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SIGNIFICANCE OF INPUT VARIABLES FOR DEPOSITION RATE AND WELD BEAD HARDNESS USING DOE APPROACH IN GMAW OF SS304

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ABSTRACT: *MIG welding is one of the most widely used welding techniques due to its versatility and ease that can be maintained in almost all kind of working conditions. 304 Stainless Steel possessing high strength and toughness is usually known to create major challenges during its welding. The MIG welding operation of SS304 (S30400) to find out the response variables as they are able to respond fast with changing input variables and these input variables or parameters should be flexible to adopt new technological changes. A framework has been developed to study performance measurement based on previous researches on "Design of Experiment (DOE) approach and Taguchi Method". In this study four input or control parameters namely current, voltage, wire speed and gas flow rate which are responsible (significant) for major changes in two response variables namely hardness and deposition rate has been used. This study analyzes the future effects of variation to the input parameters. The results prove that during the welding of 304 Stainless Steel, voltage and Current are the most significant factors for the effect on hardness and wire speed and current are most significant factors that are affecting deposition rate.*

KEYWORDS: *DOE; deposition rate; GMAW; hardness; MIG Welding; Taguchi approach.*

INTRODUCTION

DESIGN of Experiments (DOE) is a powerful statistical technique introduced by R. A. Fisher in England in the 1920's to study the effect of multiple variables simultaneously. In his early applications, Fisher wanted to find out how much rain, water, fertilizer, sunshine, etc. are needed to produce the best crop. Since that time, much development of the technique has taken place in the academic environment, but did help generate many applications in the production floor [1].

The DOE using Taguchi approach can economically satisfy the needs of problem solving and product/process design optimization projects. By learning and applying this technique, engineers, scientists, and researchers can significantly reduce the time required for experimental investigations.

DOE Can Be Highly Effective When

Optimize product and process designs, study the effects of multiple factors (i.e. - variables, parameters, ingredients, etc.) on the performance, and solve production problems by objectively laying out the investigative experiments (Overall application goals).

Study Influence of individual factors on the performance and determine which factor has more influence, which ones have less. It can also find out which factor should have tighter tolerance and which tolerance should be relaxed. The information from the experiment will tell how to allocate quality assurance resources based on the objective data. It will indicate whether a supplier's part causes problems or not (ANOVA data), and how to combine different factors in their proper settings to get the best results (Specific Objectives).

Steps Involved in DOE Application

Dr. Genechi Taguchi has standardized the methods for each of these DOE application steps described below. Thus, DOE using the Taguchi approach has become a much more attractive tool to practicing engineers and scientists [2].

Experiment planning and problem formulation

Experiment planning guidelines are consistent with modern work disciplines of working as teams. Consensus decisions about experimental objectives and factors make the projects more successful.

Experiment Layout

High emphasis is put on cost and size of experiments. Size of the experiment for a given number of factors and levels is standardized. Approach and priority for column assignments are established. Clear guidelines are available to deal with factors and interactions (interaction tables). Uncontrollable factors are formally treated to reduce variation. Discrete prescriptions for setting up test conditions under uncontrollable factors are described. Guidelines for carrying out the experiments and number of samples to be tested are defined.

- **Data Analysis**

Steps for analysis are standardized (main effect, NOVA and Optimum). Standard practice for determination of the optimum is recommended. Guidelines for test of significance and pooling are defined.

- **Interpretation of Results**

Clear guidelines about meaning of error term. Discrete indicator about confirmation of results (Confidence interval). Ability to quantify improvements in terms of dollars (Loss function).

- **Overall Advantage**

DOE using Taguchi approach attempts to improve quality which is defined as the consistency of performance. Consistency is achieved when variation is reduced. This can be done by moving the mean performance to the target as well as by reducing variations around the target. The prime motivation behind the Taguchi experiment design technique is to achieve reduced variation (also known as ROBUST DESIGN). This technique, therefore, is focused to attain the desired quality objectives in all steps. The classical DOE does not specifically address quality.

PROBLEM FORMULATION

The literature review reflects that in the welding operation, the input parameters such as current, voltage, wire speed, gas flow rate affects the physical characteristics of weld bead like hardness and deposition rate to a significant extant [3].

Some research work has been reported in this regard for various work materials such as High-Chromium-High-Carbon die steel, polycarbonate and ABS (acrylonitrile-butadienestyrene)

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blend, RDE-40 aluminium alloy, aluminium alloy A319, SS316 L, stainless steel and carbon steel, Inconel 718, AISI1040 steels etc. However there is critical need for exploring these issues in welding of SS304 (S30400) for which almost no work has been reported.

Parameters

To identify the parameters those affect hardness of weld bead and deposition rate during the welding operation the following variables are studied preliminarily before actual experiment. The parameters can be classified as under

- *Machine Based Parameters*- These parameters involve current, voltage, wire speed, gas flow rate and automatic movement of torch.
- *Work Material Based Parameters*- These are the geometry of work piece, thickness, weldability, hardness and chemical composition of work material [3].
- *Input (control) Parameters*- Current, voltage, wire speed and gas flow rate are selected as control parameters. These four parameters are selected because of their ease of control and due to the limitations of available experimental setup. Parameters used for the actual experiment are given below-

TABLE I Control Parameters

Control Factors	**Symbol**
Current	Factor A
Voltage	Factor B
Wire speed	Factor C
Gas flow	Factor D

Level of Various Control Factor

The short range of control factors will have minor effect on response parameters that is why a considerable range of control parameters had been chosen. In this experimental study, each control factor used having two levels. Details of each control factor level are as under –

TABLE II Levels of Control Factors

CONTROL FACTORS	**Levels**	
	1st level	***2nd level***
Current	150 amp	250 amp
Voltage	20 V	30 V
Wire speed	30 rpm	40 rpm
Gas flow	10 Kg/cm2	15 Kg/cm2

Response Variables

In the present study two response variables has been selected (hardness and deposition rate). The details of these response variables are given below –

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TABLE III Response Variables

S.N.	Response variable	Unit	Response type
1	Hardness	HRC	Continuous
2	Deposition Rate	Kg/hr	Continuous

Representation of Factor Levels

The notation used for the factors having their specific meaning, as given below –

TABLE IV: Factor Levels

Factors	Level-1	Level-2
Current	A1	A2
Voltage	B1	B2
Wire speed	C1	C2
Gas Flow Rate	D1	D2

TABLE V: Values of Input Parameters

A For Current Where; A1=150amp A2=250amp	B For Voltage Where; B1=20V B2=30V
C For wire speed Where; C1=35cm/sec C2=50 cm/sec	D For Gas Flow Rate Where; D1=10Kg/cm² D2=15Kg/cm²

TABLE VI: Standard L8 Orthogonal Array

EXP. NO.	FACTORS			
	A	***B***	***C***	***D***
1	1	1	1	1
2	1	1	2	2
3	1	2	1	2
4	1	2	2	1
5	2	1	2	1
6	2	1	1	2
7	2	2	2	2
8	2	2	1	1

TABLE VII : Parameters Setting For Each Run

Experiment no. 1	Experiment no. 2	Experiment no. 3	Experiment no. 4
A1=150amp	A1=150amp	A1=150amp	A1=150amp
B1=20V	B1=20V	B2=30V	B2=30V

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C1=35cm/sec	C2=50 m/sec	C1=35cm/sec	C2=50 m/sec
D1=10Kg/cm²	D2=15Kg/cm²	D2=15Kg/cm²	D1=10Kg/cm²
Experiment no. 5	**Experiment no. 6**	**Experiment no. 7**	**Experiment no. 8**
A2=250amp	A2=250amp	A2=250amp	A2=250amp
B1=20V	B1=20V	B2=30V	B2=30V
C2=50 cm/sec	C1=35cm/sec	C2=50 cm/sec	C1=35cm/sec
D1=10Kg/cm²	D2=15Kg/cm²	D2=15Kg/cm²	D1=10Kg/cm²

TABLE VIII: Control Log for Experimentation

Exp. No.	Current (A) Amp	Voltage (B) V	Wire Speed (C) cm/sec	Gas Flow (D) Kg/cm²
1	150	20	35	10
2	150	20	50	15
3	150	30	35	15
4	150	30	50	10
5	250	20	50	10
6	250	20	35	15
7	250	30	50	15
8	250	30	35	10

CONDUCTING THE EXPERIMENT

Once the factors are assigned to a particular column of the selected orthogonal array, the test strategy has been set and physical preparation for performing the test is initiated. Some decisions need to be made concerning the order of test.

Randomizing the order of performing the test of various trails should include some form of Randomization**.** The randomized trail order protects the experiment from any unknown and uncontrolled factors that may vary during the experiment and may influence the result.

Analysis of Experimental Results

A number of methods have been suggested by the Taguchi for analyzing the data, in the present study following methods are used:-

- Plot of average response
- ANOVA for raw data

The plot of average response at each level of a parameter indicates the trend. It is a pictorial representation of the effect of parameters on the response. The S/N ratio treated as response of experiments, which is measure of the variation within a trail when noise factors are present. A standard ANOVA is conducted on raw data which identified the significant parameters.

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Conformation Experiments

The conformation experiments are the final step in verifying the conclusion from the previous of experimentation. The optimum conditions are set for the significant factors and levels and server tests are made under constant conditions. The conformation experiments are a crucial step and should not be omitted.

Deposition Rate Calculation

Deposition rates are calculated by doing actual welding tests, and the following shows the formula for measuring deposition rates.

$$\boldsymbol{Dep.Rate} = \frac{(\boldsymbol{Wt.of\ \ plate\ after\ welding - Wt.\ of\ \ plate\ before\ welding})}{\boldsymbol{Measured\ Time}} \quad \textbf{(1)}$$

TABLE IX: Deposition Rate

Experiment no. 1	Experiment no. 2	Experiment no. 3	Experiment no. 4
1) 1.5000 2) 1.5240	1) 2.5000 2) 1.7230	1) 1.2500 2) 1.3650	1) 2.6500 2) 1.9983
Experiment no. 5	**Experiment no. 6**	**Experiment no. 7**	**Experiment no. 8**
1) 2.5540 2) 2.6231	1) 2.1100 2) 2.0654	1) 2.9560 2) 2.8546	1) 1.7265 2) 2.1631

Hardness Measurement

Hardness is a resistance to deformation. The **hardness** of **steel** is generally determined by testing its resistance to deformation. There are three general types of hardness measurements [4, 5].

The hardness was tested by Rockwell hardness-testing machine with 'C' scale. Hardness is measured for two runs of each experiment are given below:-

Major load: - 150kg

Scale: - Rockwell 'C' scales (HRC)

Minor load: - 10kg

Indenter: - Diamond Indenter

TABLE X HARDNESS

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Experiment no. 1	Experiment no. 2	Experiment no. 3	Experiment no. 4
1) 27.50 2) 30.00	1) 24.00 2) 28.00	1) 16.00 2) 22.00	1) 19.00 2) 26.00
Experiment no. 5	**Experiment no. 6**	**Experiment no. 7**	**Experiment no. 8**
1) 40.50 2) 55.00	1) 63.00 2) 73.00	1) 15.75 2) 25.00	1) 13.25 2) 21.00

RESULTS

The analysis of result obtained has been performed according to the standard procedure recommended by Taguchi.

S/N Ratio

The S/N ratio is obtained by using Taguchi approach. Here the term SIGNAL represents the desirable value (mean) and NOISE represents the undesirable value. Thus S/N ratio represents the amount of variation present in the performance characteristics.

- For the Deposition Rate the Larger is Better S/N ratio corresponding to different experimental runs has been tabulated in the table no. – 11 along the mean value of deposition rate.
- For Hardness the Larger is Better S/N ratio was also applied for transforming the raw data. The variation for the different experimental runs has been tabulated in the table no.-12

Main Effect Due To Parameters

The main effect can be studied by the level average response analysis of mean data and S/N ratio. The analysis is done by averaging the mean and/or S/N data at each level of each parameter and plotting the value in graph. The level average response from the mean data helps in analyzing the trend of performance characteristics with respect to variation of the factors under study. The main effect of raw data and those of S/N ratio for response variables have been shown in figures – 11 to 12.

Analysis Of Variance (ANOVA)

The ANOVA (general linear model) for mean has been performed to identify the significant parameters to quantify their effect on performance characteristics. The ANOVA test for raw data is given in table no. – 15 and 16.

TABLE XI TEST DATA FOR DEPOSITION RATE

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Exp. No.	**Deposition Rate**		**Deposition Rate Mean Value**	**Deposition Rate S/N Ratio**
	1st Run	***2nd Run***		
1	1.5000	1.5240	1.51200	3.59022
2	2.5000	1.7230	2.11150	6.04810
3	1.2500	1.3650	1.30750	2.30363
4	2.6500	1.9983	2.32415	7.06831
5	2.5540	2.6231	2.58855	8.25881
6	2.1100	2.0654	2.08770	6.39188
7	2.9560	2.8546	2.90530	9.25985
8	1.7265	2.1631	1.94480	5.61299
Average			2.0976875	6.06672375
Max.	2.9560	2.8546	2.90530	9.25985
Min.	1.2500	1.3650	1.30750	2.30363

TABLE XII TEST DATA FOR HARDNESS

Exp. No.	**Hardness**		**Hardness Mean Value**	**Hardness S/N Ratio**
	1st Run	***2nd Run***		
1	27.50	30.00	28.750	29.1481
2	24.00	28.00	26.000	28.2223
3	16.00	22.00	19.000	25.2488
4	19.00	26.00	22.500	26.7271
5	40.50	55.00	47.750	33.2779
6	63.00	73.00	68.000	36.5797
7	15.75	25.00	20.375	25.5043
8	13.25	21.00	17.125	23.9992
Average			31.1875	28.5884
Max.	63.00	73.00	68.000	36.5797
Min.	13.25	21.00	17.125	23.9992

TABLE XIII FACTOR EFFECT ON AVERAGE RESPONSE

Factor Effect	**Levels**	**Deposition Rate**	**Hardness**
Current	A1	1.814	24.06
	A2	2.382	38.31
Voltage	B1	2.075	42.63
	B2	2.120	19.75
Wire Speed	C1	1.713	33.22
	C2	2.482	29.16
Gas Flow Rate	D1	2.092	29.03
	D2	2.103	33.34

TABLE XIV FACTOR EFFECT ON S/N RATIO

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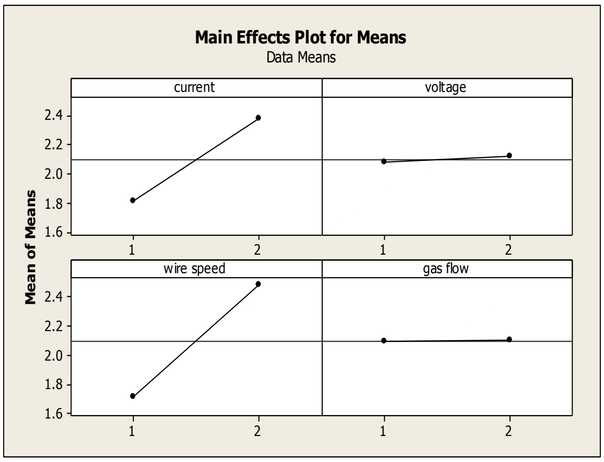
Factor Effect	Levels	Deposition Rate	Hardness
Current	A1	4.753	27.34
	A2	7.381	29.84
Voltage	B1	6.072	31.81
	B2	6.061	25.37
Wire Speed	C1	4.475	28.74
	C2	7.659	28.43
Gas Flow Rate	D1	6.133	28.29
	D2	6.001	28.89



Optimal combination A2 B2 C2 D2

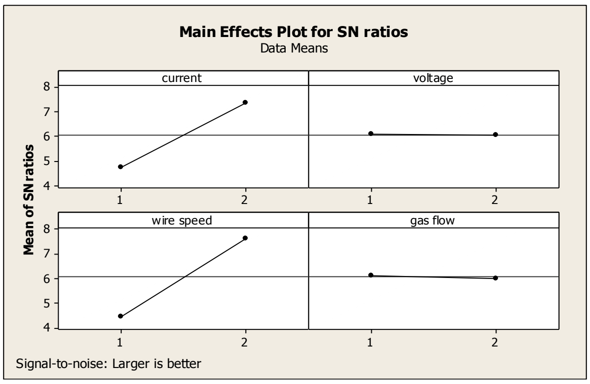
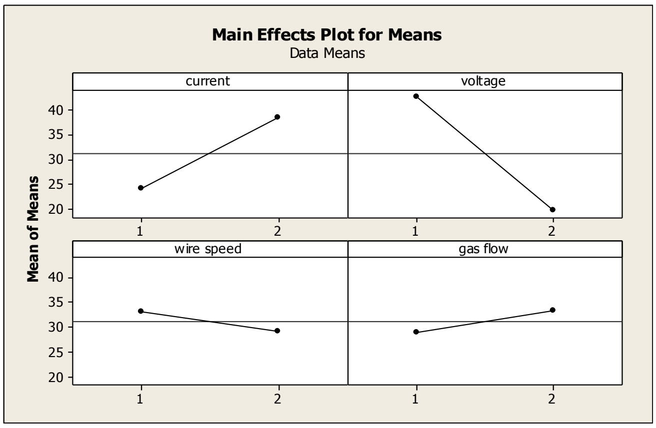


Figure 1. Effect of Process Parameters on Deposition Rate - Raw Data and S/N Ratio



Optimal combination A2 B1 C1 D2

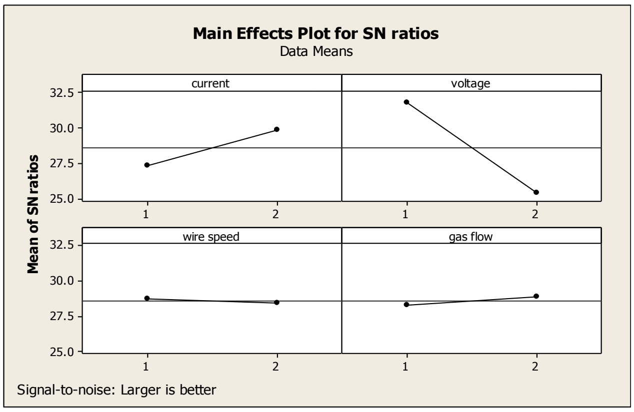


Figure 2. Effect of Process Parameters on Hardness - Raw Data and S/N Ratio

TABLE XV ANOVA TEST SUMMERY FOR HARDNESS

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Current	1	812.2	812.2	812.2	05.46	0.039
Voltage	1	2093.1	2093.1	2093.1	14.06	0.003
Wire speed	1	66.0	66.0	66.0	00.44	0.519
gas flow	1	74.4	74.4	74.4	00.50	0.494
Error	11	1637.8	1637.8	148.9		
Total	15	4683.6				
S = 12.2022 R-Sq = 65.03% R-Sq(adj) = 52.31% Order of significance 1: Voltage; 2: Current; 3: Gas Flow						

TABLE XVI ANOVA TEST SUMMERY FOR DEPOSITION RATE

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Current	1	1.28959	1.28959	1.28959	17.09	0.002
Voltage	1	0.00828	0.00828	0.00828	00.11	0.747
wire speed	1	2.36775	2.36775	2.36775	31.38	0.000
gas flow	1	0.00045	0.00045	0.00045	00.01	0.940
Error	11	0.83000	0.83000	0.07545		
Total	15	4.49608				
S = 0.274691 R-Sq = 81.54% R-Sq(adj) = 74.83% Order of significance 1:Wire Speed; 2: Current;						

DISCUSSION

After performing experiment and analyzing the results, the discussion for the effect of different input parameters on response variables is described below:

Effect on Deposition Rate

It can be seen for the figure-1 that the wire speed and current affects the Deposition Rate very significantly. The different input parameters used in the experimentation can be ranked in order of increasing effect as gas flow, voltage, current and wire speed.

It is clear from the figure-1 that wire speed and current affects deposition rate significantly. The slope of current and wire speed indicates that increase in wire speed results in increase of current and it is also practical that for higher wire feeding there should be higher current to melt the wire coming out continuously at higher speed. So basically for the deposition rate heat is required to melt the wire hence according to **$H=I^2RT$** (H- Heat, I- Current) current and heat are directly proportional to wire speed. Similarly voltage and current are also related to each other according to **$V=IR$.** So we can say that each control factor is related to each other partially or directly influencing the deposition rate.

The analyses of variance test results showed that the **A_2 B_2 C_2 D_2** is the optimal parameters setting for the deposition rate. In this study we concluded that the optimal input parameters setting for the current is 250 amp, voltage is 30 V, wire speed is 50 cm/sec and gas flow is 15 Kg/cm² while welding the stainless steel 304 on the MIG welding machine as far as the deposition rate is concerned.

Effect on Hardness

It can be seen for the figure-2 that the voltage and Current are the most significant factors that are affecting the Hardness. The different input parameters used in the experimentation can be ranked in order of increasing effect as wire speed, gas flow, current and voltage.

From the figure-2 it can be conclude that wire speed and gas flow are less significant than current and voltage. Higher current will result in quick melting of wire electrode. This allows the proper filling of the joint to be made hence increase the strength of the desired weld bead

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and also allows directional solidification of molten metal. The slope of wire speed and gas flow indicates that gas flow and wire speed are almost equal, which may result in shielding phenomenon.

The analyses of variance test results for Hardness confirms the optimal parameters setting as **A_2 B_1 C_1 D_2.** In this study we concluded that the optimal input parameters setting for the current is 250 amp, voltage is 20 V, wire speed is 35 cm/sec and gas flow is 15 Kg/cm² during the welding of stainless steel 304 on the MIG welding machine as far as the Hardness is concerned.

Prediction of Mean

The estimate of the mean is only a point estimate based on the average of results obtained from experiment. It is therefore customary to represent the values of a statistical parameters as a range within which it is likely to fall, for a given level of confidence(Ross,1996). This range termed as the confidence interval (CI). In other words -

The confidence interval is a maximum and minimum value between which the true average should fall at some stated percentage of confidence (Ross, 1996).

The Taguchi approach for predicting the mean performance characteristics and determination of confidence interval for the predicted mean has been applied. The average value of performance characteristics obtained through the confirmation experiments must be within the 95% confidence interval (α= 0.05)

For Hardness overall population of mean is μ = 31.1875.

The predicted optimum value of Hardness is calculated as –

Optimum combination for Hardness is **A_2 B_1 C_1 D_2.**

Hence, $\mu H = (\mu A_2 + \mu B_1 + \mu C_1 + \mu D_2) - (3\mu) = 53.94$

$\mu H = 53.94$

Similarly, Deposition Rate

$\mu D = 2.79$

For calculation of CI_{ce}, the following equation has been used

$$\boldsymbol{CIce} = [\boldsymbol{Fa}(\mathbf{1}, \boldsymbol{fe})\boldsymbol{Ve}\{(\mathbf{1}/\boldsymbol{neff}) + (\mathbf{1}/\boldsymbol{R})\}]^{½} \qquad \textbf{(2)}$$

Where *Fa(l,fe)* = the F ratio at a confidence level of factor against DOF 1, and error degree of freedom *fe*

$$\boldsymbol{Neff} = \frac{\mathbf{N}}{[\mathbf{1} + \textbf{\textit{total DOF associated in the estimation of Mean}}]}$$

- N = Total number of results
- R = Sample size for confirmation experiment.
- Ve = Error variance

For Hardness

$$CIce(\mathrm{H}) = \pm 24.21$$

The 95% confidence level for µH is.

$$CIce(H) = 29.73 \leq \mu H \geq 78.15$$

For Deposition Rate

$$CIce(D) = \pm 1.72$$

The 95% confidence level for µD is

$$CIce(D) = 1.07 \leq \mu D \geq 4.51$$

The predicted optimum values and the confidence interval have been tabulated in table. Experiments were conducted at optimum setting of process parameters for all the response factors.

TABLE: XVII COMPARISON OF PREDICTED AND EXPERIMENTAL VALUES

Response	Predicted Value	Experimental Value	CIce
Hardness	53.94	68	29.73≤ µH ≥ 78.15
Deposition Rate	2.79	2.98	1.07≤ µD ≥ 4.51

This could be observed from the above table that the values from the confirmation experiments were contained well within the confidence interval for all the response variables. Hence, the optimization results were validated.

CONCLUSION

Based on the experiments conducted the following conclusions have been drawn:

1. Wire Speed and Current both affects the deposition rate significantly while welding the stainless steel 304 on MIG welding machine. Theoretically for the deposition rate current should be high for higher heat ($H=I^2RT$) to melt the wire electrode which is continuously fed.
2. With regard to the average response, wire speed and current are more significant for deposition rate as compare to voltage and gas flow.
3. For the S\N ratio response of deposition rate, wire speed has been found to have highest contribution followed by current. If wire speed is not proper as compare to the current then it affects the deposition rate.

   - Current too high and wire speed is low - Improper deposition of weld metal (thin bead).

- Current is low and high wire speed – wire does not melt properly.

4. The analyses of results showed that the A2 B2 C2 D2 is the optimal input parameters setting for the deposition rate when welding the stainless steel 304 on MIG welding machine. Where the values of optimal settings are –

   A_2= 250 amp B_2=30 V

   C_2= 50 cm/sec D_2= 15 Kg/cm^2

   A- Current, B- Voltage, C- Wire Speed, D- Gas Flow

5. Voltage and current significantly affect the hardness in welding the stainless steel 304 on MIG welding machine. In this case voltage and current are more significant as compare to wire speed and gas flow. For the S\N ratio, voltage has the highest contribution.
6. The analyses of results showed that the A2 B1 C1 D2 is the optimal input parameters setting for the hardness.

   A_2= 250 amp B_1=20 V

   C_1= 35 cm/sec D_2= 15 Kg/cm^2

   A-Current, B- Voltage, C- Wire Speed, D- Gas Flow

7. The optimized values of hardness and deposition rate are 68 HRC and 2.98 Kg/hr respectively. The optimized values for both hardness and deposition rate have been validate through the confirmation experiments.

Limitation of work

1. The results are valid within the specified rang of the process parameter in the present study, EWM MIG welding machine is used, which has certain limitations regarding the thickness of material and upper limit of other input parameters.

2. Some important process parameter such as welding environment, other work material properties like tensile strength and internal grain structure of weld bead could not be included in to the present study because of the limited resources of time and capital.

3. The experiments were performed on the semiautomatic MIG welding machine due to unavailability of automatic MIG welding machine.

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