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Hybrid Taguchi method for optimizing flux cored arc weld parameters for mild steel

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A B S T R A C T

Flux cored arc welding has been applied in manufacturing industries for more than fifteen years. The quality of weld mainly depends on the mechanical properties of the weld, which in turn relays on the interaction of the weld parameters. This paper discusses the multi response optimization of weld parameters using grey based Taguchi method. Grey relational analysis was carried out to convert multi objective criterion into equivalent single objective function; overall grey relational grade, which is optimized by the Taguchi technique. Experiments are conducted using Taguchi's L_{27} orthogonal array. The weld parameters used in this study were welding current, welding speed, and arc voltage with bead hardness and material deposition rate as responses. Taguchi's Signal-to-Noise (S/N) ratio is computed based on their performance characteristics. Grey relational grade was obtained using Signal-to-Noise ratio values of responses. Based on the grey relational grade, optimum levels of parameters have been identified. Significant contributions were estimated using Analysis of Variance (ANOVA). A confirmation test was conducted to validate the proposed method. This evaluation procedure could be used in decision-making to select process parameters for a welding operator. The proposed and developed method has good accuracy and competency with the predicted value enhancing automation and robotization.

A R T I C L E   I N F O

Keywords:
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1. Introduction

Generally, the quality of a weld joint is directly influenced by the welding input parameters during the welding process; therefore, welding can be considered as a multi-input multi-output process. Unfortunately, a common problem that has faced the manufacturer is the control of the process input parameters to obtain a good welded joint with the required bead geometry and weld quality with maximum deposition rate. Weld deposition rate is the weight (in kg) of weld metal deposited per unit of arc-on-time (usually one hour). The weight deposited is less than the weight of the filler metal used, because of various losses. The ratio of the weight of metal deposited in the weld to that of filler metal employed, expressed in percent, is called the deposition efficiency. Flux cored arc welding process is a fully automated process, in which the welding electrode is a tubular wire that is continuously fed to the weld area [1]. The flux materials are in the core of the tube. The outer shell of the tube conducts the electricity that forms the arc and then becomes the filler metal as it is consumed. Recent studies indicate that FCAW has a number of advantages over the common welding techniques available that use solid wires such as manual metal arc welding and gas metal arc welding [2]. Using FCAW in any repair technique can provide better control over current and heat input that is necessary to carry out the temper bead repair. As a fully automatic process, FCAW should also have cost advantages over other commonly used processes. Flux cored arc welding is considered a high deposition rate welding process that adds the benefits of flux to the simplicity of metal inert gas welding [3]. Many research attempts have been made by researchers to establish flux cored arc welding process. Mathematical modeling [4], particle swarm optimization algorithm [5], simulated annealing algorithm [6], memetic algorithm [7], Taguchi method [8], were used to optimize the parameters of flux cored arc welding process. Traditional Taguchi method can optimize a single objective function whereas it cannot solve multi objective function [9]. This paper explores the development of grey based Taguchi method for multi response optimization of flux cored arc weld parameters.

2. Grey based Taguchi method

To resolve the problems subjected to multiple quality characteristics, a decision maker should rely on the subjective experiences of engineers to attain a compromise. As a result, uncertainty will be increased during the process. Hence some researchers have concentrated on achieving multiple quality characteristic at a time as a function of different appropriate level of input parameter settings. Orthogonal array with principle component analysis and Taguchi method and response surface methodology applied [10, 11] to optimize multiple quality characteristics during laser cutting of different thin sheets. Fuzzy based desirability function is used to optimize parameters of weld [12].

Grey relational analysis aims to fulfil the crucial mathematical criteria for multiple quality characteristic problems [13]. It avoids the inherent shortcomings of conventional, statistical methods and requires a limited data to estimate the behavior of an uncertain system. It provides an efficient solution to the uncertain, multi-input and discrete data problem. The main function of Grey relational analysis is to indicate the relational degree between two sequences by using discrete measurement method the distance. It can be effectively recommended as a method for optimizing the complicated interrelationships among multiple performance characteristics.

2.1 Taguchi method

The quality engineering methods of Taguchi, employing design of experiments provide an efficient and systematic way to optimize designs for performance, quality and cost. It is one of the most important statistical tools for designing high quality systems at reduced cost [14, 15]. The use of Taguchi method simplifies the optimization procedure for determining the optimal welding parameters in the FCAW process. The Taguchi method is performed to reduce the sources of variation on the quality characteristics of product, and reach a target of process robustness. The control factors that may contribute to reduce variation (improved quality) can be quickly identified by looking at the amount of variation present as a response. Taguchi recommends the use of the loss function to measure the performance characteristic deviating from the desired value. The value of the loss function is then transformed into an S/N ratio. Usually, there are three categories [16] of performance characteristic in the analysis of the S/N ratio, i.e. lower-the-better, higher-the-better, and nominal-the-best. The deposition rate and hardness are the higher the better performance characteristic. The S/N ratio η_{ij} for the i^{th} performance characteristic in the j^{th} experiment can be expressed as Eq. 1.

$$\eta_{ij} = -10\log(L_{ij}) \tag{1}$$

The loss function L_{ij} for higher-the-better performance characteristic is expressed in Eq. 2:

$$L_{ij} = \frac{1}{n}\sum_{k=1}^{n}\frac{1}{y_{ijk}^{2}} \tag{2}$$

where n is the number of replication, k is the number of tests, y_{ijk} is experimental value of the i^{th} performance characteristic in the j^{th} experiment at the k^{th} tests.

For lower-the-better performance characteristic, L_{ij} is expressed in Eq. 3.

$$L_{ij} = \frac{1}{n}\sum_{k=1}^{n} y_{ijk}^2 \tag{3}$$

For nominal-is-best performance characteristics, the S/N ratio is expressed in Eq. 4.

$$\eta_{ij} = 10\log\left(\frac{\bar{y}}{\sigma}\right) \tag{4}$$

The S/N ratio for each level of process parameters is computed based on the S/N analysis. This S/N ratio value can be considered for the optimization of single response problems. However, optimization of multiple performance characteristics cannot be straightforward as in the optimization of a single performance characteristic.

2.2 Grey relational analysis

The grey relational analysis is based on the grey system theory used to solve complicated interrelationship multiple performance characteristics problems effectively. A grey system has a level of information between black and white. Black represents having no information and white represents having all information. Grey based Taguchi method is successfully applied to optimize film coating process [17], drilling process [18], plasma arc weld parameters [19], bead geometry in SAW process, and wire electrical discharge machining process [20, 21].

Depending upon the characteristics of a data sequence, there are various methodologies of data pre-processing available for this analysis. Experimental data y_{ij} is normalized as Z_{ij} ($0 \le Z_{ij} \le 1$) for the i^{th} performance characteristics in the j^{th} experiment is expressed as:

For S/N ratio with larger-the-better:

$$Z_{ij} = \frac{y_{ij} - min\big(y_{ij}, i = 1,2,\dots,n\big)}{max\big(y_{ij}, i = 1,2,\dots,n\big) - min\big(y_{ij}, i = 1,2,\dots,n\big)} \tag{5}$$

For S/N ratio with smaller-the-better:

$$Z_{ij} = \frac{max\big(y_{ij}, i = 1,2,\dots,n\big)}{max\big(y_{ij}, i = 1,2,\dots,n\big) - min\big(y_{ij}, i = 1,2,\dots,n\big)} \tag{6}$$

For S/N ratio with nominal-the-best:

$$Z_{ij} = \frac{\big(y_{ij} - \text{Target}\big) - min\big(\left|y_{ij} - \text{Target}\right|, i = 1,2,\dots,n\big)}{max\big(\left|y_{ij} - \text{Target}\right|, i = 1,2,\dots,n\big) - min\big(\left|y_{ij} - \text{Target}\right|, i = 1,2,\dots,n\big)} \tag{7}$$

Then, the grey relational coefficients are calculated to express the relationship between the ideal and the actual experimental results. The grey relational co-efficient is expressed in Eq. 8:

$$\gamma_{ij} = \frac{\Delta min + \xi\Delta max}{\Delta_{oj}(k) + \xi\Delta max} \tag{8}$$

where $j = 1, 2,\dots, n$, $k = 1, 2,\dots, m$, n is the number of experimental data items, and m is the number of responses. $y_o(k)$ is the reference sequence $y_o(k) = 1$, $k = 1, 2,\dots, m$, and $y_j(k)$ is the specific comparison sequence.

The absolute value of the difference between $y_o(k)$ and $y_j(k)$:

$$\Delta_{oj} = \|y_o(k) - y_i(k)\| \tag{9}$$

Δ_{min} is the smallest value of $y_j(k)$:

$$\Delta_{min} = \min_{\forall j \in i} \min_{\forall k} \|y_o(k) - y_i(k)\| \tag{10}$$

Δ_{max} is the largest value of $y_j(k)$:

$$\Delta_{max} = \max_{\forall j \in i} \max_{\forall k} \|y_o(k) - y_i(k)\| \tag{11}$$

ξ is the distinguishing coefficient which is defined in the range 0 to 1 (the value is adjusted based on the practical needs of the system)

The Grey relational grade is expressed in Eq. 12:

$$\bar{\gamma}_j = \frac{1}{k}\sum_{i=1}^{m} y_{ij} \tag{12}$$

where j is the grey relational grade for the j^{th} experiment and k is the number of performance characteristics. Higher grey relational grade implies the better product quality, therefore, on the basis of grey relational grade, the factor effect is estimated using ANOVA [23] and the optimal level for each controllable factor is determined.

3. Experimental work

Experiments are conducted using SUPRA INVMIG 500 welding machine using DC electrode positive (DCEP). Test pieces of size 200 mm × 150 mm × 6 mm are cut from low carbon structural steel (IS: 2062) plate and its surfaces are ground to remove oxide scale and dirt before cladding. Flux cored mild steel electrode (E71T-1) of 1.2 mm diameter is used for welding. CO_2 gas at a constant flow rate of 15 L/min is used for shielding. The experimental setup used consists of a traveling carriage with a table for supporting the specimens. The welding torch is held stationary in a frame mounted above the work table, and it is provided with an attachment for both up and down movement and angular movement for setting the required nozzle-to-plate distance and welding torch angle, respectively. Single pass welding bead on joint weld with square butt weld is performed on the weld plates by varying the initial parameters as shown in Table 1. The working ranges for the process parameters are selected from the American Society Welding handbook [24]. Each trial of experiment was done twice and the average value is taken.

Deposition rate and hardness are considered as objectives. The metal deposition rate is calculated with the help of stop watch and length of the electrode melt during the welding process. Brinnel hardness test is performed using Brinnel hardness testing machine. Based on the designed orthogonal array combination a series of joining processes are performed in welding machine. Experimental results are summarized in Table 2.

Table 1 Welding Parameters and their levels

Factors	Welding parameters	Level 1	Level 2	Level 3
I	Welding current (A)	180	220	260
V	Arc voltage (V)	20	24	28
S	Electrode stick-out (mm)	19	21	24

Table 2 Experimental results for hardness and deposition rate

Exp. No.	I	V	S	Hardness (HB)	Deposition rate (kg/h)
1	1	1	1	320.96	2.12
2	1	1	2	496.41	2.15
3	1	1	3	469.83	2.21
4	1	2	1	465.45	1.48
5	1	2	2	589.83	1.92
6	1	2	3	519.96	2.21
7	1	3	1	433.83	1.44
8	1	3	2	580.99	1.48
9	1	3	3	519.83	2.16
10	2	1	1	329.96	2.58
11	2	1	2	259.83	5.26
12	2	1	3	445.07	2.86
13	2	2	1	449.96	2.45
14	2	2	2	595.07	2.01
15	2	2	3	265.07	5.61
16	2	3	1	389.96	2.37
17	2	3	2	549.96	2.31
18	2	3	3	459.83	2.26
19	3	1	1	269.96	4.08
20	3	1	2	485.09	3.39
21	3	1	3	345.09	4.32
22	3	2	1	424.15	3.01
23	3	2	2	515.09	3.75
24	3	2	3	488.41	3.83
25	3	3	1	319.96	3.97
26	3	3	2	464.15	4.18
27	3	3	3	449.83	3.71

4. Results and discussion

S/N ratios for deposition rate and hardness are computed using Eq. 1, Eq. 2, and Eq. 3. Using Eq. 5 and Eq. 6 the S/N ratios are normalized and shown in Table 3. Grey relational coefficient for each performance characteristic is calculated using Eq. 8. The value for ξ is taken as 0.5 since both the process parameters are of equal importance. The grey relational grade is calculated using Eq. 12, which is the overall representative of both the responses shown in Table 4.

Now, the multiple objective optimization problems have been transformed into a single equivalent objective function optimization problem using this approach. The higher grey relational grade is said to be close to the optimal. The mean response table for overall grey relational grade is shown in Table 5 and is represented graphically in Fig 1. With the help of the response table and response graph, the optimal parameter combination has been determined as $I_1V_3S_3$.

Using the grey relational grade value, ANOVA is formulated for identifying the significant factors. The results of ANOVA are presented in Table 6. From ANOVA, it is clear that welding speed (64.42 %) influences more on welding of mild steel plates followed by arc voltage (18.54 %) and welding current (1.07 %).

In order to predict the optimum condition, the expected mean at the optimal settings (μ) is calculated by using the following model $\mu = \bar{I}_1 + \bar{V}_3 + \bar{S}_3 - 2 \cdot \bar{T}_{gg}$, where $\bar{I}_1$, $\bar{V}_3$, and $\bar{S}_3$ are the mean values of the grey relational grade with the parameters at optimum levels, and $\bar{T}_{gg}$ is the overall mean of average grey grade. The expected mean (μ) at optimal setting is found to be 0.5950.

Table 3 S/N ratios and their normalize values

Exp. No.	S/N ratio		Normalized values of S/N ratio	
	Hardness (HB)	Deposition rate (kg/h)	Hardness (HB)	Deposition rate (kg/h)
1	50.129	6.5267	0.1823	0.1631
2	53.9168	6.6488	0.7057	0.1703
3	53.4388	6.8878	0.6264	0.1847
4	53.3575	3.4052	0.6134	0.0096
5	55.4145	5.666	0.9844	0.1151
6	54.3194	6.8878	0.776	0.1847
7	52.7464	3.1672	0.519	0
8	55.2834	3.4052	0.958	0.0096
9	54.3172	6.6891	0.7756	0.1727
10	50.3692	8.2324	0.2092	0.2734
11	48.2938	14.4197	0	0.9161
12	52.9686	9.1273	0.5526	0.3405
13	53.0635	7.7833	0.5671	0.2422
14	55.4914	6.0639	1	0.1367
15	48.4672	14.9793	0.0156	1
16	51.8204	7.495	0.3882	0.223
17	54.8066	7.2722	0.8654	0.2086
18	53.2519	7.0822	0.5966	0.1966
19	48.626	12.2132	0.0302	0.6331
20	53.7164	10.604	0.6719	0.4676
21	50.7586	12.7097	0.2543	0.6906
22	52.5504	9.5713	0.4902	0.3765
23	54.2377	11.4806	0.7614	0.554
24	53.7757	11.664	0.6818	0.5731
25	50.1019	11.9758	0.1794	0.6067
26	53.3332	12.4235	0.6095	0.6571
27	53.061	11.3875	0.5668	0.5444

Table 4 Grey relational coefficients of responses

Exp. No.	S/N ratio		Grey relational grade
	Hardness (HB)	Deposition rate (kg/h)	
1	0.3795	0.374	0.3767
2	0.6295	0.376	0.5028
3	0.5724	0.3801	0.4762
4	0.5639	0.3355	0.4497
5	0.9697	0.361	0.6654
6	0.6906	0.3801	0.5353
7	0.5097	0.3333	0.4215
8	0.9225	0.3355	0.629
9	0.6902	0.3767	0.5334
10	0.3874	0.4076	0.3975
11	0.3333	0.8563	0.5948
12	0.5277	0.4312	0.4795
13	0.536	0.3975	0.4668
14	1	0.3668	0.6834
15	0.3368	1	0.6684
16	0.4497	0.3915	0.4206
17	0.7879	0.3872	0.5876
18	0.5535	0.3836	0.4685
19	0.3402	0.5768	0.4585
20	0.6038	0.4843	0.5441
21	0.4014	0.6178	0.5096
22	0.4951	0.445	0.4701
23	0.677	0.5285	0.6027
24	0.6111	0.5395	0.5753
25	0.3786	0.5597	0.4692
26	0.5615	0.5932	0.5773
27	0.5358	0.5232	0.5295

Table 5 Response table for overall grey relational grade

Factors	Level 1	Level 2	Level 3
I	0.51	0.4821	0.4367
V	0.5296	0.5685	0.5985
S	0.5262	0.5151	0.5306

Table 6 Response table for overall grey relational grade

Factors	Degrees of freedom	Sum of squares	Mean squares	*F* value	Contribution (%)
I	2	0.00198	0.000993	0.68	1.07
V	2	0.0342	0.017102	11.65	18.54
S	2	0.1188	0.05943	40.47	64.42
Error	20	0.0293	0.00146		15.88
Total	26	0.18441			100

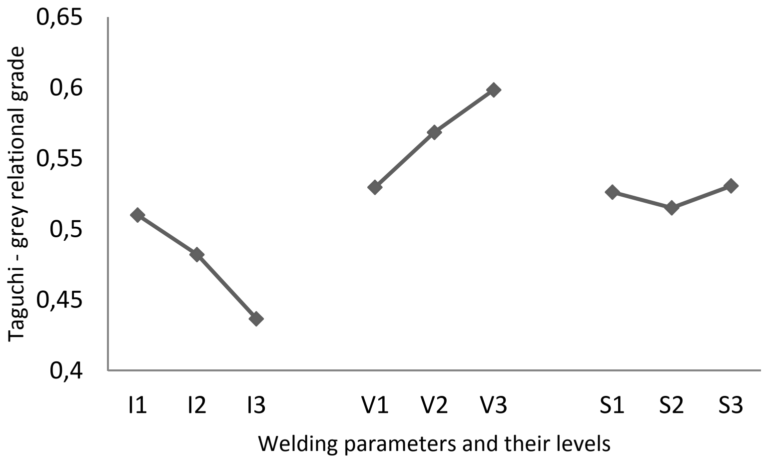

Fig. 1 Response graph for grey relational grade

Once the optimal level of the process parameters has been determined, the final step is to predict and verify the improvement of the performance characteristic using the optimal level of weld parameters. Table 7 shows the comparison of the multiple performance characteristics for initial and optimal welding parameters. The initial designated levels of welding parameters are I2, V1, and S3. As noted from Table 7, the deposition rate is increased from 2.06 kg/h to 2.16 kg/h and the hardness is increased from 480.31 to 519.83.The estimated grey relational grade is increased from 0.4818 to 0.5334. It is clearly shown that the multiple objectives of the weld process are together improved remarkably.

Table 7 Results of initial and optimal welding performance

	Initial process parameters	Optimal process parameters	
		Prediction	Experiment
Level	$I_2V_1S_3$	$I_1V_3S_3$	$I_1V_3S_3$
Hardness	480.31		519.83
Deposition rate	2.06		2.16
Grey relational grade	0.4818	0.595	0.5334
Improvement of Grey relational grade		0.1132	0.0516

5. Conclusion

Effects of welding parameters and the optimum welding parameters for a FCAW process on the multiple performance characteristics are systematically investigated by Taguchi-based grey relational analysis. Application of Taguchi optimization technique coupled with grey relational analysis has been adopted for estimating the optimal parametric combination to achieve acceptable (maximum) bead hardness and deposition rate. Signal-to-Noise ratio is computed based on their performance characteristics.

Grey relational grade is obtained using Signal-to-Noise ratio values of responses. Based on grey relational grade, optimum levels of parameters have been identified. The significant contributions are estimated using analysis of variance. It is found that electrode stick out (64.42 %) influences more followed by arc voltage (18.57 %) and welding current (1.07 %). The best performance characteristics is obtained with lower welding current of 180 A, higher arc voltage of 28 V and higher electrode stick out of 24 mm. Confirmatory experiments prove that the determined optimal conditions of weld parameters to satisfy real conditions. The proposed and developed algorithm simplifies the optimization design of weld parameters with multiple-performance characteristics. Thus, the solutions from this method can be used by engineers willing to search for any weld optimal solution.

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