Optimization of weld bead geometry in Shielded Metal Arc Welding using Taguchi Based Grey Relational Analysis

S.M.Ravikumar[1*], Dr.P.Vijian[2]
[1]Department of Mechanical Engineering, M.A.M. College of Engineering, Siruganur, Tiruchirappalli, 621 105, India
smravik@yahoo.co.in
[2] Department of Mechanical Engineering, Government College of Technology,
Coimbatore, 641 013, India, vijianp@rediffmail.com

***Abstract*--- In this paper, the optimization of the Shielded Metal Arc Welding (SMAW) process parameters in wind velocity with multi-response criteria using Taguchi orthogonal array with grey relational analysis is studied. Based on Taguchi L_9 orthogonal array nine experimental conditions were performed. The input process parameters such as Welding current, Welding speed and Wind velocity are selected using L_9 orthogonal array to obtain the desired output i.e., bead width, reinforcement and depth of penetration. The quality of the weld is evaluated by studying the features of weld bead geometry. Grey relational analysis is applied to optimize the input parameters simultaneously considering output variables. In addition the analysis of variance (ANOVA) is also applied to identify the most significant factor. Optimal result has been verified through additional experiment. This indicates application feasibility of the Grey-based Taguchi technique can be improved effectively through this approach.**

***Index Term*-- Wind velocity, Taguchi Method, Multi-response optimization, Grey relational analysis.**

I. INTRODUCTION

Shielded Metal Arc Welding (SMAW), commonly called stick, or covered electrode, welding, is a manual welding process whereby an arc is generated between a flux-covered consumable electrode and the workpiece. The process uses the decomposition of the flux covering to generate a shielding gas and to provide fluxing elements to protect the molten weld-metal droplets and the weld pool [1]. Welding quality is strongly characterized by the weld bead geometry shown in Fig.1. The weld bead geometry plays an important role in determining the mechanical properties of the welded joints. Therefore, it is very important to select the welding process parameters obtaining optimal weld bead geometry. Tarng et al. [2] investigated the welding process parameters for obtaining optimal weld bead geometry in gas tungsten arc welding. The Taguchi method is used to formulate the experimental layout, to analyze the effect of each welding process parameters on the weld bead geometry of the front height, front width, back height, and back width of the weld bead and to predict the optimal setting for each welding process parameters. The Taguchi method is very popular for solving optimization problems in the field of production engineering [3]. The method utilizes a well-balanced experimental design called orthogonal array design, and signal-to-noise ratio (S/N ratio), which serve the objective function to be optimized. The Taguchi method coupled with Grey relational analysis has a wide area of application [4]. This approach can solve multi-response optimization problem simultaneously. Gunaraj et al. [5] applied response surface methodology (RSM) in developing mathematical models and plotting contour graphs relating important input variables namely the open-circuit voltage (V), the wire feed rate (F), the welding speed(S) and the nozzle to plate distance (N), to the output variables namely penetration (P), the reinforcement(R), the width (W) and the percentage dilution (D) of the weld bead in the SAW of pipes. Palani et al.[6] developed the models using three factor, five level factorial design for 317L flux cored stainless steel wire with IS:2062 structural steel as base plate. The values of penetration (P), width (W) and reinforcement(R) increase with the increase in welding current, whereas these values decrease with the increase in welding speed. However, the percent dilution increases with the increase in welding speed(S) and nozzle to plate distance(N) to a higher value but starts decreasing on further increasing welding speed(S) and plate distance(N). Manonmani et al. [7] investigated the effect of laser welding parameters on the bead geometry of 2.5 mm thick AISI304 stainless steel .In this study the relationship between the process parameters (beam power, welding speed and beam angle) and the weld bead parameters (penetration, bead width and area of penetration) have been developed using RSM. Nagesh et al. [8] used BPN model to associate the welding process parameters (electrode feed-rate, arc power, arc voltage, arc current and arc length) with output features of bead geometry (bead height and width, penetration depth and area). The workpiece material was grey cast iron and a mild steel electrode was used. It showed that there was a small error percentage difference between the estimated and experimental values, which indicates that the neural networks can yield fairly accurate results.

TABLE I
Chemical composition base material and consumable (weight in %)

Material	**C**	**S**	**P**	**Si**	**Cu**	**Mn**	**Fe**
IS2062	0.20	0.055	0.005	0.100	0.350	-	Bal
E6013	0.10	0.035	0.04	0.35	-	0.3	Bal

Sathiya et al. [9] reported optimization of laser bead on plate welding parameters for 3.5 kW cooled slab laser using Taguchi technique. The welding input parameters (beam power, travel speed and focal position) with output features of bead geometry (bead width and depth of penetration).The optimized parameters are evaluated through the microstructural characterization and hardness measurements across the weld zone.

Katheresan et al.[10] reported bead-on-plate welds were carried out on AISI 316L (N) austenitic stainless steel (ASS) using flux cored arc welding (FCAW) process. The bead on plates weld was conducted as per L25orthogonal array. In this paper, the weld bead geometry such as depth of penetration (DOP), bead width (BW) and weld reinforcement (R) of AISI 316L (N) ASS are investigated.

Many researchers have applied various optimization techniques to define the desired output variables through the developing mathematical models, linear regression models, ANN models through the relationship between the input and output variables. Most of the researchers focused the welding parameters like welding current, travel speed, arc voltage, wire feed rate, nozzle to plate distance, arc length, electrode position and open circuit voltage but wind velocity is not net reported.

In the present study, it is intended to determine the optimal process condition in SMAW process to yield desired weld quality in terms of bead geometry and to evaluate the effect of various parameters on overall feature of bead geometry. Grey relational analysis is performed to combine the multiple responses in to one numerical value, rank these scores, and determine the optimal welding parameter settings. Also confirmation tests are performed by using experiments. ANOVA is performed to investigate the more influencing parameters on the multiple performance characteristics.

II. EXPERIMENTAL PROCEDURE

In this study, the SMAW process is done on 100 mm x 50 mm x 6 mm mild steel plates. The experimental setup of the workpiece for SMAW process is shown in Fig.2. The chemical compositions of the mild steel plates IS 2062 and the welding consumable used for SMAW is E6013, size of the electrode of 3.5 mm are shown in Table I.

Experiments have been conducted for various welding process parameters like welding current, welding speed and wind velocity to obtain bead-on-plate welding SMAW process. Wind levels are induced using an air blower and wind is measured using an anemometer. Three values are taken for each parameter. The welding current is varied as 100,120 and 140 amps respectively. Similarly welding speed is varied as 2, 3 and 4 mm/s and the wind velocity is varied as 3, 5 and 7 m/s respectively. The process parameters and levels are listed in Table II.

TABLE II
Process parameters and their levels welding speed (S) 2, 3, 4 mm/s

Sl. no	Parameter	Notation	Unit	Level 1	Level 2	Level 3
1	Welding current	I	Amps	100	120	140
2	Welding speed	S	mm/s	2	2	4
3	Wind velocity	V	m/s	3	5	7

The Taguchi method has become a powerful tool for improving productivity during research and development so that high quality products can be produced quickly at low cost. Taguchi's parameter design is an important tool for robust design. Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments only [11, 12].The methodology of Taguchi for three factors at three levels is used for the implementation of the plan of experiments. Nine experiments are carried out based on the L_9 orthogonal array. Only the main effects are of interest and factor interactions are not studied.

After welding, the welded plates are cross sectioned at their mid points to obtain test specimens of 10 mm wide. These specimens are prepared by the usual metallurgical polishing methods and etched with 5% nital. The weld bead profiles are measured by optical microscope (10X) and presented in Fig.3. and the bead dimensions, viz. Bead width (W), Reinforcement (R) and Penetration (P) are observed.

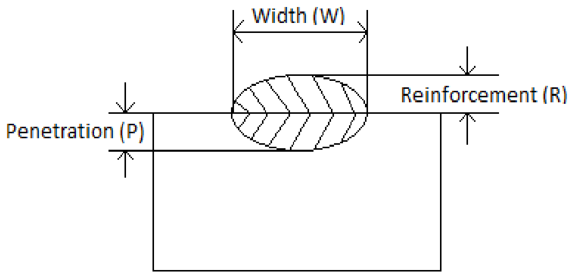

Fig.1.Weld bead geometry


Fig.2. Experimental set up for SMAW process

TABLE III
L_9 Taguchi's orthogonal array, coded form

Trail no	Welding Current (I)	Welding Speed (S)	Wind Velocity (V)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Fig.3. Bead profiles (Sample no.8)

III. DETERMINATION OF WELDING PROCESS PARAMETERS

In this section, the use of grey based Taguchi method to determine the welding process parameters are reported. Optimal welding process parameters with considerations of the multiple performance characteristics are obtained and verified.

A. L_9Othogonal array experiment

In the present study, the interaction between the welding process parameters is neglected. The degrees of freedom required for the study is six and Taguchi's L_9 orthogonal array is used to define the nine trial conditions. The Experimental layout for the welding process parameters using L_9 orthogonal array is shown in Table III. and corresponding response values are shown in Table IV.

TABLE IV
L_9 Taguchi's orthogonal array, natural values and corresponding response values

	Process parameter			Response values		
Trail no	Welding Current (I)	Welding Speed (S)	Wind Velocity (V)	Bead Width (mm)	Reinforcement (mm)	Penetration (mm)
1	100	2	3	15.50	2.00	1.30
2	100	3	5	10.00	2.66	0.70
3	100	4	7	6.50	1.65	1.02
4	120	2	5	15.58	1.52	0.99
5	120	3	7	9.00	1.69	1.13
6	120	4	3	6.82	1.43	1.12
7	140	2	7	14.50	1.36	1.56
8	140	3	3	9.00	1.47	1.40
9	140	4	5	7.50	1.42	1.18

B. Grey Relational Analysis (GRA)

In the grey relational analysis, a data preprocessing is first performed in order to normalize the raw data for analysis. In the present study, a linear normalization of the experimental results performed in the range between zero and one, which is also called grey relational generating [13, 14].

Experimental data have been normalized first. The normalized data for each of the parameters of bead geometry have been furnished in Table V. For Bead width, reinforcement, lower the better (LB) and for depth of penetration, the higher-the-better (HB) or larger-the-better (LB) criterion has been selected. The normalized experimental results x_{ij} can be expressed as:

$$x_{ij} = \frac{y_{ij} - \min_j y_{ij}}{\max_j y_{ij} - \min_j y_{ij}} \quad (1)$$

y_{ij} for the i^{th} experimental results in the j^{th} experiment. Table.V shows the normalized results for bead width, reinforcement and penetration. Basically, the larger the normalized results the better the performance and the best-normalized results should be equal to one.

TABLE V
Data preprocessing of each performance characteristics (Grey relational generation)

Trail no	Bead width mm	Reinforcement mm	Penetration mm
1	0.0088	0.5077	0.6977
2	0.6145	0.0000	0.0000
3	1.0000	0.7769	0.3721
4	0.0000	0.8769	0.3372
5	0.7247	0.7462	0.5000
6	0.9648	0.9462	0.4884
7	0.1189	1.3000	1.0000
8	0.7247	0.9154	0.8140
9	0.8899	0.9538	0.5581

Next, the grey relational coefficient is calculated to express the relationship between the ideal (best) and the actual normalized experimental results. The grey relational coefficient ξ_{ij} for the i^{th}performance characteristic in the j^{th}experiment can be expressed as:

$$\xi_{ij} = \frac{\min_i \min_j |x_i^0 - x_{ij}| + \zeta \max_i \max_j |x_i^0 - x_{ij}|}{|x_i^0 - x_{ij}| + \zeta \max_i \max_j |x_i^0 - x_{ij}|} \quad (2)$$

Where x_i^0 is the ideal normalized results for i^{th} performance characteristics and ζ is the distinguishing coefficient which is defined in the range 0≤ ζ≤1. In the present study the value of ζ is assumed as 0.5.

Then, the grey relational grade is computed by averaging the grey relational coefficient corresponding to each performance characteristics. The overall evaluation of the multiple performance characteristics is based on the grey relational grade, i.e.

$$\gamma_j = \frac{1}{m}\sum_{i=1}^{m}\xi_{ij} \quad (3)$$

Where γ_j the grey relational grade for the j^{th}experiment and m is the number of performance characteristics.

TABLE VI
Evaluated Grey relational coefficient and Grade values

Trail no	Bead width (mm)	Reinforcement (mm)	Penetration (mm)	Grey relational grade	Rank
1	0.3353	0.5039	0.6232	0.4875	8
2	0.5647	0.3333	0.3333	0.4104	9
3	1.0000	0.6915	0.4433	0.7116	5
4	0.3333	0.8025	0.4300	0.5219	7
5	0.6449	0.6633	0.5000	0.6027	6
6	0.9342	0.9028	0.4943	0.7771	2
7	0.3620	1.0000	1.0000	0.7873	1
8	0.6449	0.8553	0.7288	0.7430	4
9	0.8195	0.9155	0.5309	0.7553	3

Table.VI shows the grey relational grade for each experiment using L_9 orthogonal array. A higher grey relational grade indicates better product quality. It has been shown that experiment 7 has the best multiple performance characteristics among the 9 experiments because it has the highest grey relational grade as shown in Table.VI. In other words, optimization of the complicated multiple performance characteristics can be converted in to the optimization of a single grey relational grade.

The effect of each welding process parameter on the grey relational grade at different levels can be separated out because the experimental design is L_9 orthogonal. The mean of the grey relational grade for each level of the welding process parameters is summarized and shown in Table VII. In addition, the total mean of the grey relational grade for the nine experiments is also calculated and listed in Table VII. Fig.4 shows the grey relational grade graph for the levels of welding process parameters. Basically, the larger the grey relational grade, the better is the multiple performance characteristics. However, the relative importance among the welding process parameters for the multiple performance characteristics will still need to be known so that the optimal combinations of the welding process parameter levels can be determined more accurately[15].

TABLE VII
Response table for the grey relational grade

Parameter	Grey relational grade				
	Level 1	**Level 2**	**Level 3**	**Max-Min**	**Rank**
Welding current	0.5365	0.6339	**0.7619***	0.2254	1
Welding speed	0.5989	0.5854	**0.7480***	0.1626	2
Wind velocity	0.6692	0.5626	**0.7006***	0.1380	3
* Optimum levels Total Mean Value of the Grey Relational Grade= 0.6441					

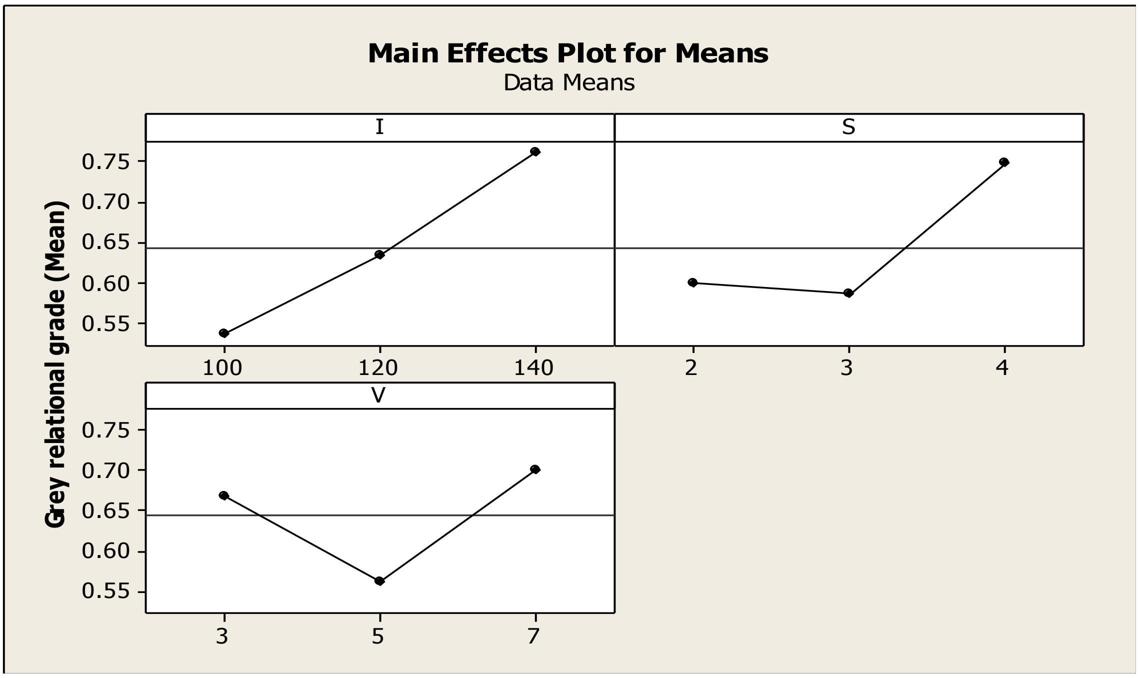

Fig.4. Main effects plot for Grey relational grade

TABLE VIII
Results of the analysis of variance

Source	DF	Seq SS	Adj SS	Adj MS	F	%C
Welding current	2	0.076657	0.076657	0.038328	20.34	47.71
Welding speed	2	0.048842	0.048842	0.024421	12.96	30.40
Wind velocity	2	0.031395	0.031395	0.015697	8.33	19.54
Error	2	0.003769	0.003769	0.001885		2.35
Total	8	0.160663				100

C. Analysis of Variance

The purpose of the analysis of variance is to investigate which welding process parameters significantly affect the performance characteristic. This is accomplished by separating the total variability of the grey relational grades, which is measured by the sum of the squared deviation from the total mean of the grey relational grade, into contributions by each welding process parameter and the error. The percentage contribution by each of the process parameter in the total sum of the squared deviations can be used to evaluate the importance of the process parameter change on the performance characteristic. In addition, the F-test named after Fisher can also be used to determine which welding process parameters have a significant effect on the performance characteristic. Usually, the change of the welding process parameter has a significant effect on the performance characteristic when the F value is large. Table VIII shows the results of ANOVA analysis.

Results of analysis of variance indicate that welding current is the most significant welding process parameter followed by welding speed and wind velocity.

D. *Confirmation Experiment*

Once the optimal level of welding process parameters is selected the final step is to predict and verify the improvement of the performance characteristics using the optimum level of the welding process parameters. The estimated grey relational grade $\hat{\gamma}$ using the optimum level of the welding parameters can be calculated as

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{q}(\bar{\gamma} - \gamma_m) \quad (4)$$

Where γ_m the total mean of the grey relational grade, $\bar{\gamma}$ is the mean of the grey relational grade at the optimum level and q is the number of welding parameters that significantly affects the multiple performance characteristics. Based on equation (4) the estimated grey relational grade using the optimal welding parameters can then be obtained. Table.IX shows the results of the confirmation experiment using the comparison of experimental results using initial and optimal welding process parameters. It will be noted that the welding performance has been greatly improved through this study. The table.9 shows, the bead width decreased from 15.5 mm to 12.5 mm, the reinforcement decreased from 2.0 mm to 1.45 mm, the penetration is increased from 1.3 mm to 2.6 mm and Grey relational grade improved is 0.4348.

TABLE IX
Results of welding performance using initial and optimal welding process parameters

	Initial welding parameters	Optimal welding parameters	
		Prediction	Experiment
Setting level	$A_1B_1C_1$	$A_3B_3C_3$	$A_3B_3C_3$
Bead width(mm)	15.5		12.5
Reinforcement(mm)	2.0		1.45
Penetration(mm)	1.3		2.6
Grey relational grade	0.4875	0.9223	
Improvement in grey relational grade = 0.4348			

IV. CONCLUSIONS

The use of the grey-based Taguchi method to determine the SMAW process parameters using the wind velocity with consideration of multiple performance characteristics has been reported in this paper. A grey relational analysis performs the multiple performance characteristics into the optimization of the single performance characteristics called the grey relational grade. It has been found that the optimal welding process parameters are welding current 140A, welding speed 4mm/sec and wind velocity 7m/s. Further it has been observed that the analysis of variance shows that the welding current is the most significant welding process parameter (47.71%) followed by welding speed (30.40%) and wind velocity (19.54%) influence respectively.

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