

# Optimization and prediction of dilution percentage in submerged arc welding process

S. PRAVEEN<sup>1</sup>,

Gnanamani College of Technology<sup>1</sup>, Dept of Mechanical Engineering<sup>1</sup>, INDIA

S. PRAVEEN KUMAR<sup>2</sup>,

Gnanamani College of Technology<sup>2</sup>, Dept of Mechanical Engineering<sup>2</sup>, INDIA

**Abstract:** Weld dilution is an important feature of weld bead geometry that determines the mechanical and chemical properties of a welded joint. For submerged arc welding, several welding process parameters are reported to be controlling the dilution. This paper presents the effect of welding parameters like welding speed, welding current and voltage on penetration over mild steel plates. Three levels and three factors full factorial design method was used for conducting the experimental runs and linear regression models were developed accordingly. Nine experimental runs (L9) based on an orthogonal array Taguchi method were performed. The adequacy of the models was tested by applying S/N ratio and the predicted values from the models were plotted against the observed values through scatter diagram. Results showed that the proposed two level full factorial empirical models could predict the weld dilution with reasonable accuracy and ensure uniform weld quality. By using the Grey Relational Analysis technique, optimization of the complicated multiple process responses can be converted into optimization of a single grey relational grade and Optimization of a factor is the level with the highest grey relational grade.

**Keywords:** Taguchi method; Dilution; Grey relational analysis; S/N ratio .

## 1. Introduction

Welding is the process of joining similar metals by application of heat with or without application of pressure and addition of filler material. It is used as permanent fasteners. In the every metal industry welding is used widely. In fact, the future of any new metal may depend on how far it would lend itself to fabrication by welding.

The weldability has been defined as the capacity of being welded into inseparable joints having specified properties such as definite weld strength proper structure. The weldability of any metal depends on five major factors. These are melting point, thermal conductivity, thermal expansion, surface condition, and change in microstructure. Weld surfacing is a metal deposition process in the form of a single or multiple layers over a base metal, generally named as substrate. Based on the function, there are several classifications in surfacing process, namely a) hardfacing - the deposition to produce high wear resistance surfaces over a ductile base metal; b) cladding - to produce high corrosion resistant surfaces through deposition; c) buttering - a process of making chemically or metallurgical compatible surfaces; and d) the metal deposition to reconstruct and reuse the worn out parts. Surfacing by fusion welding process has been increasingly becoming popular as it substantially saves some of the most imperative costs that involve men, machines, materials and manufacturing and has been evolved rapidly in recent years for a wide range of industrial applications.

Among many of these features of weld bead geometry, one of the most important is the weld dilution. The dilution percentage, by definition is the ratio between the area of reinforcement ( $A_r$ ) to the total area of weldment ( $A_t$ ). It is the single most important factor between a conventional welding of a joint and a weld surfacing, although surfacing is fundamentally a welding process. The weld bead geometry which determines the dilution, plays an important role in determining the mechanical properties of the weld. To obtain the desired dilution, it is necessary to have a complete

control over the related process control parameters so as to ascertain the relevant bead shape and geometry which would eventually determine the capacity of the weldment. Controlling of dilution is one of the major requirements for a successful weld surfacing process as the composition and properties of weld deposit have a very strong relationship with the dilution that prevails after welding. For cladding however, a low dilution is highly desirable as the final deposit composition needs to be closer to the corrosion resistant filler metal. There have been several attempts made by the researchers, to investigate dilution in several fusion welding processes however, there are very little work done with robotic CO<sub>2</sub> process.

## 2. Design of Experiments

Design of Experiments (DOE) is a powerful analysis tool for modelling and analysing the influence of multiple control factors on the performance output. DOE refers to planning, designing and analysing an experiment so that valid and objective conclusions can be drawn effectively and efficiently.

## 3. Taguchi Experiment: Design and Analysis

Essentially, traditional experimental design procedures are too complicated and not easy to use. A large number of experimental works have to be carried out when the number of process parameters increases. To solve this problem, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments. Taguchi methods have been widely utilized in engineering analysis and consist of a plan of experiments with the objective of acquiring data in a controlled way, in order to obtain information about the

behaviour of a given process. The greatest advantage of this method is the saving of effort in conducting experiments; saving experimental time, reducing the cost, and discovering significant factors quickly. Taguchi's robust design method is a powerful tool for the design of a high-quality system. In addition to the S/N ratio, a statistical analysis of variance (ANOVA) can be employed to indicate the impact of process parameters on metal removal rate values. The steps applied for Taguchi optimization in this study are as follows. Select noise and control factors

- Select Taguchi orthogonal array
- Conduct Experiments
- measurement of dilution
- Analyze results; (Signal-to-noise ratio)
- Predict optimum performance
- Grey Relational Analysis

TABLE I  
PARAMETER LEVEL

Levels	Voltage(V)	Current(I)	Speed(f)
	v	A	mm/min
1	24	350	260
2	26	385	285
3	28	420	310



Fig 1 Experiments 1- 9



Fig 2. After Etching 1-9

### 3.1 Measurement of Dilution of Weld

The welded plates were checked for any visible defects and uniformity and then cross-sectioned at their axial midpoints to make test specimens. These 15 mm wide test specimens were metallurgically polished and etched with 5% nital solution

After completing all the experiments, samples were prepared for calculation of dilution by cutting, polishing and etching. For measuring the dilution, first of all the samples were scanned on a scanner at 1:1 scale. Then these scanned samples were opened in the Foxit reader software in which the total welding area, reinforcement area, penetration area, bead width, reinforcement height and penetration height were calculated only by selecting the scanned figure. The

bead geometry of these samples was measured by using Foxit reader software which was used in calculation of dilution by measuring penetration area and reinforcement area.

TABLE II  
PENETRATION AREA AND REINFORCEMENT AREA

	Reinforcement area	Penetration area	Dilution
Runs	$A_r$	$A_p$	D
	mm <sup>2</sup>	mm <sup>2</sup>	%
1	11.04	12.64	53.4%
2	9.95	14.20	58.8%
3	8.08	10.08	55.5%
4	5.87	18.83	76.2%
5	8.27	11.47	58.1%
6	10.09	10.37	50.7%
7	19.61	21.12	51.9%
8	10.69	15.20	58.7%
9	11.88	12.14	50.5%

### 3.2 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 takes 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.

S/N ratio is used as measurable value instead of standard deviation due to the fact that, as the mean decreases, the standard deviation also decreases and vice versa. In other words, the standard deviation cannot be minimized first and the mean brought to the target. In practice, the target mean value may change during the process development. Two of the applications in which the concept of S/N ratio is useful are the improvement of quality through variability reduction and the improvement of measurement. The S/N ratio characteristics can be divided into three categories given by.

Taguchi Analysis: Dilution versus Voltage, Current, Speed

Response Table for Signal to Noise Ratios

Larger is better

Level	Voltage	Current	Speed
1	34.94	35.50	34.67
2	35.67	35.35	35.70
3	34.58	34.35	34.82
Delta	1.09	1.14	1.03
Rank	2	1	3

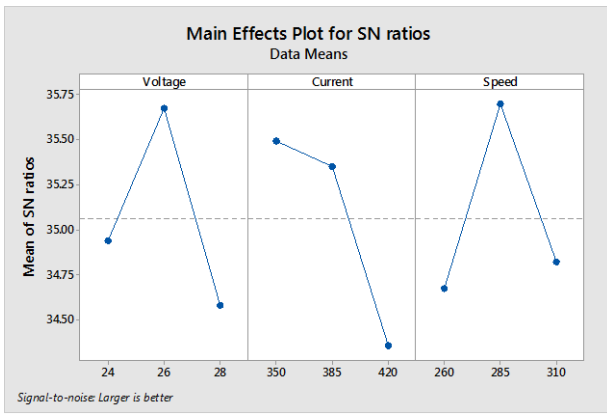


Fig 3 Response Table for Signal to Noise Ratios  
 Larger is better

### 3.3 ANOVA (Analysis of variance)

ANOVA is a statistically based, objective decision-making tool for detecting any differences in the average performance of groups of items tested. ANOVA helps in formally testing the significance of all main factors and their interactions by comparing the mean square against an estimate of the experimental errors at specific confidence levels.

### 3.4 Development Mathematical Modeling

The response function representing the weld dilution can be expressed as

% D=f ( V, I, F, S) and the relationship selected being a multiple regression model. The general form of a regression mathematical model is as follow:

The techniques of fitting of polynomial model in one variable can be extended to fitting of polynomial models in two or more variables.

A second order polynomial is more used in practice and its model is specified by

This is also termed as response surface. The methodology of response surface methodology is used to fit such models and helps in designing an experiment. This type is generally covered in the topics in design of experiment.

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

- Reinforcement area = 51 + 0.10 Voltage + 0.087 Current - 0.038 speed
- Penetration area = -56.4 + 0.54 Voltage + 0.234 Current + 0.231 speed
- Dilution = 35.5 + 0.05 Voltage + 0.0137 Current + 0.063 speed

## 4. Grey Relational Analysis

Planning the experiments through the Taguchi orthogonal array has been used quite successfully in process optimization. Therefore, this study applied a Taguchi L9 orthogonal array to plan the experiments on Welding process. Three controlling factors including Current, Voltage and Speed were selected. The Grey relational analysis is then applied to examine how the welding process factors influence the Reinforcement Area, Penetrated Area and Dilution. An optimal parameter combination was then obtained. Through analyzing the Grey relational grade

matrix, the most influential factors for individual quality targets of welding process can be identified.

In grey relational analysis, the data pre-processing is the first step performed to normalize the random grey data with different measurement units to transform them to dimensionless parameters. Thus, data pre-processing converts the original sequences to a set of comparable sequences. Different methods are employed to pre-process grey data depending upon the quality characteristics of the original data. The original reference sequence and pre-processed data (comparability sequence) are represented by  $x_i^{(0)}(k)$  and  $x_i^*(k)$   $i = 1, 2, \dots, n$  respectively, where m is the number of experiments and n is the total number of observations of data. Depending upon the quality characteristics, the three main categories for normalizing the original sequence are identified as follows:

If the original sequence data has quality characteristic as 'larger-the-better' then the original data is pre-processed as "larger the best"

$$x_i^*(k) = \frac{x_i^{(0)}(k) - \text{MIN } x_i^{(0)}(k)}{\text{MAX } x_i^{(0)}(k) - \text{MIN } x_i^{(0)}(k)}$$

If the original data has the quality characteristic as 'smaller the better', then original data is pre-processed as 'smaller-the best'

$$x_i^*(k) = \frac{\text{max } x_i^{(0)}(k) - x_i^{(0)}(k)}{\text{max } x_i^{(0)}(k) - \text{min } x_i^{(0)}(k)} \quad \text{----- (2)}$$

However, if the original data has a target optimum value (OV) then quality characteristic is 'nominal-the-better' and the original data is pre-processed as 'nominal-the-better':

$$x_i^*(k) = 1 - \frac{x_i^{(0)}(k) - OV}{\text{max } x_i^{(0)}(k) - \text{min } x_i^{(0)}(k)}$$

Also, the original sequence is normalized by a simple method in which all the values of the sequence are divided by the first value of the sequence.

$$x_i^*(k) = \frac{x_i^{(0)}(k)}{x_i^{(0)}(1)}$$

Where  $\text{max } x_i^{(0)}(k)$  and  $\text{min } x_i^{(0)}(k)$  are the maximum and minimum values respectively of the original sequence  $x_i^{(0)}(k)$ . Comparable sequence  $x_i^*(k)$  is the normalized sequence of original data.

### 4.1 Grey Relation Coefficient and Grey Relation Grade

Next step is the calculation of deviation sequence,  $\Delta_{oi}(k)$  from the reference sequence of pre-processes data  $x_0^*(k)$  and the Comparability sequence  $x_i^*(k)$ . The grey relational coefficient  $\xi$  is calculated from the deviation sequence using the following relation:

$$\xi_{ij} = \frac{\Delta_{min} + \zeta \Delta_{max}}{\Delta_{oi}(k) + \zeta \Delta_{max}} \leq 1 \quad \text{----- (3)}$$

Where  $\Delta_{oi}(k)$  is the deviation sequence of the reference Sequence  $x_0^*(k)$  and comparability sequence  $x_i^*(k)$

$$\Delta_{oi}(k) = |x_0^*(k) - x_i^*(k)|$$

$$\Delta_{max} = \max_{j \in i} \max_{\forall k} |x_0^*(k) - x_i^*(k)|$$

$$\Delta_{min} = \min_{j \in i} \min_{\forall k} |x_0^*(k) - x_i^*(k)|$$

The distinguishing coefficient ( $\xi$ ) value is chosen to be 0.5. A grey relational grade is the weighted average of the grey relational coefficient and is defined as follows:

$$Y(x_0^*, x_i^*) = \sum_{k=1}^n \xi_i(k) \tag{4}$$

The grey relational grade  $Y(x_0^*, x_i^*)$  represents the degree of correlation between the reference and comparability sequences. If two sequences are identical, then grey relational grade value equals unity. The grey relational grade implies that the degree of influence related between the comparability sequence and the reference sequence. In case, if a particular comparability sequence has more influence on the reference sequence than the other ones, the grey relational grade for comparability and reference sequence will exceed that for the other grey relational grades. Hence, grey relational grade is an accurate measurement of the absolute difference in data between sequences and can be applied to appropriate the correlation between sequences.

The experimental results for Reinforcement Area, Penetrated Area and Dilution factor are listed below. Typically, larger values of Penetrated Area and Dilution, and smaller values of Reinforcement Area are desirable. Thus the data sequences have the smaller-the-better characteristic, the “smaller-the-better” methodology, was employed for data pre-processing.

The values of the F, T and Ra are set to be the reference sequence  $x_0^0(k)$ ,  $k = 1-3$ . Moreover, the results of 27 experiments were the comparability sequences  $x_i^{*0}(k)$ ,  $i=1, 2, \dots, 27$ . All of the sequences after implementing the data pre-processing. The reference and the comparability sequences were denoted as  $x_0^*(k)$  and  $x_i^*(k)$ , respectively.

### 4.2 Calculation of Reference Sequence and Deviation Sequence

To calculate Reference sequence value for the experimental value of Reinforcement Area, Penetrated Area and Dilution, sequence data for Penetrated Area has quality characteristic as ‘larger-the-better’.

Substitute the value of Penetrated Area in the equation (1) as follows:

$$x_1^*(1) = \frac{19.61 - 11.04}{19.61 - 5.87} = 0.62373,$$

$$x_1^*(2) = \frac{12.64 - 10.08}{21.12 - 10.08} = 0.23188$$

$$x_1^*(3) = \frac{53.4 - 50.5}{76.2 - 50.5} = 0.11042$$

After calculating the reference sequence next step is to calculate the deviation sequence value subtracting it from the value 1.0000

$$\Delta_{oi}(k) = |x_0^*(k) - x_i^*(k)|$$

$$\Delta_{o1}(1) = |1.0000 - 0.62373| = 0.376274$$

$$\Delta_{o1}(2) = |1.0000 - 0.23188| = 0.768116$$

$$\Delta_{o1}(3) = |1.0000 - 0.11042| = 0.889577$$

Similarly, the reference sequence value for Penetrated Area and Dilution are calculated

### C. CALCULATION OF GRC AND GRG

After the calculation of normalized values, the GRC (grey relational coefficient) is calculated. The GRC expresses the relationship between the ideal and the actual normalized experimental results. The Grey Relational Coefficient,  $\xi_{ij}$  is expressed as,

$$\xi_i(k) = \frac{\Delta_{min} + \zeta \Delta_{max}}{\Delta_{oi}(k) + \zeta \Delta_{max}}$$

$\zeta$  is the distinguishing coefficient, which is defined in the range  $0 \leq \zeta \leq 1$ . But for practical purposes,  $\zeta$  is taken as 0.5.

TABLE III  
 GREY RELATION COEFFICIENT AND GREY RELATION GRADE

	Grey relation coefficient			GRG	Grey order
	$\xi_i(1)$	$\xi_i(2)$	$\xi_i(3)$	Y	
1.	0.570598	0.394286	0.359822	0.441568	7
2.	0.627397	0.44373	0.424233	0.498453	4
3.	0.756608	0.333333	0.38263	0.490857	6
4.	1	0.706786	1	0.902262	1
5.	0.7411	0.363876	0.414731	0.506569	3
6.	0.619477	0.339275	0.334575	0.431109	8
7.	0.333333	1	0.345085	0.559473	2
8.	0.587682	0.482517	0.422986	0.497728	5
9.	0.533385	0.38069	0.333333	0.415803	9

After the calculation of GRC values, the data can be reduced to a single value known as Grey Relational Grade (GRG).

$$\xi_i(1) = \frac{0.00 + 0.5}{0.376274 + 0.5} = 0.570598$$

$$\xi_i(2) = \frac{0.00 + 0.5}{0.768116 + 0.5} = 0.394286$$

$$\xi_i(3) = \frac{0.00 + 0.5}{0.889577 + 0.5} = 0.359822$$

Grey relation grade

$$\zeta = \frac{0.570598 + 0.394286 + 0.359822}{3} = 0.441568$$

## 5. Conclusion

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

3. For main effects 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 feed rate has the most significant effect on the weld dilution found by S/N ratio

5. Statistical results shows the voltage , current, feed rate and electrode distance affects the Dilution of weld by 8%, 24.7%, 29% and 22.46% in the Gas metal Arc welding process.

6. The Reinforced Area, Penetration Area and % dilution predicted by the result of regression analysis as follows

$$\text{Reinforcement area} = 51 + 0.10 \text{ Voltage} \\ + 0.087 \text{ Current} - 0.038 \text{ speed}$$

$$\text{Penetration area} = -56.4 + 0.54 \text{ Voltage} \\ + 0.234 \text{ Current} + 0.231 \text{ speed}$$

$$\text{Dilution} = 35.5 + 0.05 \text{ Voltage} + 0.0137 \text{ Current} \\ + 0.063 \text{ speed}$$

7. According to grey relational theory the experiment with Voltage of 26V, Current of 350A and speed of 285mm/min are optimum.

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