Parametric Optimization of Gas Metal Arc Welding Process by Taguchi Method on Weld Dilution

M. Aghakhani, E. Mehrdad, and E. Hayati

***Abstract*—Gas metal arc welding is a fusion welding process having wide applications in industry. In this process proper selection of input welding parameters is necessary in order to obtain a good quality weld and subsequently increase the productivity of the process. In order to obtain a good quality weld, it is therefore, necessary to control the input welding parameters. One of the important welding output parameters in this process is weld dilution affecting the quality and productivity of weldment. In this research paper using Taguchi's method of design of experiments a mathematical model was developed using parameters such as, wire feed rate (W), welding voltage (V), nozzle-to-plate distance (N), welding speed (S) and gas flow rate (G) on weld dilution. After collecting data, signal-to-noise ratios (S/N) were calculated and used in order to obtain the optimum levels for every input parameter. Subsequently, using analysis of variance the significant coefficients for each input factor on the weld dilution were determined and validated. Finally a mathematical model based on regression analysis for predicting the weld dilution was obtained. Results from this research work show that wire feed rate (W),arc voltage (V) have increasing effect while nozzle-to-plate distance (N) and welding speed (S) have decreasing effect on the dilution whereas gas Flow rate alone has almost no effect on dilution but its interaction with other parameters makes it quite significant in increasing the weld dilution.**

***Index Terms*—Gas Metal Arc Welding (GMAW), Weld Dilution, Taguchi Method, Regression Analysis, Signal-to-Noise Ratio(S/N).**

I. Introduction

The GMAW has got wide applications in industries due to the advantages such as high reliability, all position capability, low cost, high productivity, high deposition rate, ease of use, absence of fluxes, cleanliness and ease of mechanization. This process establishes an electric arc between a continuous filler metal electrode and the weld pool, with shielding from an externally supplied gas, which may be an inert gas, an active gas or a mixture. The most important gases which have been used in order to shield the weld pool are Argon (Ar), Helium (He), CO_2 and O_2 . The heat of the arc melts the surface of the base metal and the end of the electrode. The electrode molten metal is then transferred through the arc to the workpiece where it combines with the molten metal from the weld puddle and creates the weld bead.

In this welding process the quality of the weld joint can be defined by many characteristics. One of these characteristics is weld dilution which is the area of penetration divided by the total weld bead area as shown in Fig. 1, where A_p is the bead penetration area, A_r is the bead reinforcement area. Then dilution is defined as:

$$\%Dilution = 100(A_p / (A_p+A_r)) \quad (1)$$

In order to obtain a good quality weld and at the same time consuming lesser amount of consumable such as material, filler wire, gas, time and decreasing costs and subsequently increasing productivity, it is therefore required to control the input welding parameters of the gas metal arc welding process. In this connection using the concept of loss function, signal -to-noise ratios for dilution was utilized and based on this the optimum levels for input welding parameters were determined.

The method presented in this study is an experimental design process called the Taguchi design method. Taguchi design, developed by Dr. Genichi Taguchi, is a set of methodologies by which the inherent variability of materials and manufacturing processes has been taken into account at the design stage [1]. Although similar to design of experiment (DOE), the Taguchi design only conducts the balanced (orthogonal) experimental combinations, which makes the Taguchi design even more effective than a fractional factorial design. By using the Taguchi techniques, industries are able to greatly reduce product development cycle time for both design and production, therefore reducing costs and increasing profit [2].

Taguchi proposed that engineering optimization of a process or product should be carried out in a three-step approach: system design, parameter design, and tolerance design.

In system design, the engineer applies scientific and engineering knowledge to produce a basic functional prototype design.

The objective of the parameter design [3] is to optimize the settings of the process parameter values for improving performance characteristics and to identify the product parameter values under the optimal process parameter values. The parameter design is the key step in the Taguchi method to achieving high quality without increasing cost.

The steps included in the Taguchi parameter design are: selecting the proper orthogonal array (OA) according to the numbers of controllable factors (parameters); running experiments based on the OA; analyzing data; identifying the optimum condition; and conducting confirmation runs with the optimal levels of all the parameters [1].

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The main effects indicate the general trend of influence of each parameter. Knowledge of the contribution of individual parameters is the key to deciding the nature of the control to be established on a production process. Analysis of variance (ANOVA) is the statistical treatment most commonly applied to the results of the experiments to determine the percentage contribution of each parameter against a stated level of confidence [3].

Taguchi suggests [4] two different routes for carrying out the complete analysis. In the standard approach the results of a single run or the average of repetitive runs are processed through the main effect and ANOVA (raw data analysis). The second approach, which Taguchi strongly recommends for multiple runs, is to use the signal-to-noise (S/N) ratio for the same steps in the analysis.

To determine the effect of the GMAW process parameters on dilution 25 experiments were designed and conducted using Taguchi method. For this purpose the effects of wire feed rate (W), welding voltage (V), nozzle-to-plate distance (N), welding speed (S) and gas flow rate (G) on weld bead dilution were investigated.

Reference [5] studied the effect of main variables such as wire feed rate, welding voltage, nozzle-to- plate distance and welding speed on dilution in GMAW process, and showed that the most significant factor on dilution are wire feed rate and welding voltage .Dilution will increase with the increase in wire feed rate and welding voltage, and decrease with the increase in welding speed and nozzle-to- plate distance. Reference [6] analyzed defects in GMAW process using Taguchi method.

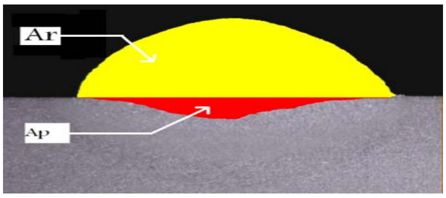

Fig 1. Dilution of bead-on-plate weld

Reference [7] used a four-factor-five levels factorial technique to predict weld bead geometry (penetration, reinforcement, width and percentage dilution) in the deposition of 316L stainless steel on to structural steel IS 2062 using the GMAW process. The process parameters such as open-circuit voltage, wire feed rate, welding speed and nozzle-to-plate distance were controlled and the effect of each factor on the weld features were determined and presented graphically. A modified Taguchi method has been adopted to analyze the effect of each welding process parameter consist of arc gap, flow rate, welding current and travel speed on the weld pool geometry and then determined the TIG welding process parameters combination associated with the optimal weld pool geometry by [8].

Taguchi method and regression analysis is used to optimize Nd-YAG laser welding parameters to seal an iodine-125 radioisotope seed into a titanium capsule [9]

II. Design of Experiments

A. Experimental Procedure

The experiments were conducted using a semiautomatic PARS MIG welding machine using direct current electrode positive. Test pieces of size 200×100×6 mm were cut from ST-37 plates and their surfaces were ground to remove oxide scale and dirt and moreover, consumable electrode of 0.8 mm diameter was used for depositing the weld beads on the base metal. Chemical composition of base metal and filler wire is given in Table I and Table II respectively. Shielding of the gas puddle and molten metal droplets from the electrode was carried out by a Gas mixture of 80% argon and 20% CO_2. The experimental setup is shown in Fig. 2.


Fig 2. The experimental setup

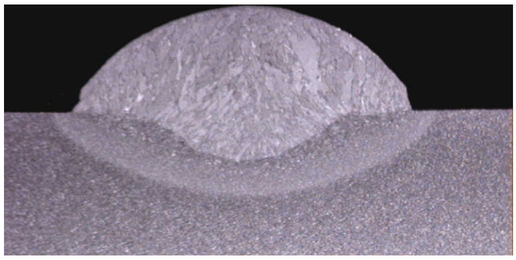
Fig 3. Prepared sample of weld bead

B. Development of Design Matrix

To select an appropriate orthogonal array for experiments, the total degrees of freedom need to be computed. The degrees of freedom are defined as the number of comparisons between process parameters that need to be made to determine which level is better and specifically how much better it is. For example, a five-level process parameter counts for four degrees of freedom. The degrees of freedom associated with interaction between two process parameters are given by the product of the degrees of freedom for the two process parameters [10]. In the present study, the interaction between the welding parameters is neglected.

Once the degrees of freedom required are known, the next step is to select an appropriate orthogonal array to fit the specific task. Basically, the degrees of freedom for the orthogonal array should be greater than or at least equal to those for the process parameters. In this study, an L25 orthogonal array was used.

The input welding process parameters considered for this research work were wire feed rate (W), welding voltage (V), welding speed (S), nozzle-to-plate distance (N) and gas flow rate (G).The output quality characteristic was dilution. All these parameters were investigated on 5 levels. The welding input variables and their limits are given Table III. For avoiding systematic errors further in carrying out the experiments, 25 experiments were randomized for placing bead-on-plate welds on the ST-37 steel plates. The experimental layout for the welding process parameters using L_{25} orthogonal array and the experimental results for the weld bead dilution are shown in Table IV.

TABLE I. THE CHEMICAL COMPOSITION OF FILLER WIRE

Element	Cr	P	S	Si	Ti	Mn	C	Fe
w%	0.031	0.007	0.01	0.024	0.002	0.417	0.113	Bal

TABLE II. THE CHEMICAL COMPOSITION OF STEEL ST-37

Element	Cr	P	S	Si	Ti	Mn	C	Fe
w%	0.031	0.007	0.01	0.024	0.002	0.417	0.113	Bal

TABLE III. WELDING VARIABLES AND THEIR LEVELS

	Notation	level					Units
Variable		***1***	***2***	***3***	***4***	***5***	
Wire feed rate	W	8	9	10	11	12	m/min
Arc voltage	V	26	28	30	32	34	volts
Nozzle-to-plate-distance	N	12	14	16	18	20	mm
Welding speed	S	20	23.5	27	30.5	34	cm/min
Gas flow rate	G	10	12	14	16	18	lit/min

TABLE IV. DESIGN MATRIX

Run Number	W	V	N	S	G	DILUTION %
1	1	1	1	1	1	22.1
2	1	2	2	2	2	29.2
3	1	3	3	3	3	20.4
4	1	4	4	4	4	22.2
5	1	5	5	5	5	25.2
6	2	1	2	3	4	16.3
7	2	2	3	4	5	15.8
8	2	3	4	5	1	23.5
9	2	4	5	1	2	32.6
10	2	5	1	2	3	44.2
11	3	1	3	5	2	12.4
12	3	2	4	1	3	26.8
13	3	3	5	2	4	24.6
14	3	4	1	3	5	49
15	3	5	2	4	1	35.9
16	4	1	4	2	5	18.8
17	4	2	5	3	1	22.4
18	4	3	1	4	2	36.2
19	4	4	2	5	3	33.7
20	4	5	3	1	4	53.8
21	5	1	5	4	3	21.0
22	5	2	1	5	4	26.5
23	5	3	2	1	5	42.9
24	5	4	3	2	1	40.4
25	5	5	4	3	2	39.9

C. Recording the Responses

Transverse section of each weld overlay was cut using power hacksaw from middle position of the welds. These specimens were prepared by the usual metallurgical polishing methods and etched with 2% nital. Furthermore, the prepared samples were used for measuring dilution with microscope and finally were analyzed using MINITAB software.

III. Data Analysis

A. Signal-to-noise Ratio

A class of statistics called signal-to-noise(S/N) ratios has been defined to measure the effect of noise factors on performance characteristics. S/N ratio take into account both the variability in the response data and the closeness of the average response to the target value. There are several signal-to noise ratios available depending on the type of performance characteristic. As mentioned earlier , one of the evaluation characteristic of each weldment is dilution. Greater dilution leads to a stronger weld. So the proper loss function for obtaining the signal-to-noise ratios is expressed by:

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

where L_{ij} is the loss function of the ith performance characteristic in the jth experiment, y_{ijk} the experimental value of the ith performance characteristic in the jth experiment at the kth trail, and n the number of trails. Amount of the loss function have been used to obtain signal-to-noise ratios as below:

$$\frac{S}{N} = -10 \log L_{ij} \quad (3)$$

In the Taguchi method signal-to-noise ratios is used to determine the optimum level of each factor. This is done by collecting levels with more amount of the signal-to-noise ratios. Table V is shown the amount of signal-to-noise ratios of each factor in different levels. In addition the effects of input variables on S/N ratio are given in Fig. 4.

Finally the optimum level of each factor to attain a proper weld dilution on weldment based on the Taguchi design of experiments is given in Table VI. These levels are based on coded form.

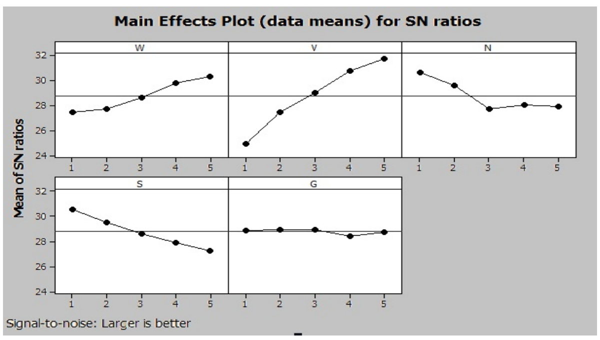

Fig 4. Effect of controllable factor on S/N ratio

TABLE V. Amount of the Signal-to-Noise Ratios

Level	W	V	N	S	G
1	27.47	24.99	30.65	30.60	28.91
2	27.76	27.46	29.57	29.53	28.93
3	28.63	29.05	27.76	28.65	28.93
4	29.77	30.74	28.08	27.92	28.41
5	30.34	31.73	27.91	27.27	28.79

TABLE VI. The Optimum Values for Input Parameters

PARAMETER	W	V	N	S	G
LEVEL	5	5	1	1	2

B. Development Mathematical Modeling

The response function representing the weld dilution can be expressed as % $D=f\,(W, V, N, S, G\,)$ and the relationship selected being a multiple regression model. The general form of a regression mathematical model is as follow:

$$\%\text{Dilution} = a_0+a_1W+a_2V+a_3N+a_4S+a_5G+a_{11}W^2+a_{22}V^2+a_{33}N^2+a_{44}S^2+a_{55}G^2+a_{12}WV+a_{13}WN+a_{14}WS+a_{15}WG+a_{23}VN+a_{24}VS+a_{25}VG+a_{34}NS+a_{35}NG+a_{45}SG \quad (4)$$

Different regression models were fitted to the above data and the coefficients values (a_i) are calculated using least squares method on MINITAB software.

C. Final Model

By neglecting insignificant factors on weld dilution using regression analysis and ANOVA final model was developed as shown below:

$$\%\text{Dilution} = 21.0 + 2.74\,W + 2.50\,V - 1.12\,N - 1.48\,S + 0.992\,VG - 0.500\,NG - 0.438\,SG \quad (5)$$

Regression coefficients and ANOVA calculation are given in Table VII and Table VIII respectively.

TABLE VII. The Coefficients of Regression Model

Peredictor	coef	SE coef	T	P
Constant	21.035	2.658	7.92	0.000
W	2.7410	0.4353	6.30	0.000
V	2.05039	0.9426	2.66	0.017
N	-1.1234	0.9426	-1.19	0.250
S	-1.484	1.035	-1.43	0.170
VG	0.9920	0.2796	-3.55	0.002
NG	-0.5002	0.2796	-1.79	0.092
SG	-0.4379	0.3139	-1.40	0.181
S=3.03918	R^2 =94.6%		R^2_{adj} = 92.3 %	

TABLE VIII. The ANOVA Table

Source	DF	SS	MS	F	P
Regression	7	2726.55	389.51	42.17	0.000
Residual error	17	157.02	9.24		
Total	24	2883.57			

IV. Results and Discussion

In this research work effect of main input welding parameters on the weld dilution in gas metal arc welding process were investigated. Results show that among main input welding parameters the effect of the wire feed rate is significant. Increasing the wire feed rate and the arc voltage increases the weld dilution whereas increasing the nozzle-to-plate distance and the welding speed results in the decrease in weld the dilution. In this research work it was observed that the gas flow rate did not contribute as such to weld dilution.

For the tow-factor interactions, the interaction between welding voltage and gas flow rate,-between nozzle-to-plate distance and the gas flow rate, and between the welding speed and gas flow rate are significant.

V. Conclusions

This paper has presented an application of the parameter design of the Taguchi method in the optimization in the GMAW parameters. A five -factor five level Taguchi experimental design was used to study the relationships between the weld dilution and the five controllable input welding parameters such as, wire feed rate, welding voltage, nozzle-to-plate distance ,welding speed, gas flow rate.

The following conclusions can be drawn based on the experimental results of this research work:

1-Taguchi's robust orthogonal array design method is suitable to analyze this problem as described in this paper.

2-It is found that the parameter design of Taguchi method provides a simple, systematic and efficient methodology for the optimization of the GMA welding parameters.

3-For main effects wire feed rate, welding voltage, welding speed, nozzle-to-plate distance; have significant effect on the weld dilution. This is consistent with the conclusions from the study of other investigators.

4- The wire feed rate has the most significant effect on the weld dilution

5-The gas flow rate did not have any significant effect as such as far as the dilution is concerned.

VI. Acknowledgments

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