Experiment (DOE) and Response Surface Methaolodgy (RSM) technique for modeling and optimization purposes for CO2-MAG welding [6-13]. Therefore, the aim of this paper is to determine experimentally the effect of input parameters of this welding process on the welding velocity and arc energy.

2. Experimental Procedure

2.1. Used Material and Samples Preparation

Low carbon steel material type AISI 1010 in form of plate with 5 mm thickness in the hot rolled condition was used in this work to prepare samples for welding test. Chemical analysis for this material was carried out, and the results are given in Table 1. Also, the mechanical properties of this steel were obtained by tensile test according to ASTM-E8 standard, and the resulted data are listed in Table 2, presenting the average of three readings for three tested samples .Samples were then prepared with dimensions of 50 mm× 25 mm×5 mm to be welded in a closed Butt weld joint design by CO2-MAG process. Table 1 and Table 2 indicate that the used material matches to the standard base metal [14].

2.2. Used Welding Parameters

The effective selected input factors of CO2-MAG welding in this work were welding speed, arc voltage and wire feed speed in two levels, as shown in Table 3. These parameters were used based on the ability of welding machine and experimental skill of the welder operator.

Table 1,
Chemical composition of AISI 1010 the Steel Plate With Standard Type (wt%).

Material	C	Si	Mn	P	S	Cr	Mo
Used Material	0.13	0.015	0.450	0.003	0.003	0.001	0.002
Standard Steel AISI 1010 [12]	0.08 – 0.13	0.1 max	0.3 - 0.6	0.04 max	0.05 max	--	--
Material	**Ni**	**Al**	**Co**	**Cu**	**V**	**Fe**	
Used Material	0.043	0.036	0.007	0.001	0.001	Bal.	
Standard Steel AISI 1010 [12]	--	--	--	--	--	Bal.	

Table 2,
Mechanical Properties for Steel.

Material	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
Steel Sample	262	391	42

Table 3,
Levels of Input Parameters Used with Respective Coding.

Input parameter	Unit	Low Level - 1	High Level + 1	-alpha	+alpha
Voltage	volt	19	21	18	22
Wire feeding speed	cm/min	125	175	100	200
Gas flow rate	L/min	8	12	5	14

2.3. Welding Test

CO_2-MAG welding tests were conducted for twenty samples using the welding factors mentioned above and depending on the design matrix established by Design of Experiment Software, as given in Table 4. These tests were achieved randomly to prevent any systematic error. The wire filler type 'AWS ER70S-6'1.2 mm diameter in form of rod was used for welding samples.

Table 4,
Design Matrix for Input Factors and Experimental Values of Output (Responses).

Std. No.	Run No.	Type of point	Voltage (volt)	Wire feed speed (cm/min)	Gas flow rate (L/min)	Welding velocity (mm/min)	Arc Energy (Joul/mm)
1	12	Factorial	19	125	8	64.66	920
2	7	Factorial	21	125	8	73.14	950
3	8	Factorial	19	175	8	90	1640
4	1	Factorial	21	175	8	105	1400
5	14	Factorial	19	125	12	69.72	925
6	4	Factorial	21	125	12	85.68	900
7	16	Factorial	19	175	12	103.44	1380
8	18	Factorial	21	175	12	114	1325
9	9	Axial	18	150	10	66.66	1600
10	15	Axial	22	150	10	85	1530
11	6	Axial	20	100	10	65	230
12	2	Axial	20	200	10	125	1180
13	19	Axial	20	150	6	95.32	1050
14	10	Axial	20	150	14	115	850
15	3	Center	20	150	10	70	1750
16	11	Center	20	150	10	75	1700
17	17	Center	20	150	10	74.5	1690
18	5	Center	20	150	10	71	1715
19	13	Center	20	150	10	75.5	1800
20	20	Center	20	150	10	73.8	1640

2.4. Determination of Welding Velocity

Speed of welding is defined as the rate of travel of the electrode along the seam or the rate of travel of the work under the electrode along the seam. Therefore, the welding speed during welding each sample was calculated using the following formula [15]:

$$S = \frac{d}{t} \qquad ...(1)$$

Where, S = welding Speed (mm/min).
d = Travel of electrode (mm).
t = Arc time (min).

In the present, the travel of electrode (d) was first measured using a digital venire (with accuracy of 0.01mm). Then, the arc time (t) was measured for the period between the start and end of achieving the welding pass using a stop watch. According to equation (1), the welding velocity (S) was calculated.

2.5. Determination of Arc Energy

Arc energy (heat input rate) is a relative measure of the energy transferred per unit length of weld. It is typically calculated as the ratio of the power (i.e., voltage, current) to the velocity of the heat source (i.e., the arc) as follows [16].

$$Q = \frac{V*I*60}{S} \qquad \dots (2)$$

Where, Q = Arc energy (J/mm), V = arc voltage (volts) and I = welding current (ampere).

For calculating the arc energy (Q), the reading of both arc voltage (V) and welding current (I) were taken from the welding machine indicators during the welding process. Then, using the calculated welding velocity (S) as mentioned in section (2.4), the arc energy (Q) was obtained by equation (2).The results of measurements and calculations for these responses are also listed in Table 4.

3. Results and Discussion

3.1. Mathematical Model of Welding Velocity

For the welding velocity parameter, the analysis of variance (ANOVA) was established by DOE software as shown Table 5. illustrating that the input parameters individually as well as the quadratic terms of voltage, wire feeding speed and gas flow rate are all statistically significant and have the greatest influence on the welding velocity response according to their P-values (< 0.05). The lack of fit test indicates a good model, since it is insignificant with P-value greater than 0.05. So, this analysis indicates that this model is significant at 95% confidence. In addition, this model showed a good agreement between the predicted and actual values for welding velocity, as shown in Fig.1. Therefore, the final predicted equation for the welding velocity in terms of the coded input factors is:

$$\text{Welding velocity} = +74.28 + 5.42 * A + 14.95 * B + 4.96 * C + 5.35 * B^2 + 7.89 * C^2 \qquad \dots (3)$$

And , the final equation in terms of actual factors:

$$\text{Welding velocity} = + 241.40000 + 5.41750 * \text{Voltage} - 1.97110 * \text{Wire feeding speed} - 36.98125 * \text{Gas flow rate} + 8.56400E\text{-}003 * \text{Wire feeding speed}^2 + 1.97313 * \text{Gas flow rate}^2 \qquad \dots (4)$$

Table 5,
Analysis of Variance (ANOVA) for Response Surface Reduced Quadratic Model (Welding Velocity).

Source	**Sum of squares**	**df**	**Mean square**	**F value**	**p-value Prob > F**
Model	6508.89	5	1301.78	243.24	< 0.0001 significant
A-Voltage	469.59	1	469.59	87.74	< 0.0001
B-Wire feeding speed	3577.24	1	3577.24	668.42	< 0.0001
C-Gas flow rate	394.02	1	394.02	73.62	< 0.0001
B^2	754.99	1	754.99	141.07	< 0.0001
C^2	1641.57	1	1641.57	306.73	< 0.0001
Residual	74.93	14	5.35		
Lack of Fit	49.33	9	5.48	1.07	0.4970 not significant
Purr Error	25.60	5	5.12		
Core Total	6583.81	19			

Std. Dev. = 2.31	**R-Squared = 0.9886**
Mean = 84.87	**Adj R-Squared = 0.9846**
C.V. % = 2.73	**Pred R-Squared = 0.9792**
PRESS = 137.26	**Adeq Precision = 50.037**

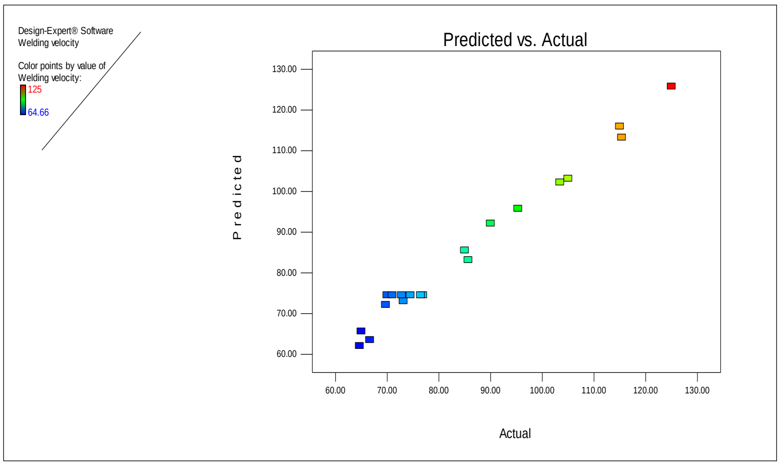

Fig. 1. Predicted Versus Actual Welding Velocity Data.

The statistical properties of this model were diagnosed, and it was found that the residuals that falling on a straight line implying errors are normally distributed, as shown in Fig.2. Additionally, the residuals versus predicted actual for welding velocity data revealed no obvious pattern or unusual structure implying models are accurate as shown in Fig.3.

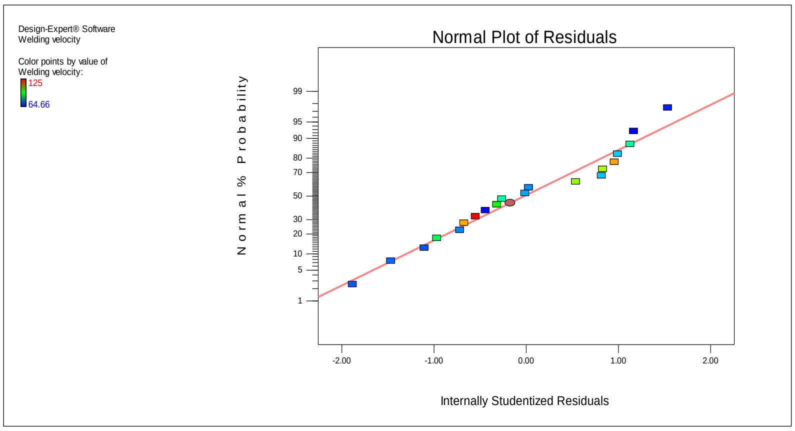

Fig. 2. Normal Probability Plot of Residuals for Welding Velocity Data.

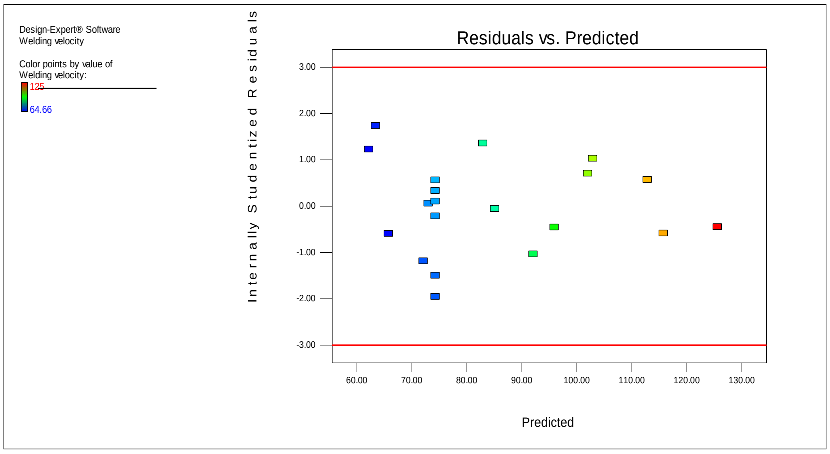

Fig. 3. Residuals versus Predicted Welding Velocity Data.

The perturbation of the predicted welding velocity response resulted by varying only one parameter at a time from the center point of the investigated region is shown in Fig.4. It can be seen that increasing all the three input parameters generally increase the welding velocity, since these input parameters increased the fusion effect of the weld joint, which necessitates increasing the welding velocity to keep the stability of the welding process.

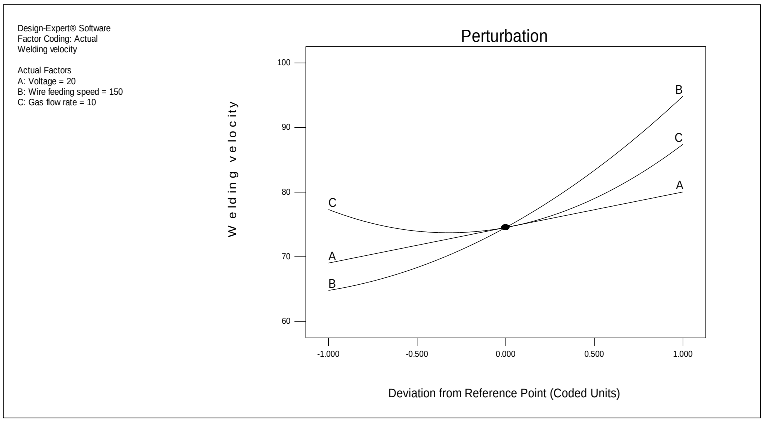

Fig. 4. Perturbation of Welding Velocity on Wire Feeding Speed and Gas Flow Rate.

Due to no statistical problems found, the response surface plots were generated in terms of 2D surface plot as shown in Figs.5-7 depicting the welding velocity as a function of voltage and wire feeding speed at various gas flow rates 8, 10 and 12 L/min, respectively. These figures indicate that both voltage and wire feeding speed have greater influence on increasing the welding velocity than the gas flow rate which has a slight effect. This is possibly due to increase of molten material accumulated in the weld joint caused by higher voltage and wire feeding speed. Also, this is more likely ascribed to the increased chemical reaction of CO_2 with the accumulated molten material in the weld joint.

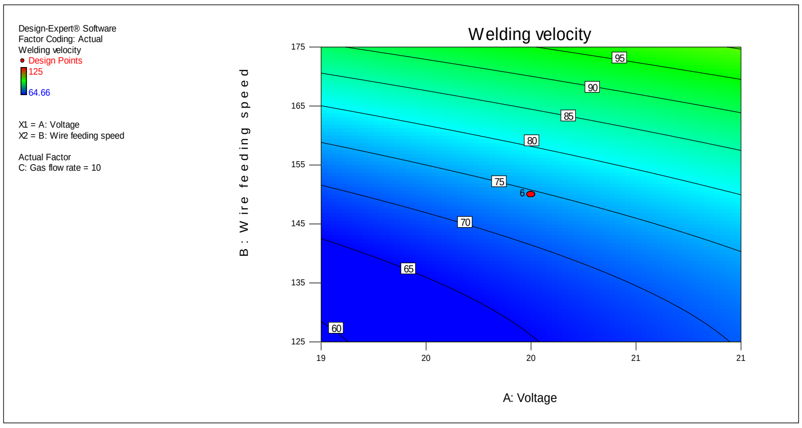

Fig. 5. Contour Graph of Welding Velocity as A function of Voltage and Wire Feeding Speed Gas Flow Rate 8 L/min.

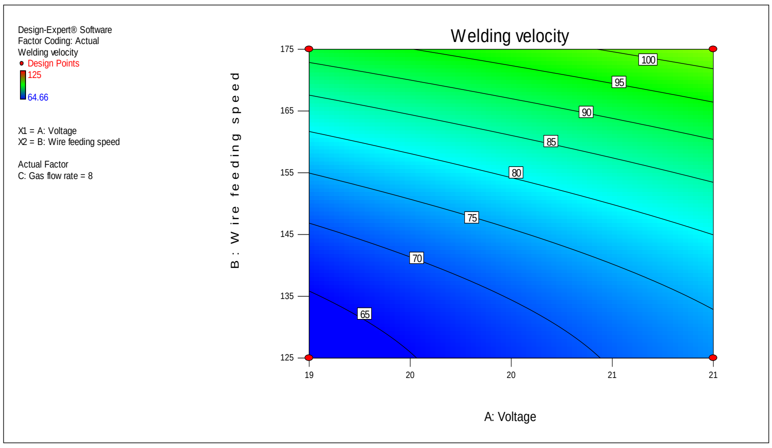

Fig. 6. Contour Graph of Welding Velocity as function of Voltage and Wire Feeding Speed Gas Flow Rate 10 L/min.

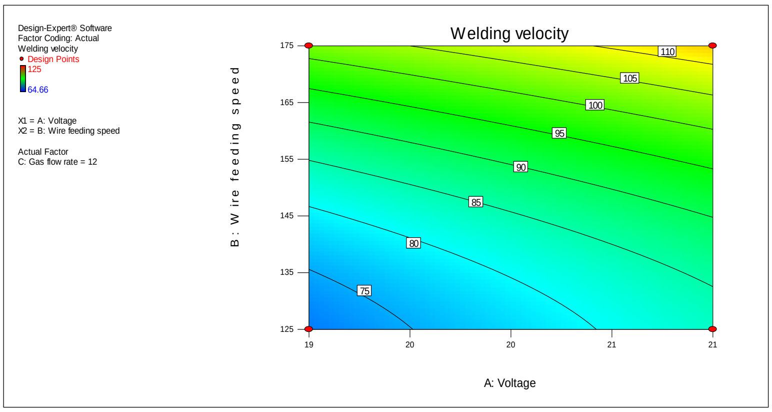

Fig. 7. Contour Graph of Welding Velocity as A function of Voltage and Wire Feeding Speed Gas Flow Rate 12 L/min.

Figures 8-10 show 3D surface plots for welding velocity as a function of voltage and wire feeding speed at different gas flow rates, showing similar behavior as mentioned above. Eventually, these observations are confirmed by the cube plot for the welding velocity, as shown in Fig. 11.

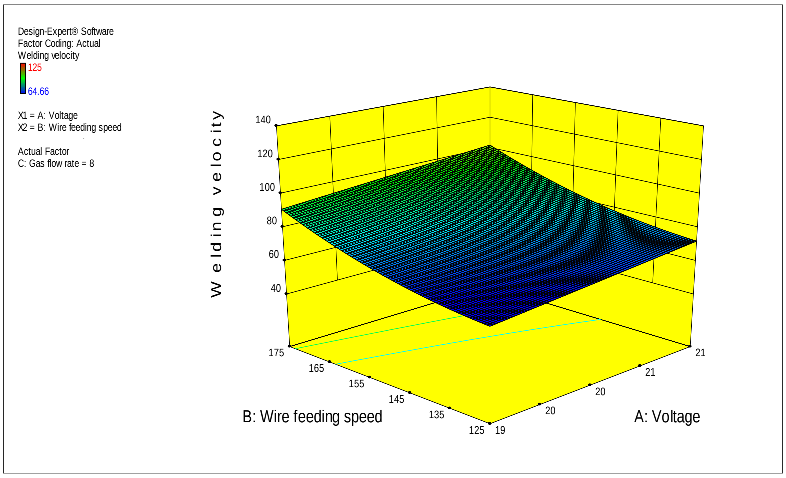

Fig. 8. 3D Graph of Welding Velocity as A function of Voltage and Wire Feeding Speed at Gas Flow Rate 8 L/min.

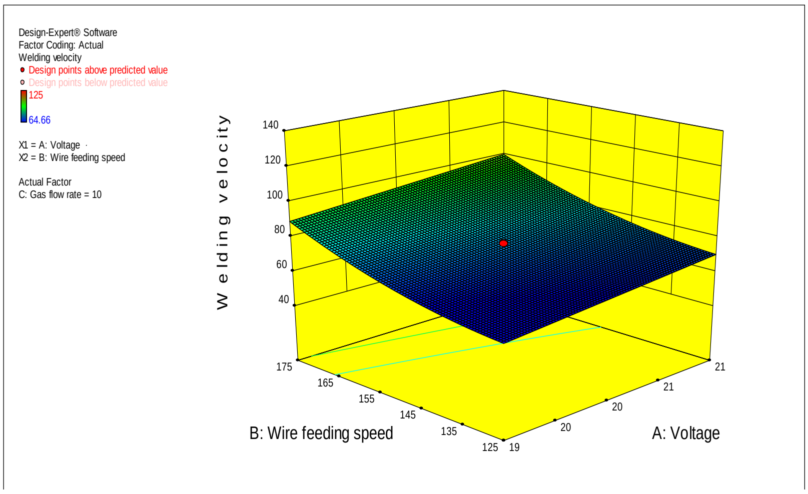

Fig. 9. 3D Graph of Welding Velocity as A function of Voltage and Wire Feeding Speed at Gas Flow Rate 10 L/min.

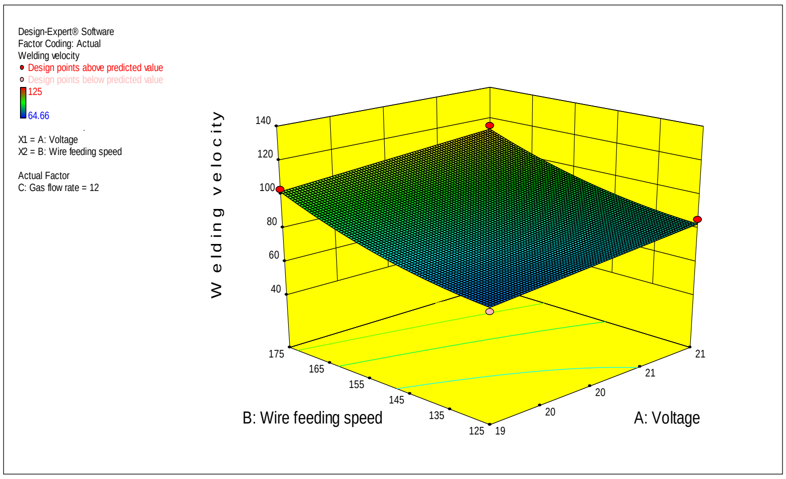

Fig. 10. 3D Graph of Welding Velocity As a function of Voltage and Wire Feeding Speed at Gas Flow Rate 12 L/min.

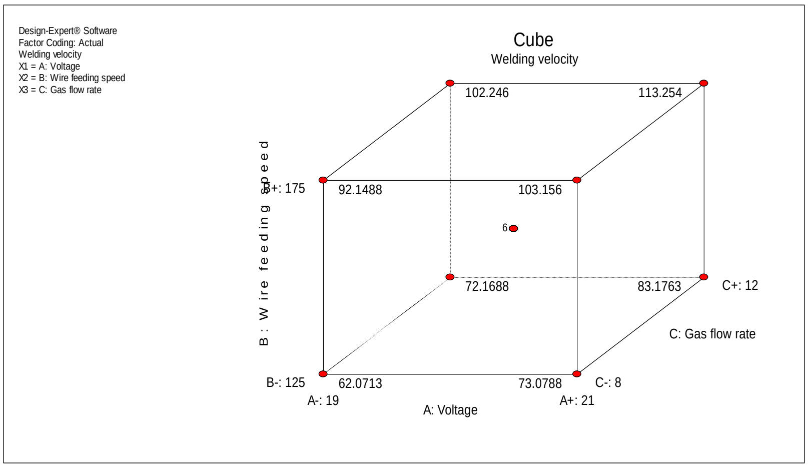

Fig. 11. Cube Shape of Welding Velocity.

3.2. Mathematical Model of Arc Energy

Similarly, the analysis of variance (ANOVA) for RSM reduced quadratic model was determined for the arc energy as given in Table 6. The results in this table show that the wire feeding speed (B) and gas flow rate (C) are statistically significant, since their P-values were very small (< 0.5).While the voltage (A) has no influence on the weld joint. Moreover, this table also indicate that the lack of fit was insignificant (P-value > 0.05), indicating that this model is adequate and significant at 95% confidence. So, the final predicted equation for the arc energy in terms of the coded input factors is:

$$\text{Arc energy} = + 1706.02 - 26.88 * A + 246.87 * B - 48.75 * C - 42.61 * A^2 - 257.61 * B^2 -196.36 * C^2 \quad \ldots (5)$$

And , the final equation in terms of actual factors is:

$$\text{Arc energy} = - 30222.61364 +1677.67045 * \text{Voltage} +133.52955 * \text{Wire feeding speed} + 957.44318 * \text{Gas flow rate} - 42.61364 * \text{Voltage}^2 - 0.41218 * \text{Wire feeding speed}^2 - 49.09091 * \text{Gas flow rate}^2 \quad \ldots (6)$$

Table 6,
Analysis of Variance (ANOVA) for Response Surface Reduced Quadratic Model (Arc energy).

Source	**Sum of squares**	**df**	**Mean square**	**F value**	**p-value Prob > F**
Model	3.257E+006	6	5.428E+005	114.66	< 0.0001 significant
A-Voltage	11556.25	1	11556.25	2.44	0.1422
B-Wire feeding speed	9.752E+005	1	9.752E+005	206.00	< 0.0001
C-Gas flow rate	38025.00	1	38025.00	8.03	0.0141
A^2	45657.47	1	45657.47	9.65	0.0084
B^2	1.669E+006	1	1.669E+006	352.49	< 0.0001
Residual	61538.07	13	4733.70		
Lack of Fit	46617.23	8	5827.15	1.95	0.2390 not significant
Purr Error	14920.83	5	2984.17		
Core Total	3.318E+006	19			

Std. Dev. = 68.80	**R-Squared = 0.9815**
Mean = 1308.75	**Adj R-Squared = 0.9729**
C.V. % = 5.26	**Pred R-Squared = 0.9529**
PRESS = 1.563E+005	**Adeq Precision = 37.446**

The adequacy of this model was checked to examine the predicted model. Two types of model diagnostics, the normal probability plot and residuals versus the actual values plot, were used for verification, as shown in Figs. 12 and 13 for arc energy respectively. It can be observed from these plots that there was no violation of the normality assumption, since they normal probability plot followed a straight line pattern, the residual was normally distributed, and as long as the residuals versus the predicted values show no unusual pattern and no outliers. Also, this model shows a good agreement between the predicted and actual values for arc energy, as depicted in Fig. 14.

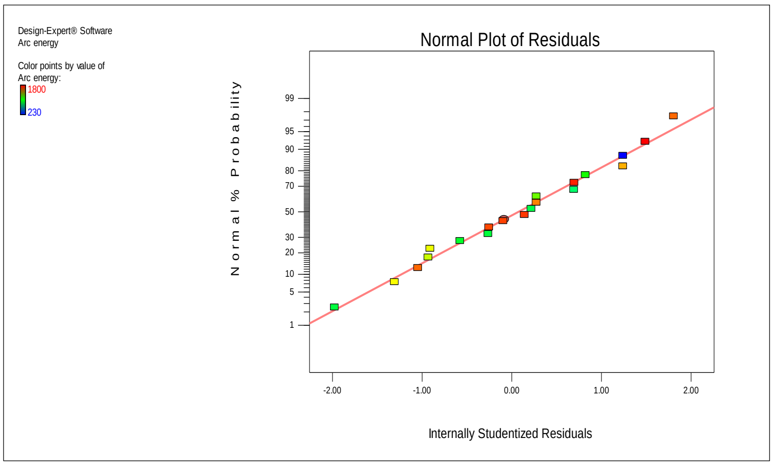

Fig. 12. Normal Probability Plot of Residuals for Arc Energy Data.

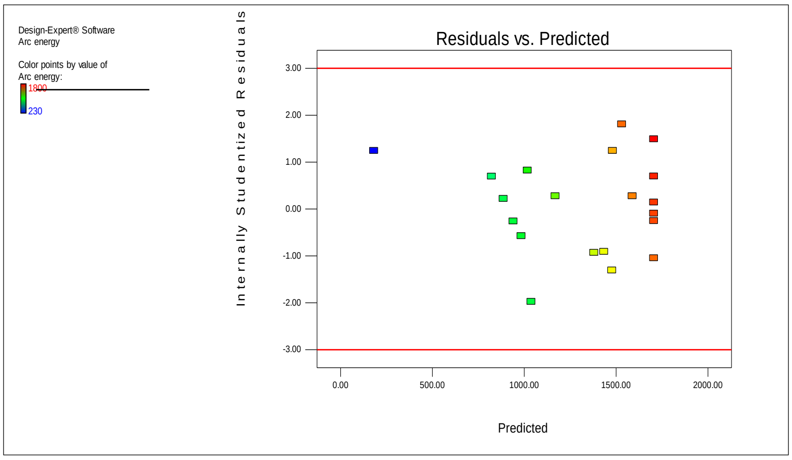

Fig. 13. Residuals versus Predicted Arc Energy Data.

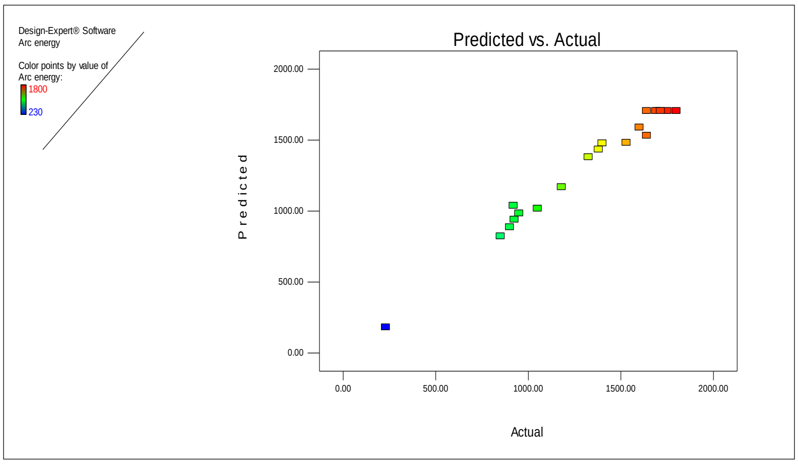

Fig. 14. Predicted Versus Actual Arc Energy Data.

The perturbation plot of the predicted responses caused by changing only one factor at a time from the center point of the experimental region is shown in Fig. 15. This figure indicates that, individually, the wire feeding speed has greater effect than the gas flow rate on arc energy, while the voltage is not influential. This is more probably because of the increasing wire feeding speed resulted in an increase in the welding velocity, leading to more accumulation of molten material due to more thermal effect and less chemical affinity of the CO_2 gas with the weld joint material.

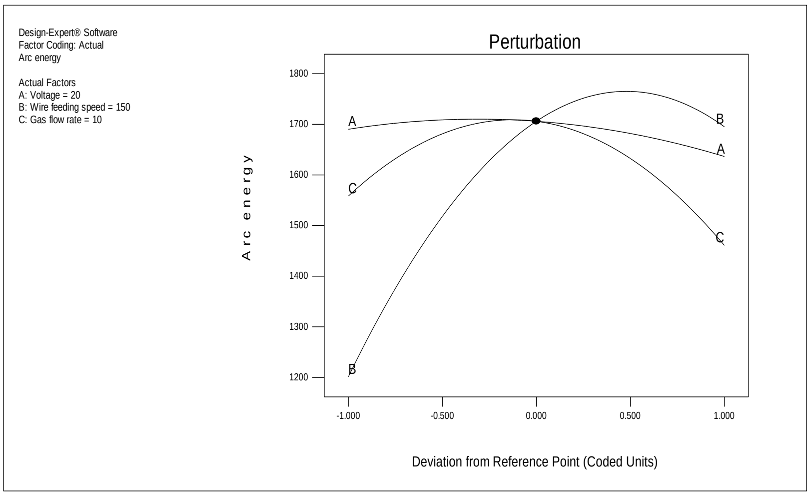

Fig. 15. Perturbation of Arc Energy on Wire Feeding Speed and Gas Flow Rate.

Because of no statistical problem with the model, Fig. 16 shows the 2D contour plot for the arc energy as a function of voltage and wire feeding speed at gas flow rate of 10 L/min. Whereas, Figs. 17-19 depict 3D surface plots for the arc energy at gas flow rate of 8, 10 and 12 L/min, respectively. It can be noted from these figures that increasing both wire feeding speed and gas flow rate increases the arc energy due to the increase of quantity of the molten material that resulted by the increasing of the welding velocity and thermal input. Finally, these observations are confirmed by the cube plot for arc energy, as shown in Fig.20.

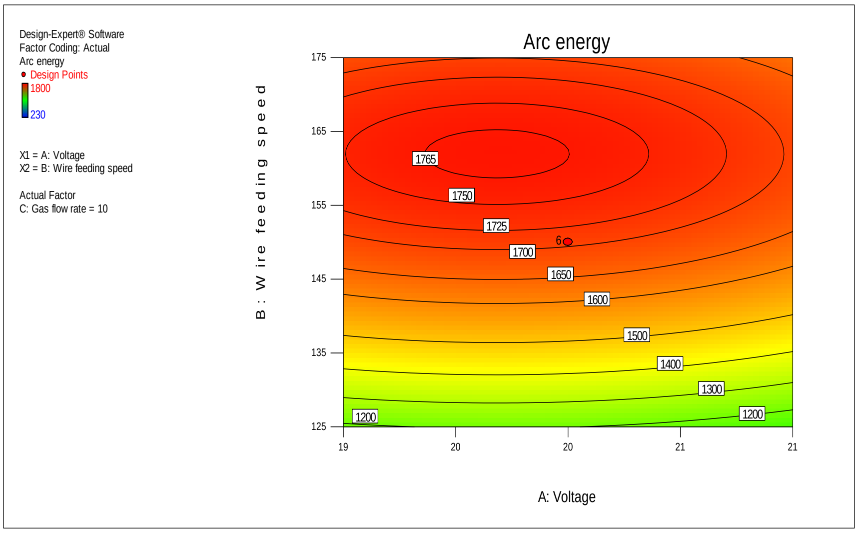

Fig. 16. Contour Graph of Arc Energy as A Function of Voltage and Wire Feeding Speed at Gas Flow Rate 8 L/min.

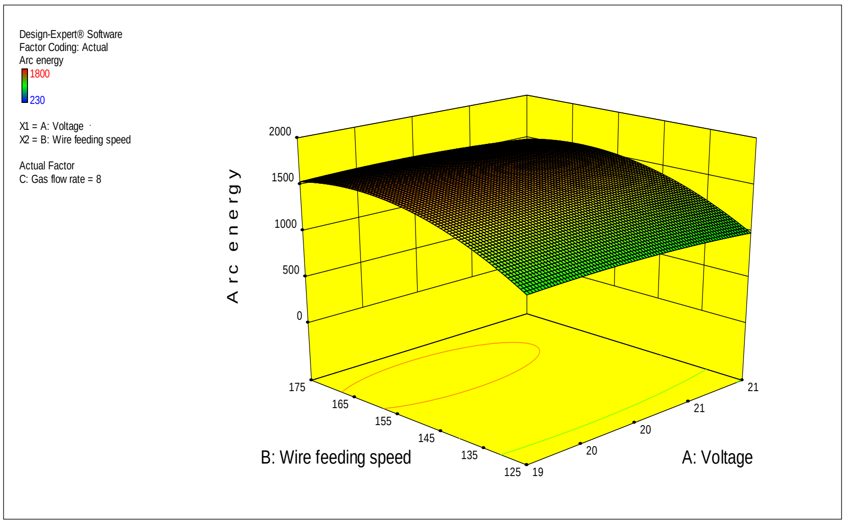

Fig. 17. 3D Graph of Arc Energy as A function of Voltage and Wire Feeding Speed at Speed at Gas Flow Rate 10 L/min.

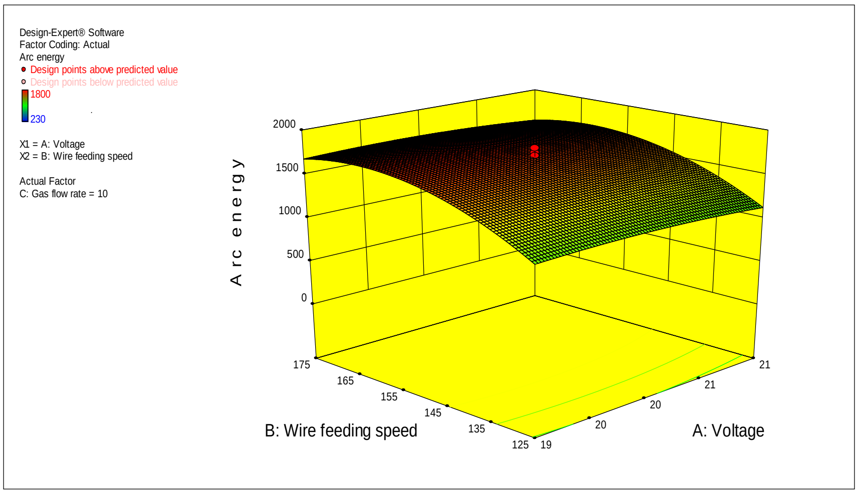

Fig. 18. 3D Graph of Arc Energy as A function of Voltage and Wire Feeding Speed at Gas Flow Rate 10 L/min.

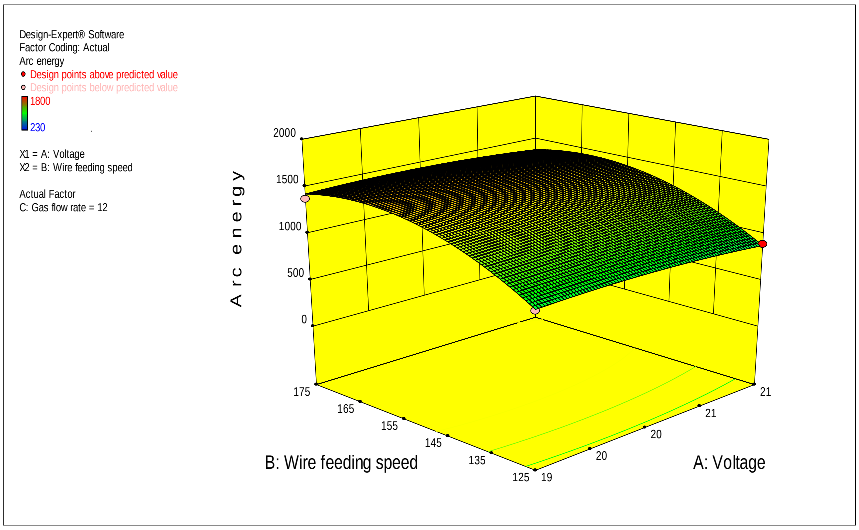

Fig. 19. 3D Graph of Arc Energy as A function of Voltage and Wire Feeding Speed at Gas Flow Rate 12 L/min.

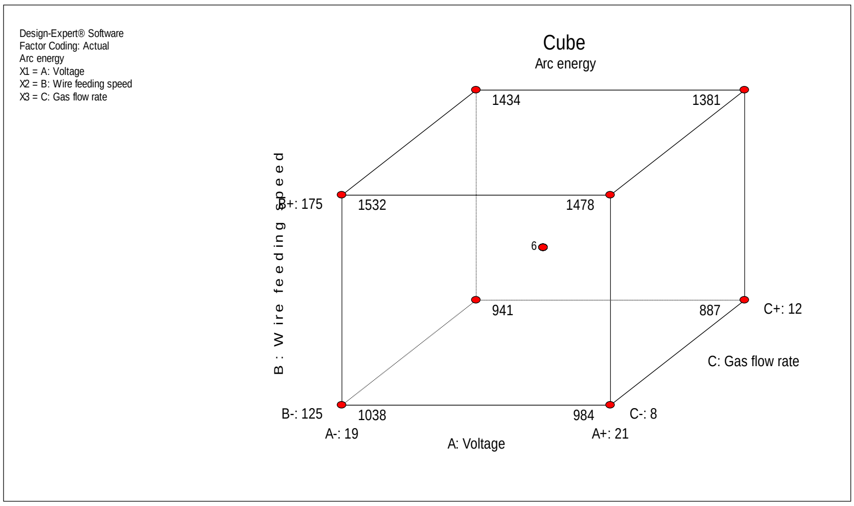

Fig. 20. Cube Shape of Arc Energy.

3.3. Numerical Optimization

The numerical optimization is provided by the Design of Experiment software to find out the optimum combinations of parameters in order to fulfill the requirements as desired. Therefore, this software was used for optimizing the welding velocity and arc energy; based on the data from the predicted models as a function of three factors: arc voltage, wire feeding speed and gas flow rate.

Table 7 lists the constrains of each variable for numerical optimization of the welding velocity and arc energy. According to this table, one possible run fulfilled the specified constrains to obtain the optimum values for welding velocity, arc energy and desirability, as listed in Table 8. It can be noted that this run gave a desirability of 0.849 with the optimum values of the Voltage (20 volt), Wire feeding speed (153 cm/min), Gas flow rate (10 L/min), Welding velocity (77.071 mm/min) and arc energy (1722 Joule/mm). Figures 21-23 show 3D surface plots for desirability, optimum value of welding velocity and optimum value of arc energy, respectively as a function of voltage and wire feeding speed at 10 L/min gas flow rate.

Table 7,
Constrains Used for the Numerical Optimization.

	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Voltage	is in range	19	21	1	1	3
B:Wire feeding speed	is in range	125	175	1	1	3
C:Gas flow rate	is in range	8	12	1	1	3
Welding velocity	minimize	64.66	125	1	1	3
Arc energy	maximize	230	1800	1	1	3

Table 8,
Optimum Solutions of the Desirability.

Number	Voltage (volt)	Wire feeding speed (cm/min)	Gas flow rate (L/min)	Welding velocity (mm/min)	Arc energy (Joul/mm)	Desirability
1	20	153	10	77.071	1722	0.849 Selected

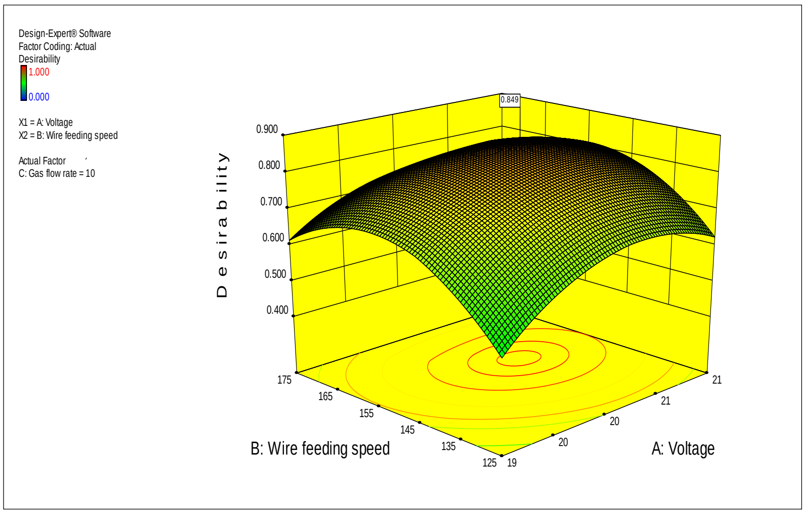

Fig. 21. 3D Graph for Desirability as A function Of Voltage and Wire Feeding Speed at Gas Flow Rate 10 L/min.

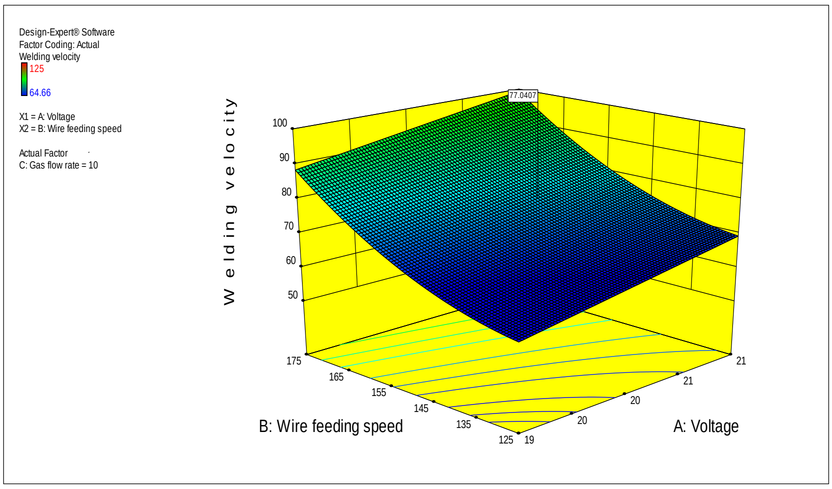

Fig. 22. The Optimum Value for Welding velocity at 10 L/min Gas Flow Rate.

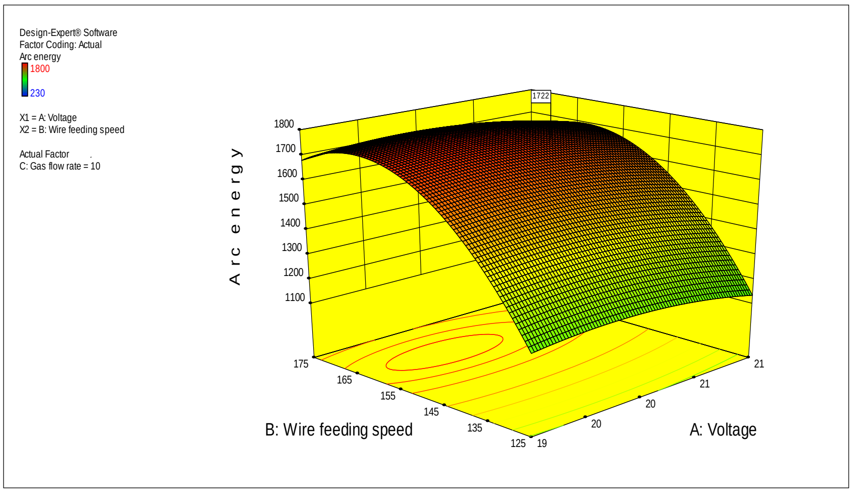

Fig. 23.The Optimum Value for Arc Energy At 10L/min Gas Flow Rate.

3.4. Weld Joint Efficiency Calculation:

In order to obtain the efficiency of the weld joint obtained by CO_2-MAG welding of low carbon steel AISI 1010, three tensile samples were first welded with the optimum welding condition given in Table – and then tensile tested to determine the ultimate tensile strength of the weld joint. The average tensile strength was found to be 285 MPa. Therefore, the efficiency of the weld joint was calculated to be 73% according to the joint efficiency definition which is the ratio of the tensile strength of the weld joint to the tensile strength of the base metal (Table 2). This result indicates the importance of using CO_2-MAG welding process and its effectiveness and suitability for welding steel AISI 1010 from strength point of view.

4. Conclusions

1. Regarding the welding velocity, a quadratic model was obtained by DOE with RSM technique for the optimum welding velocity response in terms of input welding parameters. His model indicated that the arc voltage, wire feeding speed and gas flow rate largely effective on welding velocity.
2. Concerning the arc energy, a quadratic model was obtained for the optimum arc energy response in terms of input welding parameters. This model shows that the wire feeding speed has greater impact than gas flow rate on arc energy, while the arc voltage was found not affected.
3. By numerical optimization, the optimum values of the voltage, wire feeding speed, gas flow rate, welding velocity, arc energy and desirability are (20Volt),(153cm/min),(10L/min), (77.071mm/min) (1722 Joule/mm) and (0.849), respectively.
4. DOE with RSM was found a useful tool for predicting the responses in MAG-CO2 welding technique for any given input parameters.

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أيجاد سرعة اللحام وطاقة القوس لوصلة لحام القوس المعدني الانصهاري (MAG)

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الخلاصة

يتضمن هذا البحث دراسة عملية لغرض ايجاد تأثيرسرعة اللحام وطاقة القوس التي تتكون لطريقة لحام القوس المعدني بغاز ثاني أوكسيد الكاربون في بركة اللحام الانصهاري. أن العوامل الداخلة ذات الأهمية لهذه الطريقة هي (فولتية القوس، سرعة تغذية سلك اللحام ومعدل جريان الغاز) والتي تم دراستها لأيجاد تأثيراتها على كفاءة الوصلة الملحومة . تم استعمال تقنية تصميم التجارب مع طريقة الاستجابة السطحية لبناء موديلات رياضية تخص سرعة اللحام وطاقة القوس لوصلة اللحام بدلالة عوامل اللحام الداخلة والمذكورة آنفا " . الموديلات الرياضية التربيعية التي تم الحصول عليها والتي تم التنبأ بها قد دققت أحصائيا" وحققت أغراضها بموثوقية بعد تحليلها بطريقة تحليل التباين . فضلا عن أمثلية التحليل العددي التي تم الحصول من خلالها الى أدق القيم لسرعة اللحام و طاقة القوس لوصلة اللحام .تم مقارنة النتائج المستحصلة مع النتائج التي تم التنبأ بها من جراء هذا البحث وجدت بأنها ذات تطابق جيد .