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Analysis and parametric optimization of flux cored arc welding process for IS 2062 mild steel plates using Taguchi method and utility concept

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Optimization of flux cored arc welding (FCAW) process parameters were carried out to obtain optimum weld bead geometry in mild steel plates of IS 2062 by using an alternate Taguchi method. Design of experiments based on multi-objective Taguchi approach was employed for development of mathematical model correlating important process parameters like welding voltage (V), welding current (I), stick out (N) and wire speed (T), with weld bead parameters like penetration (P) and percentage of dilution as responses. The optimum welding parameters were investigated using Taguchi method with L_{16} orthogonal array (OA). The developed models have checked for adequacy and significance based on analysis of variance (ANOVA) test. Because of high reliability, easiness in operation, high penetration good surface finish and high productivity FCAW became a natural choice for fabrication industries. Based on confirmation test, the proposed model can be effectively used to optimize the welding performance. The utility concept was used for optimization of bead geometry and results are presented.

Key words: Flux cored arc welding (FCAW), optimization, analysis of variance (ANOVA), Taguchi approach, utility concept.

INTRODUCTION

Quality is a vital factor in today's manufacturing world. Quality can be defined as the degree of customer satisfaction. Quality of a product depends on how it performs in desired circumstances. Quality is avery vital factor in the field of welding. The quality of a weld depends on mechanical properties of the weld metal which in turn depends on metallurgical characteristics and chemical composition of the weld. The mechanical and metallurgical feature of weld depends on bead geometry which is directly related to welding process parameters. In other words, quality of weld depends on in process parameters. Flux cored arc welding (FCAW) welding is a multi-objective and multifactor metal fabrication technique. The process parameters have a direct influence on bead geometry.

Figure 1 shows the weld bead geometry. Mechanical strength of weld metal is highly influenced by the composition of metal but also by weld bead shape.

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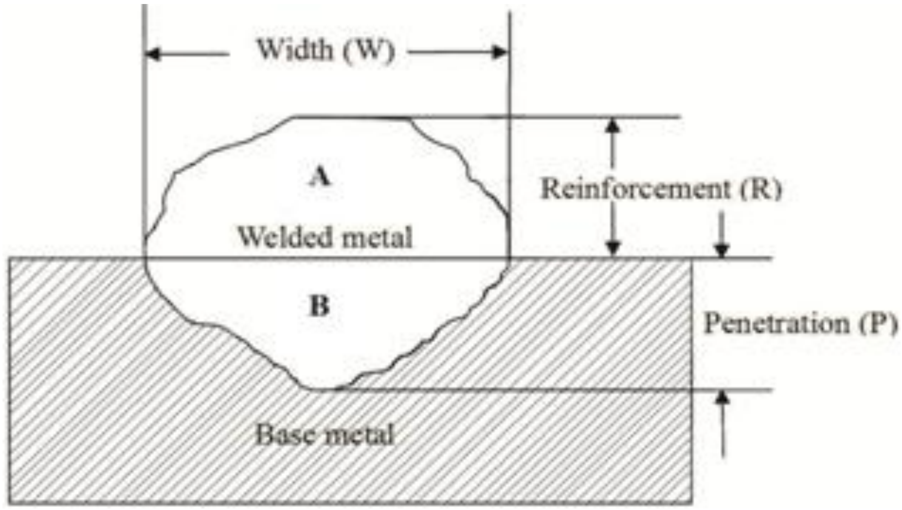

Figure 1. Weld bead geometry. Percentage dilution (D) = [B / (A + B)] × 100.

(Kannan et al., 2013). This is an indication of bead geo geometry. It mainly depends on wire speed, welding current, voltage and stick out etc. Therefore, it is necessary to study the relationship between in process parameters and bead parameters to study weld bead geometry (Lijo and Somashekher, 2013). This paper highlights the study carried out to develop mathematical models to optimize weld bead geometry, in bead on plate welding deposited by FCAW.

The multi characteristics optimization model based on Taguchi method and utility concept has been employed to determine the optimal combination of welding parameters to attain minimum percentage of dilution and maximum penetration simultaneously. The confirmation test was also conducted to verify the results.

TAGUCHI METHOD

Taguchi method uses a special type of design of orthogonal arrays (OA) to study the entire parameter space with smaller number of experiments. The OA is a small set from all possibilities which helps to determine the least number of experiments, which will further helps to determine the optimum level for each process parameters and establish the relative importance on individual process parameters. Appropriate selection of OA is the first step of Taguchi approach. The minimum number of experimental trials performed in an OA is given by N_{min} = (L-1) F + 1; where F is the number of factors and L is the number of levels. Taguchi method utilizes a statistical measure of performance called signal-to-noise (S/N) ratio. The ratio depends on the quality characteristics of product/process to be optimized. The experimental results are then transferred to S/N ratio. This ratio can be used to measure the quality characteristics deviating from desired values. Usually, there are three categories in the analysis of the S/N ratio, that is, the lower-the-better, higher-the-better and nominal-the-better. Regardless of category of quality characteristics larger S/N ratio corresponds to the better quality characteristics (Jagannatha et al., 2012). The optimal process parameters are the levels with highest S/N ratio. Analysis of variance (ANOVA) tests are performed to see that the process parameters are statically significant. Finally, a confirmation experimented is conducted to verify the optimal process parameters.

The multi-response methodology based on Taguchi's robust design technique and utility concept was used for optimizing the multi responses like dilution and penetration. Taguchi's standard S/N ratios were selected to obtain the optimum parameters. They were the larger-the-better type for penetration and dilution as calculated by Equation 1, and Equation 2 represents smaller-the-better type, respectively.

$$\eta = -10log_{10}\left|\frac{1}{p^2}\right| \tag{1}$$

$$\eta = -10log_{10}\left|D^2\right| \tag{2}$$

UTILITY CONCEPT

Welding process is a multi-factor multi-objective problem; the optimum solution is a compromise. The models developed were used for optimization of FCAW process parameters to obtain good bead geometry. Utility can be defined as the usefulness of a product or service into the levels of expectations to the consumers. The usefulness of a process can be represented by a unified index termed as utility which is the summation of the individual utilities of various quality characteristics (Norasiah et al., 2012). It is difficult to obtain the best combination process parameters, when there are multi responses to be optimized. If x_i represents the measure of effectiveness and n represents the number of responses, then overall utility function can be defined as:

$$U(x_1, x_2...............x_n) = f\,[U_1(x_1), U_2(x_2).......U_n(x_n)] \tag{3}$$

Where $U(x_1, x_2..............x_n)$ is the overall utility of n process response characteristics and $U_1(x_1)$ is the utility of I_{th} response. Assignment of weights is based on the requirements and priorities among the various responses. Therefore, weighted form can be expresses as:

Table 1. Chemical composition of base metal and filler wire.

	Elements weight (%)								
Material	**C**	**SI**	**Mn**	**P**	**S**	**Al**	**Cr**	**Mo**	**Ni**
IS 2062	0.150	0.160	0.870	0.015	0.016	0.031	-	-	-
E7 IT- 1C	1.12	0.90	1.75	0.030	0.030	-		0.30	0.50

Table 2. Welding parameters and their levels.

Parameter	Unit	Notation	Factor levels 1	2	3	4
Welding voltage	V	V	20	22	24	25
Welding current	A	I	87	123	138	155
Stick out	mm	N	15	20	25	30
Wire speed	mm/min	T	25	40	50	53

$$U(x_1, x_2..............x_n) = \sum_{i=1}^{n} WiUi(Xi) \quad (4)$$

Where $\sum_{i=1}^{n} Wi = 1$

Where W_i is the weight assigned to *i* th response. The utility concept employs the weighing factors to each S/N ratio for each trial and multi response S/N ratio calculated using Equation 5:

$$\eta = \eta_1 W_1 + \eta_2 W_2 \quad (5)$$

Where W_1 and W_2 are the weight factors associated with S/N ratios. It is taken as 0.5. The overall mean of η associated with *k* number of trials is computed as:

$$M = \frac{1}{k} \sum_{1}^{n} \eta k \quad (6)$$

These weighing factors are determined based on priorities among the various responses to be simultaneously optimized. In this experimental work, it is taken as 0.5. This gives priorities to all the responses for simultaneous maximization and minimization (Cochran and Coxz, 1987). The overall mean of η associated with *k* number of trials is computed from Equation 6.

EXPERIMENTATION

Test plates of size 300 × 200 × 6 mm were cut from mild steel plate of grade IS - 2062 and one of the surfaces is cleaned to remove oxide and dirt before welding. E7 IT-1C wire of 1.2 mm diameter was used for bead on plate welding. The properties of base metal and filler wire are shown in Table 1.

The selection of the welding electrode wire was based on the matching, the mechanical properties and physical characteristics of the base metal, weld size and existing electrode inventory (Norasiah et al., 2012). These have good surface appearance, good radiographic standard quality and minimum electrode wastage.

PLAN OF INVESTIGATION

The research work is carried out in the following steps (Tarng and Yang, 1998): Identification of factors, finding the limit of process variables, development of OA, conducting experiments as per OA, recording responses, development of mathematical models and checking adequacy of developed models. Utility concept applied further for optimization.

Identification of factors and responses

The percentage of dilution has got an important influence in welding. The properties of the welding are significantly influenced by dilution obtained. Hence, control of dilution is important in welding where a high dilution is highly desirable. When dilution is quite low, the final deposit composition will be closer to that of filler material and hence corrosion resistant properties of welding will be greatly improved. The chosen factors have been selected on the basis to get optimal dilution and optimal weld bead geometry (Kannan et al., 2013). These are wire speed rate (T), welding voltage (V), welding current (I) and stick out (N). The responses chosen were depth of penetration (P) and percentage of dilution (D). The responses were chosen based on the impact of parameters on final composite model.

Finding the limits of process variables

Working ranges of all selected factors are fixed by conducting trial run. This was carried out by varying one of the factors while keeping the rest of them as constant values. Working range of each process parameters was decided upon by inspecting the bead for smooth appearance without any visible defects. The chosen level of the parameters with their units and notation are given in Table 2.

Development of orthogonal array

In full factorial design, number of experimental runs may be high. This results increase in cost and time. In order to avoid this,

Table 3. Design matrix and observed values of weld bead geometry.

Trial No.	Design matrix				Bead parameter	
	V	I	N	T	P (mm)	D (%)
1	1	1	1	1	1.235	17.623
2	1	2	2	2	1.347	17.462
3	1	3	3	3	1.388	17.842
4	1	4	4	4	1.425	17.442
5	2	1	2	3	1.657	18.332
6	2	2	1	4	1.586	16.692
7	2	3	4	1	1.456	17.823
8	2	4	3	2	1.738	20.424
9	3	1	3	4	1.416	17.912
10	3	2	4	3	1.537	18.182
11	3	3	1	2	1.465	18.218
12	3	4	2	1	1.368	17.512
13	4	1	4	2	1.487	18.221
14	4	2	3	1	1.398	17.943
15	4	3	2	4	1.457	17.841
16	4	4	1	3	1.868	21.512

P, Penetration; D, dilution %.

Taguchi's L_{16} (4^4) OA consisting 16 sets of data has been selected to optimize the experimental data. This is shown in Table 3.

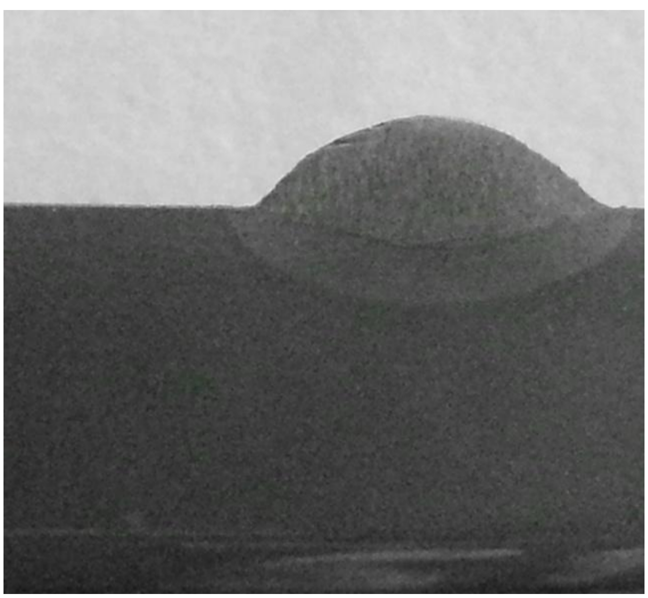

Figure 2. Welded specimen

Conducting experiments as per orthogonal array

In this work, 16 experimental runs were allowed as per the OA as shown Table 3 at random (Saurav et al., 2008). At each run settings, all parameters were disturbed and reset for next deposit. This is very essential to introduce variability caused by errors in experimental set up.

Recording of responses

For measuring the clad bead geometry, the transverse section of each weld overlays was cut using band saw from mid length. Position of the weld and end faces were machined and grinded. The specimen and faces were polished and etched using a 5% nital solution to display bead dimensions. The weld bead profiles were traced using a reflective type optical profile projector at a magnification of ×10 (Gunaraj and Murugan, 1999). Then the bead dimension such as depth of penetration and dilution were measured (Montgomery, 2003). The profiles traced using AUTO CAD software. The welded specimen is shown in Figure 2 (Kannan and Yoganath, 2010; Dawei et al., 2013). The measured weld bead dimensions and percentage of dilution is shown in Table 3.

RESULTS AND DISCUSSION

Analysis of single response

Experiments were conducted on IS 2062 mild steel plate to study the performance of bead on plate welding using the FCAW method by L_{16} OA. The values of single response S/N ratios of penetration and dilution are calculated using larger-the-better criteria, calculated using Equation 1. The combined multi-response S/N ratio is calculated using Equation 5, respectively. The individual values of S/N ratios are shown in Table 6. It can be found that the optimal combination of $V_2I_4N_1T_3$ is

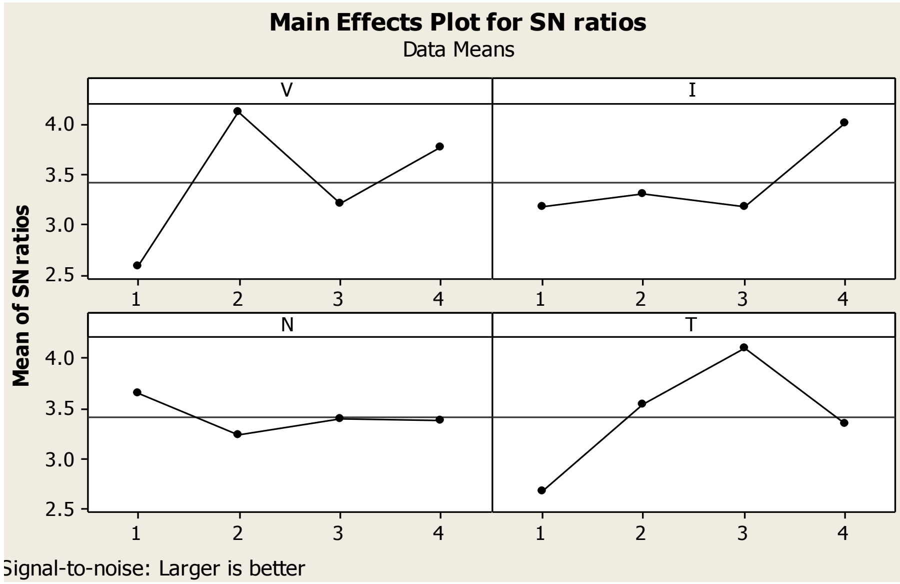

Figure 3. Main effects of plots based on S/N ratio of penetration.

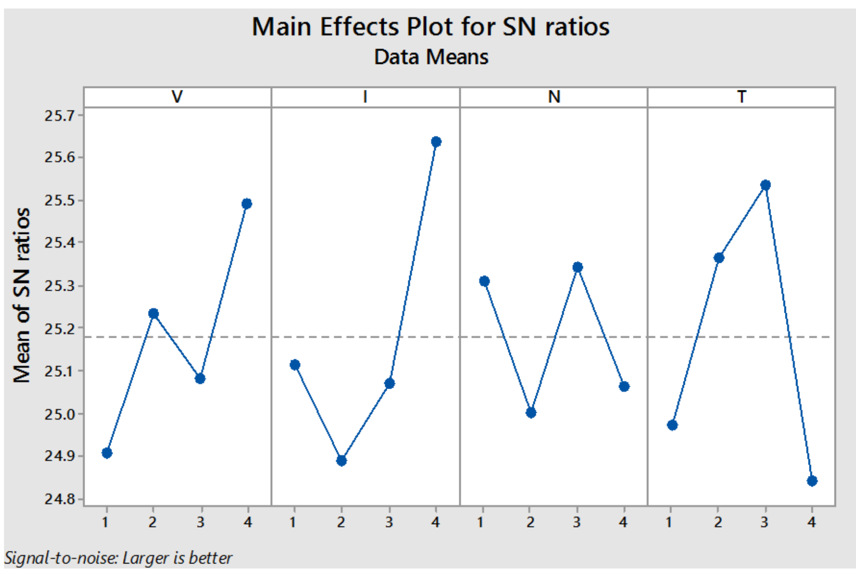

Figure 4. Main effects of plots based on S/N ratio of dilution.

the largest value of S/N ratio of penetration and for dilution it is $V_4I_4N_1T_3$, respectively. Therefore, $V_2I_4N_1T_3$ is the optimal combination of responses for penetration and for dilution $V_4I_4N_1T_3$ is the optimal combination. The main effect plots (Figures 3 and 4) shows that the optimum condition for penetration and dilution are at level, 22 V, 155 Amps, 15 mm and 53 mm/min for penetration 25V, 155 Amps, 15 mm and 53 mm/min, respectively. Table 4 and 6 show the response table for signal to noise ratios for penetration and dilution.

The statistical software MINITAB 15 is used to determine the ANOVA. The purpose of ANOVA is to investigate which welding parameter significantly affects the performance contribution. In addition, F-test was used to determine which welding factor has significant effect on performance. When F value is large then that factor has significant effect on performance. The results of ANOVA for single-response S/N ratio of dilution and penetration are shown in Tables 5 and 7, respectively. It can be seen that welding current has highest contribution

Table 4. Response table for signal to noise ratios penetration.

Level	V	I	N	T
1	2.586	3.172	3.646	2.682
2	4.114	3.072	3.241	3.538
3	3.198	3.174	3.395	4.099
4	3.763	4.007	3.380	3.343
Delta	1.528	0.835	0.405	1.417
Rank	1	3	42	

Table 5. ANOVA for penetration.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
V	3	0.036551	0.036551	0.0365512	1.55965	0.237640
I	3	0.005056	0.005056	0.0050562	0.21575	0.651356
N	3	0.035870	0.035870	0.0358705	1.53060	0.241782
T	3	0.040230	0.040230	0.0402304	1.71664	0.216825
Error	3	0.257791	0.257791	0.0234355		
Total	15	0.375499				

Table 6. Response table for signal to noise ratios on dilution.

Level	V	I	N	T
1	24.91	25.12	25.31	24.97
2	25.23	24.89	25.00	25.37
3	25.08	25.07	25.34	25.53
4	25.49	25.64	25.06	24.84
Delta	0.59	0.75	0.34	0.69
Rank	3	1	4	2

of about 65.1% for penetration and stick out with 69.7.7% contribution for dilution. The other parameters have less contribution. It is clear that the welding current and stick out are one of the significant factors that has more impact than any other factors on dilution and penetration.

Optimal parameter combination of Multi response

The optimal combination of process parameters for simultaneous optimization of dilution and penetration is obtained by means of values of multi-responses S/N ratio of overall utility and is shown in Table 8.

The larger values of multi-responses S/N ratio means the comparable sequence exhibiting a stronger correlation with the reference sequence. Based on the study, combination of $V_2I_4N_1T_3$ shows the largest values of multi-response S/N ratio for the factors V, I, N and T, respectively. Therefore, $V_2I_4N_1T_3$ is the optimal parameter combination of flux cored arc bead on plate welding for IS 2062 steel plates, which are shown in Figure 5. Table 9 shows the response table for multi-response signal to noise ratios.

The results of ANOVA for multi-response S/N ratio are shown in Table 10. On examining the percentage of contribution (P %) of different factors, it can be seen that welding current is about 34.7% and other parameters have significant contributions. It is clear that welding current is one of the significant factors that have more impact than any other factors. The main effect plot, (Figure 5), shows that optimum condition for multiple responses is/are at level, 22 V, 155 Amps, 15 mm and 53 mm/min, respectively.

Confirmation test

The final step is the verification experiments to validate

Table 7. Analysis of variance for dilution.

Source	DF	Adj SS	Adj MS	F	P
Regression	4	5.8337	1.45843	1.08	0.412
V	1	2.4490	2.44895	1.81	0.205
I	1	3.1407	3.14068	2.33	0.155
N	1	0.2160	0.21601	0.16	0.697
t	1	0.0281	0.02809	0.02	0.888
Error	11	14.8450	1.34955		
Total	15	20.6787			

Table 8. S/N ratios of penetration and dilution and multi response.

S/N ratio D (%)	S/N ratio P	S/N ratio multi response
24.9216	1.83334	13.37747
24.8419	2.58735	13.71463
25.0289	2.84779	13.93835
24.8319	3.07630	13.9541
25.2642	4.38645	14.82533
24.4502	4.00606	14.22813
25.0196	3.26323	14.14142
26.2028	4.80100	15.5019
25.0629	3.02127	14.04209
25.1928	3.73348	14.46314
25.2100	3.31675	14.26338
24.8667	2.72172	13.79421
25.2114	3.44622	14.32881
25.0779	2.91014	13.99402
25.0284	3.26919	14.1488
26.6536	5.42754	16.04057

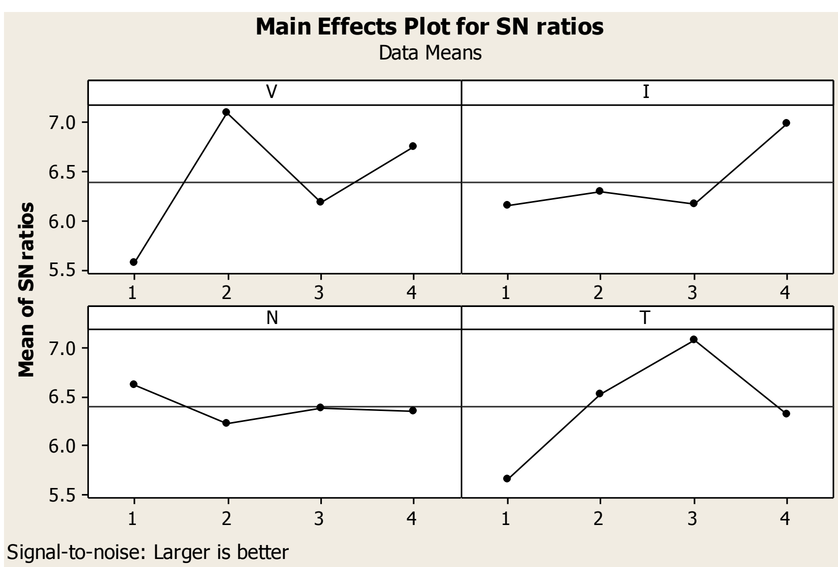

Figure 5. Main effect of plots based on S/N ratios multiple responses.

Table 9. Response table for multi-response S/N ratios.

Level	I	S	N	T
1	5.571	6.154	6.626	5.667
2	7.091	6.289	6.222	6.520
3	6.181	6.157	6.378	7.078
4	6.744	6.987	6.361	6.323
Delta	1.520	0.833	0.404	1.411
Rank	1	3	4	2

Table 10. Analysis of variance for multi response S/N ratios.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
V	3	5.3253	5.3253	1.77510	25.82	0.012
I	3	0.3385	0.3385	0.11568	1.64	0.347
N	3	1.9070	1.9070	0.63658	9.25	0.050
T	3	4.0699	4.0699	1.35664	19.73	0.018
Error	3	0.2063	0.2063	0.06876		
Total	15	11.8470				

Table 11. Results of confirmation tests

Level	Performance Characteristic	Optimal setting	Predicted S/N ratio	Experimental S/N ratio
SRO	Penetration (P)	$V_2I_4N_1T3$	5.4275	7.5062
	Dilution (D)	$V_4I_4N_1T_3$	13.7874	14.7424
MRO	P and D	$V_2I_4N_1T_3$	16.0405	17.7646

optimum conditions suggested by the matrix experiments which indeed give the projected experiment. Confirmation experiments is performed by conducting a test with a specific combination of factors and levels previously evaluated. After determining the optimum conditions new experiment was conducted with optimum levels. Then predicted parameters were calculated using Equation 7.

$$\eta\_opt = \bar{\eta} + \sum_{i=1}^{p} \eta_{mi} - \bar{\eta} \quad (7)$$

Where *m* is the total mean of the responses S/N ratio at the optimal level and m_i is the S/N ratio at the optimal parameter. The predicted optimal values of single and multi-response function are shown in Table 11. The improvement in S/N ratio is found. So there is considerable improvement in quality with multi-response function.

In order to validate the experiment, four trials are conducted according to the optimal parameters level, $V_2I_4N_1T_3$ and corresponding values of performance measures are taken. Table 11 shows the predicted multi-response S/N ratio and multi-response S/N ratio obtained from experiment. It may be noted that there is a good agreement between estimated value (16.0405) and the experiment (17.7646). Therefore, the condition $V_2I_4N_1T_3$ is treated as optimal. The optimal condition, $V_2I_4N_1T_3$, (22 V, 155 Amps, 15 mm and 53 mm/min) is confirmed by ANOVA.

Conclusions

Optimization of process parameters of FCAW has been carried out using Taguchi's OA with multi response analysis as discussed in this paper. From the analysis, the following conclusions have been drawn:

1) It has been found that the combination $V_2I_4N_1T_3$ show the largest values of multi-response S/N ratio for factors V, I, N and T. Therefore, $V_2I_4N_1T_3$ is optimal parameter combination with voltage, current, stick out and wire feed

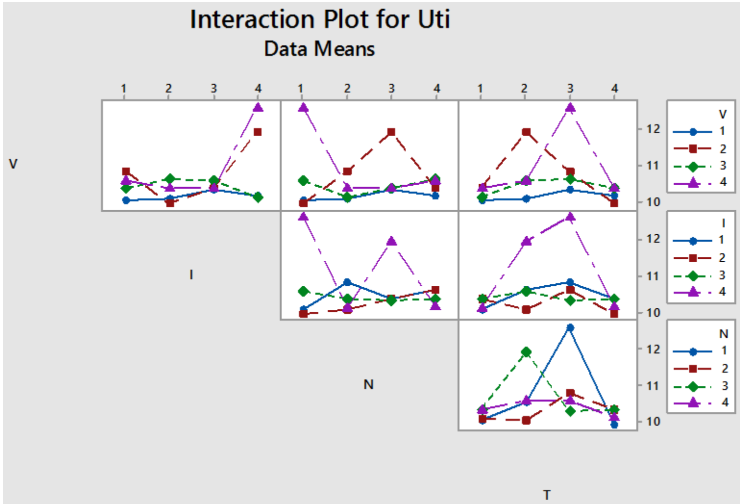

Figure 6. Interaction plot for multi-response.

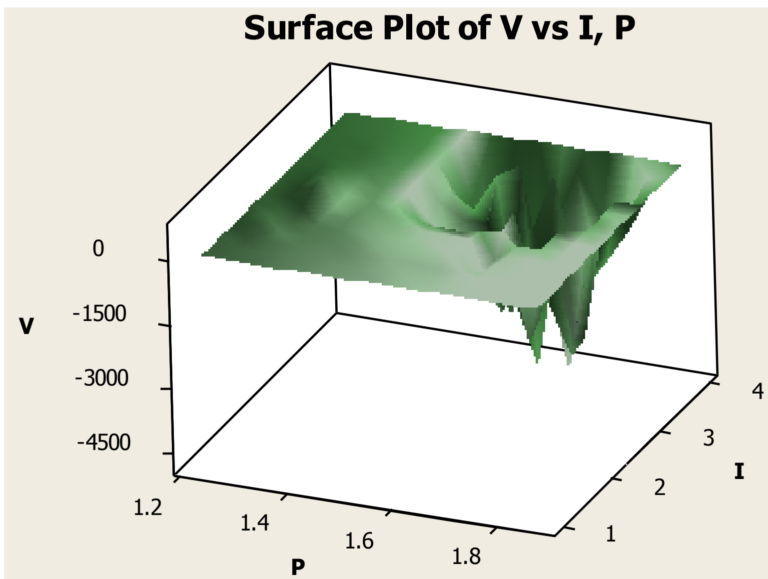

Figure 7. Interaction effect of voltage and current on penetration.

of the flux cored bead on plate welding on IS 2022 mild steel plates.
2) Through ANOVA, percentage of contribution to the stick out is more as compared to other parameters. Hence, the most significant factor for the flux cored bead on plate welding for maximization of dilution and maximization of penetration is stick out.
3) It can be found that there is a good agreement between estimated and experimental value. Therefore, in this welding process $V_2I_4N_1T_3$ is treated as optimum parameter combination.
4) From the experimental results, it can be found that welding current and stick out has largest impact on dilution and penetration.
5) Figure 6 illustrates the interaction effects of process parameters for multi-response optimization. It is observed that if the lines are parallel and not over lapping there is little or no evidence of an interaction in the parameters.
6) Figure 7 shows the interaction effects of voltage and current on penetration. Figure 8 shows surface plot voltage and current on dilution.
7) Figure 9 shows combination of process parameters with penetration.
8) Figures 10 to 13 show microstructures of various

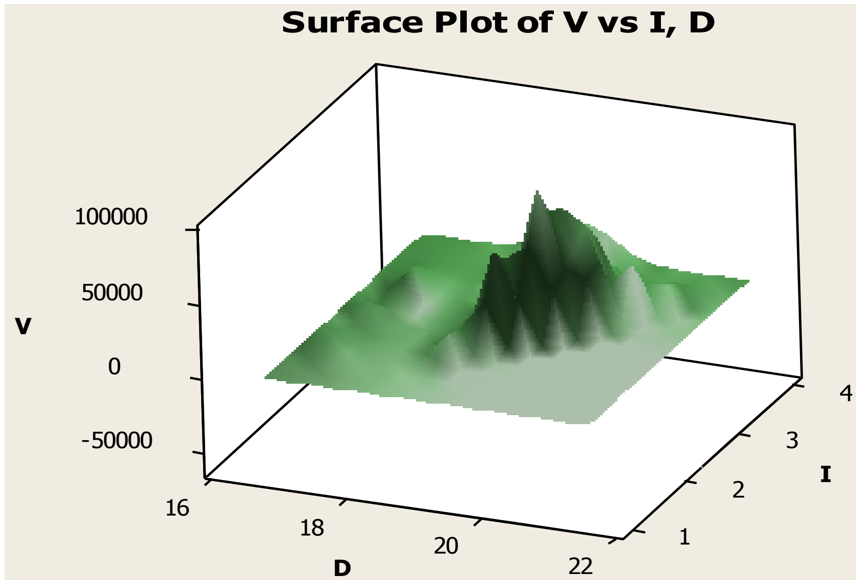

Figure 8. Interaction effects of voltage and current on dilution.

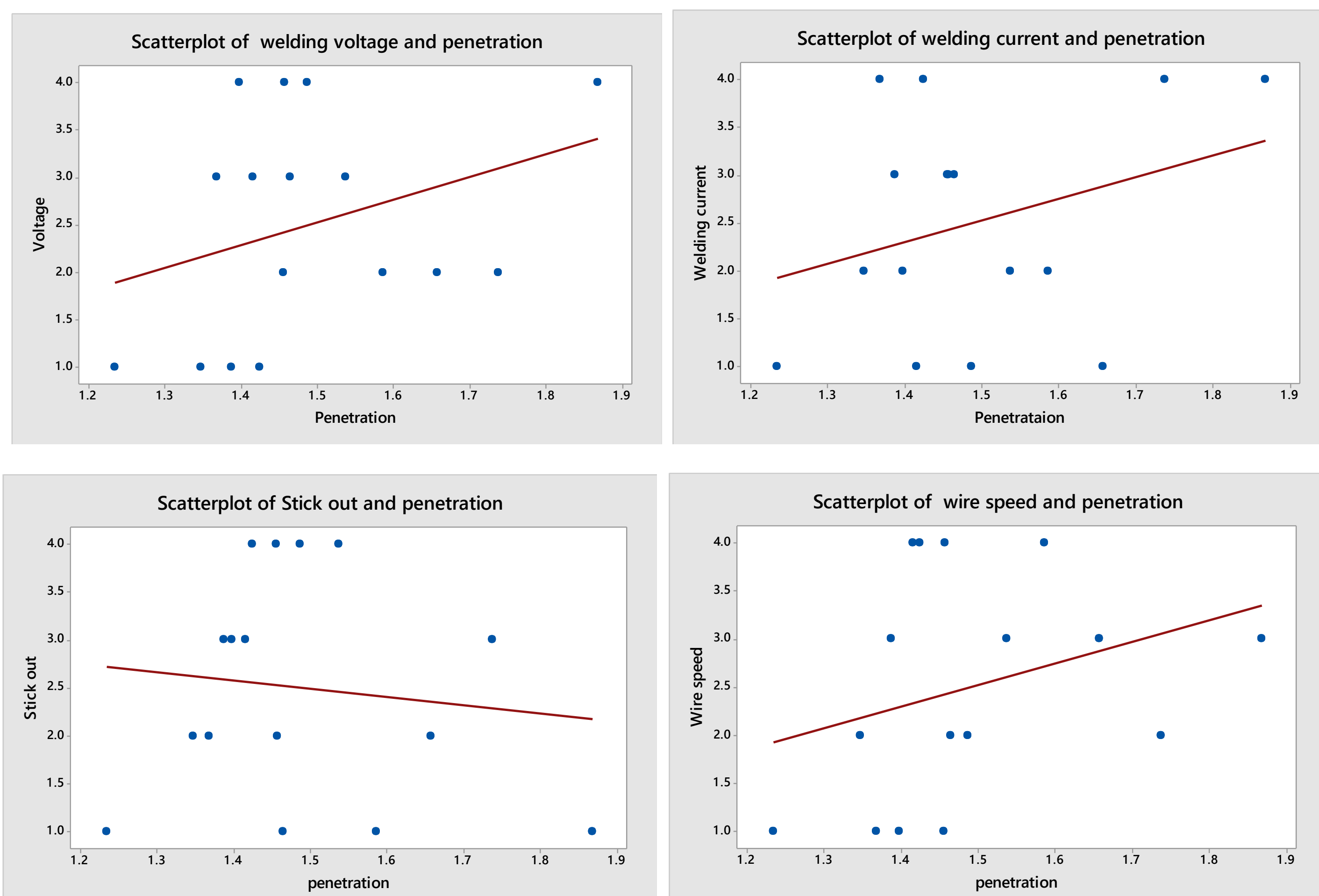

Figure 9. Combination of process parameters and penetration.

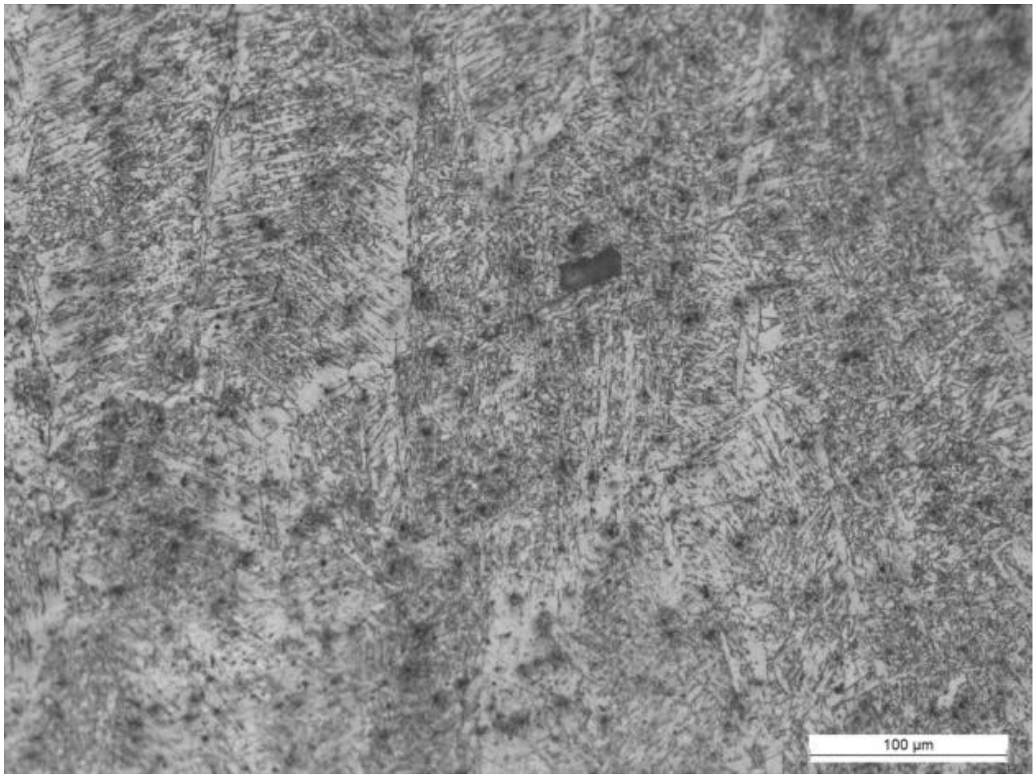

Figure 10. Microstructure of HAZ.

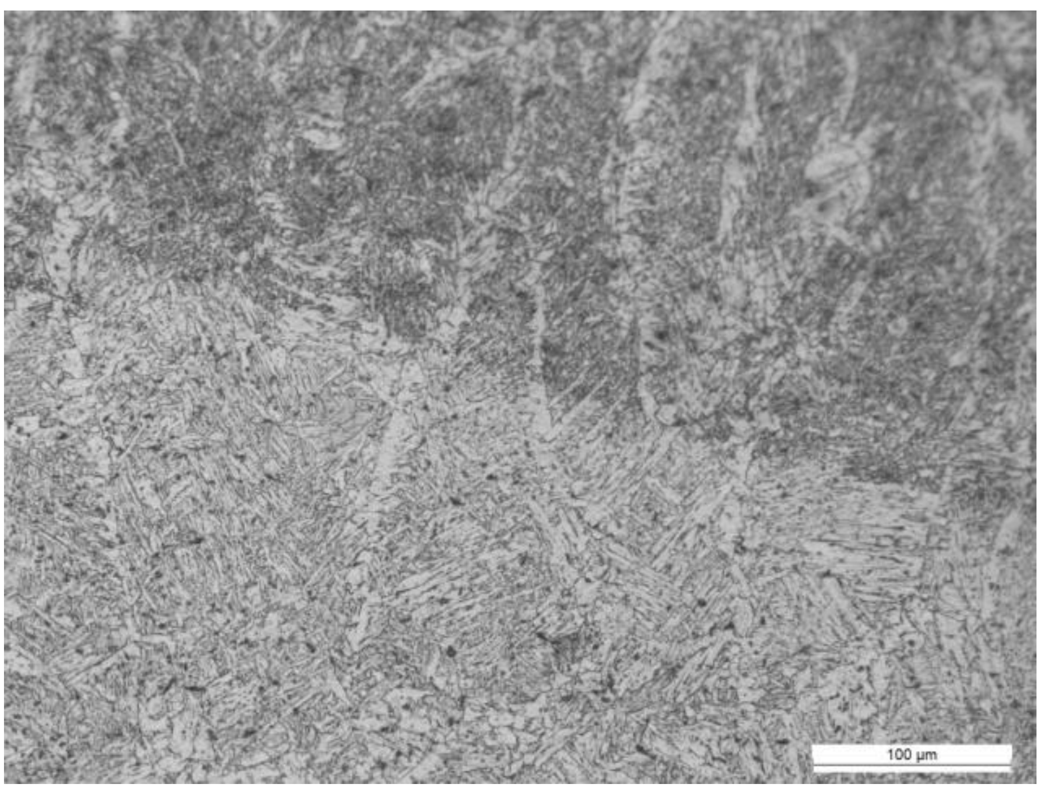

Figure 11. Microstructure of fusion line.

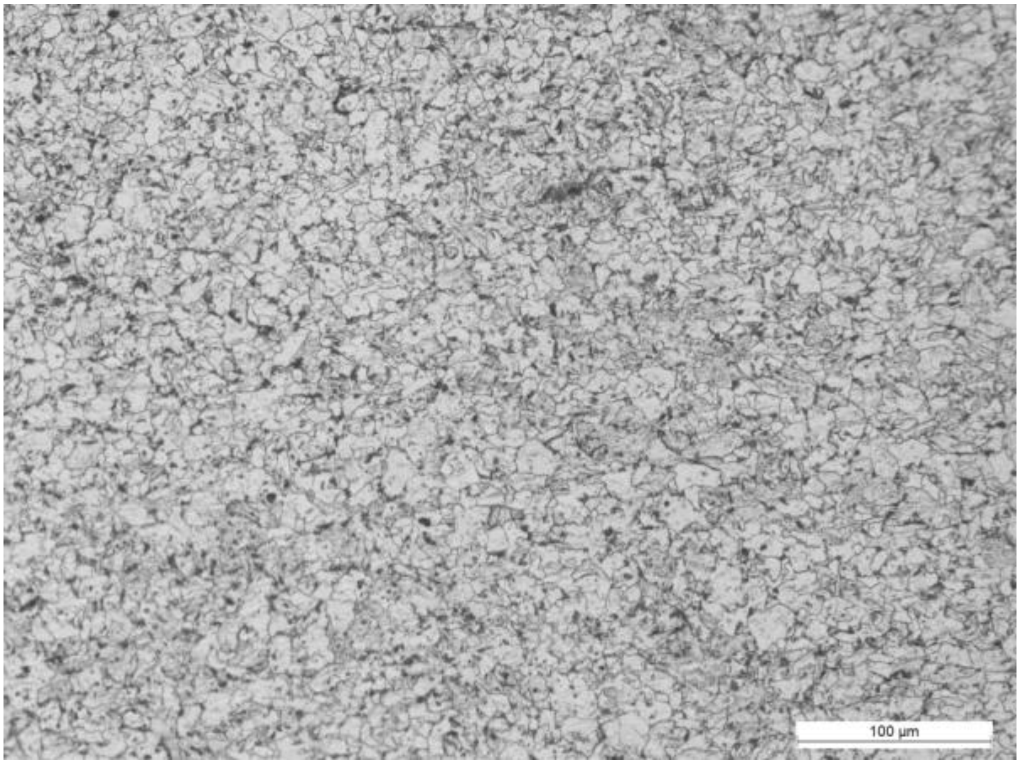

Figure 12. Microstructure of weld zone.

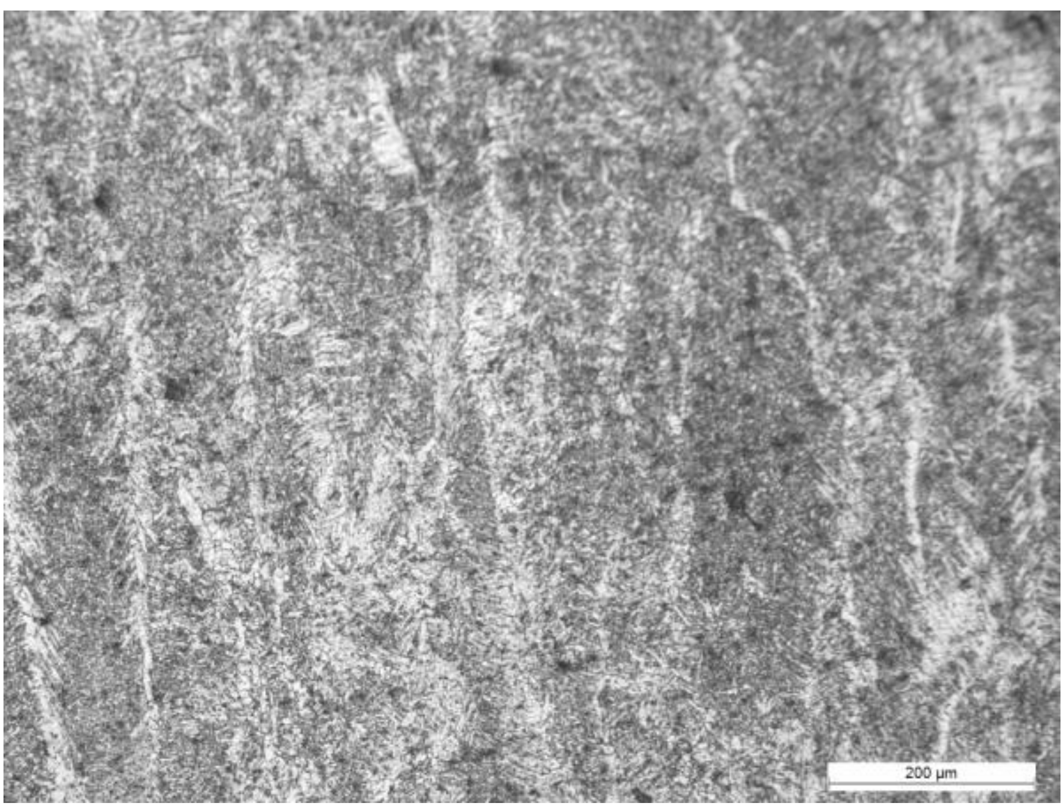

Figure 13. Microstructure of HAZ.

welding zones of specimens. From the microstructure figures, it can be seen that in the weld zone the grain structure is somewhat fine. In HAZ, it is somewhat coarse this is due to dendrite formation.

Conflict of Interest

The author(s) have not declared any conflict of interest.

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