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Parametric Optimization of Weld Reinforcements using Response Surface Methodology Optimization Process

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ABSTRACT: This study analyzes the effect of the process parameters such current, voltage, gas-flow rate and weld speed on a 10mm thick mild steel plate for minimum reinforcement height using the tungsten arc welding process. With the use of design expert, response surface methodology was applied in constructing a design matrix, analyzing the data and obtaining a mathematical model. The minimised weld reinforcement of 0.016mm was observed at a weld current setting of (200amp), voltage (18volt), gas flow rate (22L/min) and speed (4.5mm/sec) with a desirability value of 0.983. The analysis of variance (ANOVA) test performed to ascertain the adequacy of the model, showed that the welding current and gas flow rate had the most significant effect on the weld reinforcement.

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Welding is an indispensable method of joining metals, the construction and manufacturing industries all make use of one joining process or another. The reliability of engineering structures and machineries which are products of these industries depends largely on the quality of the welds as well as the quality of the materials being welded. Gas Tungsten Arc Weld (GTAW) which is one of the arc welding processes, makes use of a non-consumable electrode and a shielding gas to protect the weld against contamination. It's high quality weld, low distortion and ease of heat control advantages makes it the most commonly used welding process.

The quality of a welded joints is greatly affected by numerous weld imperfections. These weld imperfections can be classified into two: weld discontinuities and surface irregularities (Yuewi*et al* 2017). Weld discontinuities is a disruption of thetypical structure of the weldment, leading to lack of homogeneity which comprises porosity, incomplete fusion, slag inclusions, incomplete joint penetration, cold cracks and hot cracks etc. on the other hand surface irregularities are weld surface conditions that contains notches or abrupt changes in thickness and appearance. Surface irregularities include weld defects such as uneven weld bead ripples, weld undercut, excessive weld reinforcement, excessively concave or convex fillet welds, uneven-leg fillet welds, overlap and under fills etc. The quality of a weld can be achieved by meeting an acceptable bead geometry (the bead width and height/reinforcement height), a quality requirement which is greatly influenced by various process parameters involved in the process (Ravikumar and Vijian 2017). The weld pool geometry plays an important role in determining the mechanical and corrosion properties of the weld (Dasgupta and Mukherjee 2013). Inadequate weld bead geometry contributes to the failure of welded structure (Tarang and Yang, 1998).The bead width of a weld is the maximum width of the deposited weld metal. It is directly proportional to the arc current, welding voltage, the diameter of electrode and is inversely proportional to the welding speed (Jefferson 1951). The variations in Contact tube-to-Work Distance (CTWD) also affect the bead width and the height of reinforcement.

A proper bead width eliminates the lack of side wall fusion defect. It is observed that bead width enhances with increase in arc voltage and melting rate increases with reduction in electrode diameter (Chandel *et al* 1997). The reinforcement height is the bead height above the surface of the plate, it influences the strength of the weld and wire feed rate. The wire feed rate is directly proportional to the weld reinforcement irrespective of welding current and polarity and the weld reinforcement is inversely proportional to welding voltage, welding speed and diameter of the electrode. A DCEN polarity leads to larger reinforcement than with DCEP polarity (McGlone 1982).

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Table 1. Central Composite Design Matrix (CCD) and Results Obtained

Std	Run	Factor 1 Current(A) Amp	Factor 2 Voltage(V) Volt	Factor 3 Welding Speed (S) mm/min	Factor 4 Gas Flow Rate (F) lit/min	Response 1 Reinforcement Mm
25	1	240	21	4.25	18	4.02
3	2	200	24	3	14	4.31
9	3	200	18	3	22	3.57
18	4	320	21	4.25	18	4.15
12	5	280	24	3	22	4.57
1	6	200	18	3	14	2.71
21	7	240	21	1.75	18	2.87
19	8	240	15	4.25	18	3.42
7	9	200	24	5.5	14	3.81
22	10	240	21	6.75	18	3.18
15	11	200	24	5.5	22	2.76
14	12	280	18	5.5	22	3.82
26	13	240	21	4.25	18	3.63
29	14	240	21	4.25	18	3.94
30	15	240	21	4.25	18	3.88
5	16	200	18	5.5	14	3.75
27	17	240	21	4.25	18	3.49
8	18	280	24	5.5	14	3.82
6	19	280	18	5.5	14	3.76
24	20	240	21	4.25	26	3.85
13	21	200	18	5.5	22	3.86
11	22	200	24	3	22	3.37
4	23	280	24	3	14	3.43
16	24	280	24	5.5	22	3.91
17	25	160	21	4.25	18	3.71
10	26	280	18	3	22	4.01
20	27	240	27	4.25	18	3.41
28	28	240	21	4.25	18	3.85
23	29	240	21	4.25	10	4.02
2	30	280	18	3	14	3.38

Perfect reinforcement height is required to provide the strength in the welding; the thickness code has defined the limit for the reinforcement height. Excessive or under reinforcement as shown in Figure 1 below, will cause stress to develop on that particular point because of high depth width ratio (based on thickness). It is very challenging to make any weld without any reinforcement, therefore it necessary to maintain in an application an allowable reinforcement height where in the strength of the weld is not adversely affected. Removing excess reinforcement by means of grinding, machining, or any other is a costly and often dangerous.

Excessive reinforcement height is caused by too much welding amperage, inappropriate weld speed etc. (Kang *et al.* 2003), explained that the selection of significant process input parameters is very necessary to obtain accurate bead geometry, which represents the strength and quality of the weld. The objective of this study is to minimize the weld reinforcement in a 10mm mild steel welded plate using the response surface methodology.

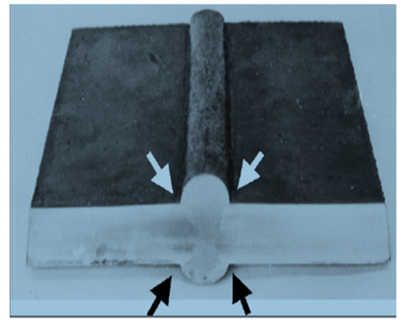

Fig 1: Welded Sample

MATERIALS AND METHODS

Methodology: The design of experiment (DOE) and the statistical analysis of the data are two major aspects of every statistical problem. These two aspects were applied to the conduct of the experiment haven, identified the different variables and their ranges, amongst which are the type and dimension of metal (10mm thick mild steel plate) as well as the input process parameter; weld current 150-240amp, arc voltage 15-25volts, welding speed 3-4.5mm/sec and gas flow rate 16-22lit/min. Central composite design which is one of the most popular designs of response surface methodology was used in constructing the design matrix and fitting the data to the model. The experiment was performed for 30 different joints and the responses of interest: the weld reinforcement was measured using a weld gauge and recorded. Figure 2 shows a picture of the welded plate.

Fig 2: Welded Sample of the Mild Steel Plate

RESULTS AND DISCUSSION

The results of the weld reinforcement was obtained and recorded as tabulated in table 1. The data obtained was analyzed using the analysis of variance (ANOVA) test, the test was performed using the statistics known as the F ratio and P value. The F ratio along with the P value was used to decide the statistical significance of terms and the model. P-values less than 0.0500 indicate model terms are significant and values greater than 0.0500 indicate insignificant terms. From the analysis recorded in Table 2, an F-value of 2.64 and P value of 0.0361 was obtained. The p value of 0.0361 indicates that the model is significant and that there is only a 3.61% chance that an F-value this large could occur due to noise. For the models terms, the current and some of the combined term (interaction) had the most significant effect on the response based on the fact that P-values less than 0.0500 indicate significant model terms.

Table 2: Analysis of Variance for Validating the Model

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	3.70	14	0.2643	2.64	0.0361	Significant
A-Current	0.4931	1	0.4931	4.92	0.0423	
B-Voltage	0.0504	1	0.0504	0.5035	0.4888	
C-Welding Speed	0.0241	1	0.0241	0.2404	0.6310	
D-Gas Flow Rate	0.0131	1	0.0131	0.1305	0.7229	
AB	0.0100	1	0.0100	0.0999	0.7563	
AC	0.0056	1	0.0056	0.0562	0.8158	
AD	0.5402	1	0.5402	5.40	0.0347	
BC	0.5256	1	0.5256	5.25	0.0368	
BD	0.3660	1	0.3660		0.0752	
CD`	0.3844	1	0.3844		0.0689	
A^2	0.0657	1	0.0657	0.1906	0.4304	
B^2	0.1746	1	0.1746	8.61	0.2064	
C^2	0.8621	1	0.8621	0.6906	0.0103	
D^2	0.0691	1	0.0691	0.6906	0.4190	
Residual	1.50	15	0.1001			
Lack of Fit	1.30	10	0.1300	3.22	0.1044	Not Significant
Pure Error	0.2019	5	0.0404			
Cor Total	5.20	29				

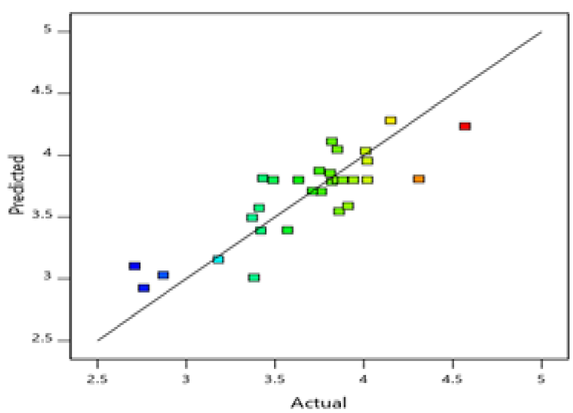

Fig 3: Reliability plot of observed and predicted weld reinforcements.

From Table 3, the goodness of fit statistics was used in obtained statistics such as the coefficient of determination R^2 which tells how well the model fits the data. An R^2 of 71.1% shows that 71.1% of the variability experienced in the analysis is explained by the model. A negative Predicted R^2 value indicates that the overall mean may be a better predictor of the weld reinforcement compared to the current model. Adeq Precision is used to measure signal to noise ratio, a ratio greater than 4 is most desirable. From the analysis in Table 3; 6.080 was obtained, which signifies an adequate signal and further proves that the model can be used to navigate the design space.

Table 3: Goodness of Fit Statistics

Std. Dev.	0.3164	R^2	0.7113
Mean	3.68	Adjusted R^2	0.4418
C.V.%	8.61	Predicted R^2	-0.4955
		Adeq precision	6.0801

Final Equation In Terms Of Coded Factors:

Reinforcement = 3.80+0.1433*A*+0.0458*B*+0.0317*C*+ 0.0233*D*+0.0250*AB*-0.0187*AC*+0.1838*AD*-0.1812*BC*-0.1512*BD*-0.1550*CD*+0.0490A^2-0.0798B^2-0.1773C^2+0.0502D^2

Where A-Current, B-Voltage, C-Welding Speed, D-Gas Flow Rate.

Final Equation in Terms of Actual Factors

Reinforcement = 6.59277-0.034557(*Current*) +0.769931(*Voltage*) +2.65280(*Welding Speed*) +0.013677(*Gas Flow Rate*) +0.000208(*Current*Voltage*) -0.000375(*Current*Welding Speed*) +0.001148(*Current*Gas Flow Rate*) -0.048333(*Voltage*Welding Speed*) -0.012604(*Voltage*Gas Flow Rate*) -0.031000(*Welding Speed*Gas Flow Rate*) +0.000031$(Current)^2$-0.008866$(Voltage)^2$-0.113467$(Welding\ Speed)^2$+0.003138$(Gas\ Flow\ Rate)^2$

To further confirm the reliability of the model, a plot was made as shown in Figure 3 between the observed experimental values and the predicted values. The plot showed that the error is uniformly distributed.

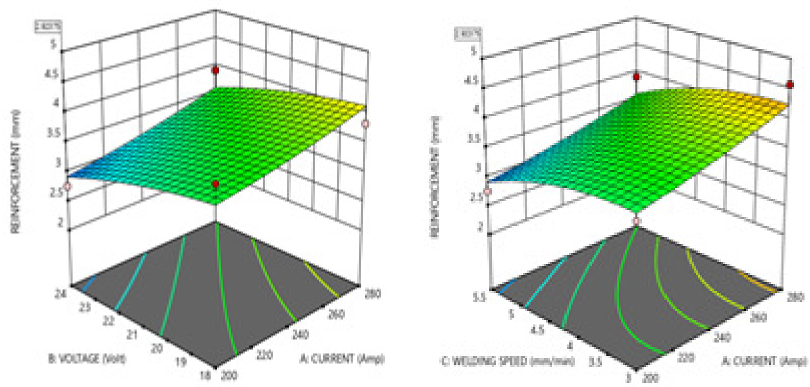

Fig 4: Graph showing Reinforcement versus Current and Voltage/ Current and Weld Speed.

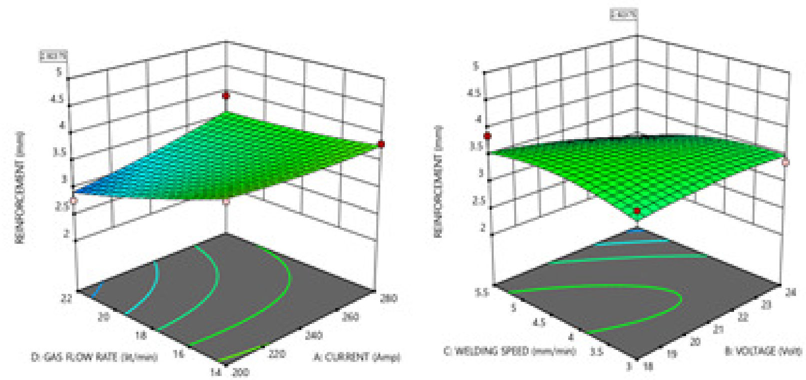

Fig 5: Graph showing Reinforcement versus Current and Voltage/ Current and Weld Speed.

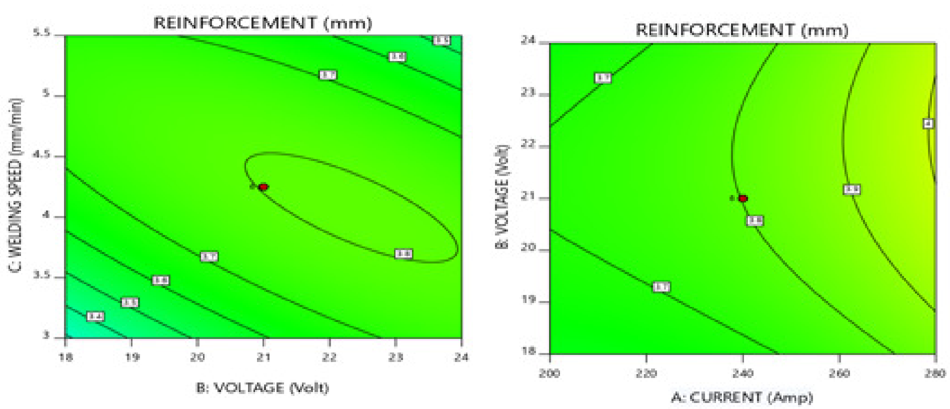

Fig 6: Contour Plot of weld reinforcement Welding Speed and Voltage/ Voltage and Current.

The model graphs shown in figures 4a and b shows the interaction of the combine variables on the weld reinforcement. Figure 5a, shows that the weld reinforcement was lower than 3mm as arc voltage increased to a maximum volts of 22V, current decreased to its bare minimum. Also the weld reinforcement decreased as the current decreased and welding speed increased.

Numerical Optimization: Results of numerical optimization performed to confirm the desirability of the overall model by design expert software, It was observed that at a current of 200 Amp, voltage of 24 Volt, gas flow rate of 5.5l/min and welding speed of 22mma minimized weld reinforcement of 2.924mm was obtained. Figure 6 and 7 below shows the contour plots for the minimized weld reinforcement against the optimized values of the selected variables.

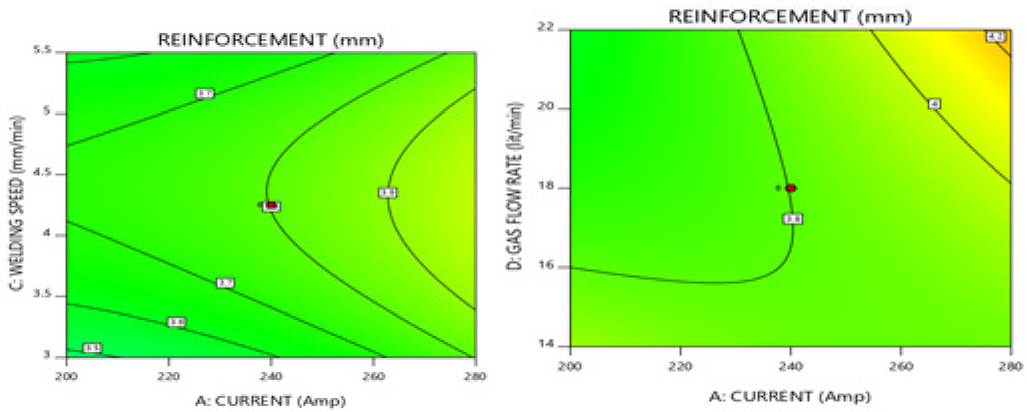

Fig 7: Contour Plot of minimized weld reinforcement Welding Speed and Current/ Gas Flow Rate and Current

Conclusion: A quadratic model was obtained using the RSM technique in optimizing the response (weld reinforcements) in the GTA welding technique for the specified input process parameters. The model indicated that the weld current had the most significant effect on the weld reinforcement, while the gas flow rate had the least effect. The 3D graphs also showed that an increase in welding current enhances the reinforcement height. By numerical optimization using the design expert software, the optimum values of the current, voltage, gas flow rate, welding speed and desirability were obtained as follows 200Amp, 24Volt, 5.5 l/min, 22mm and 0.941 respectively.

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