Optimization of Gas Metal Arc Welding Process Parameters

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Abstract. This study presents the application of Taguchi method combined with grey relational analysis to optimize the process parameters of gas metal arc welding (GMAW) of AISI 1020 carbon steels for multiple quality characteristics (bead width, bead height, weld penetration and heat affected zone). An orthogonal array of L₉ has been implemented to fabrication of joints. The experiments have been conducted according to the combination of voltage (V), current (A) and welding speed (Ws). The results revealed that the welding speed is most significant process parameter. By analyzing the grey relational grades, optimal parameters are obtained and significant factors are known using ANOVA analysis. The welding parameters such as speed, welding current and voltage have been optimized for material AISI 1020 using GMAW process. To fortify the robustness of experimental design, a confirmation test was performed at selected optimal process parameter setting. Observations from this method may be useful for automotive sub-assemblies, shipbuilding and vessel fabricators and operators to obtain optimal welding conditions.

Keywords: Gas metal arc welding, Taguchi based grey relational analysis, ANOVA, Heat affected Zone.

1. Introduction
In today’s proliferating manufacturing industries, applications of optimization techniques in Gas metal arc welding processes is indispensable for a manufacturing unit to retaliate adequately to drastic competitiveness and increasing demand of quality product. It has got extensive applications in industries because of its high reliability, ability to weld in all position, economic, productive, high deposition rate, easy to use, no fluxes and cleanliness [1]. An electric arc is generated between a continuous filler metal electrode and the weld pool. Gases are used for shielding which flow through the nozzle of the welding torch. Gases which are used to shield the weld pool are Argon (Ar), Helium (He), CO₂ and their mixtures.

GMAW is a complicated process with many interrelated parameters affecting the quality of the welded joint. The process variables with the maximum influence are the welding current, welding voltage, travel speed and arc efficiency [2].

The important factors for weld bead geometry are bead width, bead height and weld penetration.

Usually the parameters of welding are determined purely on the basis of experience of the operator or from the hand book. However, these selected welding process parameters does not ensure the optimum weld bead geometry.

In this study the welding process parameters like current, voltage, welding speed and gas flow rate along with responses i.e., bead height, bead width, weld penetration are investigated. To obtain optimum bead geometry Taguchi based Grey Relational Analysis (GRA) is employed. In present work two mild steel plates are closed butt welded by GMAW. In order to find out the input welding parameters that lead to optimum bead geometry Taguchi’s Design of Experiment (DOE) is adopted followed by GRA. Experiments are carried out with the help of L₉ orthogonal array and influence of input welding parameters on responses is examined.
2. Literature Review

Das et al. [3] welded EN-3A mild steel specimens by metal inert gas welding and showed the effect of various welding process parameters on its weldability. Parameters selected were welding current, arc voltage and welding speed. A butt joint was prepared and depth of penetrations was measured. Effect of welding parameters on penetration was observed with the help surface plots[3].

Arya et al. [4] have shown the influence of welding parameters like voltage, welding speed, welding current, gas flow rate and wire diameter. The response parameters selected for MIG welding were tensile strength, weld penetration, bead geometry, and heat affected zone (HAZ) for quality target. Taguchi method followed by grey relational analysis was adopted for optimization of tensile strength and higher penetration [4].

Datta et al. [5] performed a multiple response optimization in welding of mild steel specimens using submerged arc welding using L_{25} orthogonal array. Voltage, speed, stick out, creep feed rate and wire feed rate were taken as input welding parameters while bead width, bead height, penetration and HAZ were taken as output parameters. The process parameters were optimized using Grey-Taguchi method and welding speed was found to be the most significant factor.

Na et al. [6] examined the influence of welding process parameters on the weld bead geometry during fillet welding of 200X400X12 mm S400 steel plates. Neural network and mathematical equations were used for the prediction of bead geometry while Taguchi method was used for optimization of MIG welding process parameters.

Karadeniz et al. [7] have butt welded Erdemir 6842 steel by robotic GMAW and investigated the effect of process parameters on depth of penetration. Welding speed, arc voltage and welding current were taken as process parameters.

Aghakhani et al. [1] proposed a mathematical model with help of Taguchi Design of Experiment (DOE) to predict weld dilution. Nozzle-to-plate distance, wire feed rate, welding speed, gas flow rate and welding voltage were selected as input process variables. Analysis of response reveals that arc voltage and wire feed rate have positive effect while welding speed and nozzle-to-plate distance have negative effect on weld dilution.

Modenesi et al. [8] have investigated the effect of variation in wire diameter characteristics in gas metal arc welding using CO_{2} as shielding gas. A total of 16 samples of ER70S-6 were manufactured with little variation in mechanical strength, diameter, helix and cast. Experiments were carried out using each wire at a time. Spatter produced in each experiment was compared with the weight of the bead. The most affected factors by variation in wire characteristic are welding current, short circuit factor and transfer period.

Nagesh et al. [9] have examined the effect of arc power, electrode feed rate, arc voltage, arc current, arc travel rate and arc length on bead width, bead height and weld penetration. Artificial neural network was used to find out the estimated values. The experimental values are compared with the estimated values with very less error percentage. It was observed that high arc travel rate produces poor fusion and electrode high feed rate produces flatter weld bead.

Hooda et al. [10] proposed a response surface model for the prediction of tensile strength of metal inert gas (MIG) welding of AISI 1040 medium carbon steel plates. The welding process parameters like current, wire feed rate, voltage and gas flow rate were examined.
Patel et al. [11] investigated the effect of welding parameters like wire diameter, wire feed rate and current on weld hardness in welding of AISI 1020 carbon steel plates by MIG welding. The input welding parameters were optimized by Grey Relational Analysis (GRA) and claimed that welding current is most influencing factor.

3. Methodology

Taguchi method is robust design technique for optimization in the field of engineering. Taguchi method optimizes the input parameters on the basis of single response only. But for multiple response problems Taguchi method is inadequate. To optimize multiple response problem Taguchi method is coupled with grey relational analysis.

Grey system theory (Deng 1984) [12] was first put forward by Deng in 1982. This method examines a process that has incomplete information about the action of parameters on the output parameters.

Steps in grey relational analysis method [13]:

![Figure 1: Steps in GRA](image)

3.1. Grey relational generation

When the units in which response is measured are different for different parameters, the effect of some parameters may be neglected. These responses lead to improper results in the evaluation. In this step the measured data is normalized from 0 to 1. In Grey relational generation, the normalized bead width, bead height, penetration and HAZ, corresponding to lower-the-better (LB) criterion can be expressed as:

\[ xi(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \]  

Penetration & tensile strength should follow the larger-the-better criterion, given as:

\[ xi(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \]  

Where \( xi(k) \) is the value after the Grey relational generation, \( \max y_i(k) \) is the largest value of \( y_i(k) \) for the \( k^{th} \) response and \( \min y_i(k) \) is the smallest value of \( y_i(k) \) for the \( k^{th} \) response.
3.2. Reference sequence definition

After grey relational generation step all measured values will be scaled into [0, 1]. For an attribute \( j \) of alternative \( i \), if the value \( x_{ij} \) which has been suggest by grey relational generating step, is equal to 1, or nearer to 1 than the value for any other response, that means the performance of alternative \( i \) is the best among the attribute \( j \). In this paper the reference sequence \( x_0 \) is taken as 1 and then desires to find the response whose comparability sequence is closest to the reference sequence.

3.3. Grey relational coefficient calculation

The Grey relational coefficient \( \xi_i(k) \) can be calculated as:

\[
\xi_i(k) = \frac{\Delta_{min} - \Delta_{max}}{\Delta_{max}(k) + \Delta_{max}}
\]

Where, \( \Delta_0i = x_0(k) - x_i(k) \) difference of the absolute value \( x_0(k) \) and \( x_i(k) \), is the distinguishing coefficient \( 0 \leq \xi \leq 1 \), \( \Delta_{min} \) = the smallest value of \( \Delta_0i \), \( \Delta_{max} \) = largest value of \( \Delta_0i \). The purpose of the distinguishing coefficient is to expand or compress the range of the grey relational coefficient.

3.4. Grey Relational Grade Calculation

After calculating the entire grey relational coefficients, the grey relational grade can be then calculated by using equation

\[
\gamma_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k)
\]

Where \( n \) is the number of responses. Higher Grey relational grade means that the corresponding parameter combination is closer to the optimal condition. The grey relational grade shows the degree of similarity between the reference sequence & comparability sequence. In order to evaluate the influence of each selected input parameter on the responses, the S/N ratio for each output has to be calculated with the help of grey relational grades. The loss function of the larger-the-better characteristic can be expressed as:

\[
L_{ij} = -10\log \left( \frac{1}{N} \sum_{i=1}^{N} \left( \frac{1}{y_{ijk}} \right) \right)
\]

Where \( L_{ij} \) is the loss function of the \( i^{th} \) performance characteristic in the \( j^{th} \) experiment, \( N \) is the number of tests, and \( y_{ijk} \) is the experimental value of the \( i^{th} \) performance characteristic in the \( j^{th} \) experiment at the \( k^{th} \) test.

The loss function is further transformed into a signal-to-noise ratio. In the Taguchi method, the S/N ratio is used to determine the performance characteristic deviating from the desired value.

4. Experimental Procedure and Test Results

4.1. Experimental Details

The experiments are carried out with the help of INVA MIG 400 welding machine along with CO\(_2\) as shielding gas. These experiments are based on Taguchi’s \( L_9 \) orthogonal array. All the experiments were conducted on mild steel specimens having 200x50x6 mm size as a base metal and ER 70 S-6
wire electrode having 0.8 mm diameter as filler wire. The chemical composition of base metal by weight % is given in table 1.

TABLE 1: The chemical composition of the base metal weight%

|          | C | Mn | Si  | S  | P  | Ni |
|----------|---|----|-----|----|----|----|
| Base metal | 0.12 | 0.9 | 0.013 | 0.008 | 0.013 | .004 |

Figure 2: Experimental Setup

In this study, three input parameters namely welding current, arc voltage and welding speed have been chosen on the basis of trial and error testing. For the selection of parameters about 40 experiments were done. Several different combinations of welding speed, current and voltage were taken. Voltage ranges from, 20V- 30V, Welding speed ranges from 20 cm/min - 60 cm/min and current ranges from 150 A- 200 A.

Experiments have been done with the welding process parameters given in table 2, to obtain closed square butt welding on mild steel 6 mm thickness with 50 mm × 200 mm dimensions by gas metal arc welding process.

TABLE 2: Welding variable and their levels

| Parameter          | Unit       | Level 1 | Level 2 | Level 3 |
|--------------------|------------|---------|---------|---------|
| Voltage(Vo)        | Volt(V)    | 26      | 27      | 28      |
| Current(C)         | Ampere(A)  | 160     | 170     | 180     |
| Welding Speed(WS)  | cm/min     | 42      | 47      | 52      |

Figure 3: Mild steel specimens before welding

4.2. Test results

In total 9 experiments were performed as per L₉ orthogonal array. The design matrix is formed with the help of MINITAB 17 software. The L₉ orthogonal array along with experimental results for bead height, bead width and weld penetration is shown in table 3. The measurement of bead height (BH),
bead width (BW), weld penetration (P) and heat affected zone (HAZ) is done with the help of high pixel digital camera and image analysis software as shown in figure 5.

![Figure 5: Measurement of bead geometry by image analysis software](image)

**TABLE 3: Design matrix**

| S.No. | Vo | C  | WS | BW (mm) | BH (mm) | P  (mm) | HAZ (mm) |
|-------|----|----|----|---------|---------|--------|----------|
| 1.    | 26 | 160| 42 | 7.03    | 2.38    | 1.89   | 9.38     |
| 2.    | 26 | 170| 47 | 7.2     | 2.61    | 2.47   | 7        |
| 3.    | 26 | 180| 52 | 7.33    | 1.88    | 2.79   | 6.81     |
| 4.    | 27 | 160| 47 | 6.7     | 2.17    | 2.38   | 6.84     |
| 5.    | 27 | 170| 52 | 6.57    | 1.84    | 2.28   | 5.37     |
| 6.    | 27 | 180| 42 | 7.28    | 2.27    | 1.75   | 7.74     |
| 7.    | 28 | 160| 52 | 6.65    | 1.94    | 2.16   | 6.39     |
| 8.    | 28 | 170| 42 | 9.05    | 2.38    | 2.45   | 8        |
| 9.    | 28 | 180| 47 | 7.37    | 2.08    | 2.78   | 8.31     |

5. Implementation of Grey-Taguchi Method

To obtain Grey relational generation experimental data have been normalized by using Equations (1) and (2). Larger-the-better (LB) criterion is selected for penetration and smaller-the-better (SB) is selected for bead width, bead height and HAZ. The normalized value for each response is presented in table 4.

**TABLE 4: Normalized values (NV) of bead width (BW), bead height (BH), penetration (P) & HAZ**

| SN. | BW  | NV  | BH  | NV  | P   | NV  | HAZ | NV  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1   | 7.03| 0.814| 2.38| 0.298| 1.89| 0.134| 9.38| 0   |
| 2   | 7.2 | 0.745| 2.61| 0   | 2.47| 0.692| 7   | 0.598|
| 3   | 7.33| 0.693| 1.88| 0.948| 2.79| 0.605| 6.84| 0.633|
| 4   | 6.7 | 0.947| 2.17| 0.571| 2.38| 0.599| 5.37| 1   |
| 5   | 6.57| 1 | 1.84| 1 | 2.28| 0.509| 5.37| 1   |
| 6   | 7.28| 0.713| 2.27| 0.441| 1.75| 0 | 7.74| 0.408|
| 7   | 6.65| 0.967| 1.94| 0.870| 2.16| 0.394| 6.39| 0.745|
| 8   | 9.05| 0 | 2.38| 0.298| 2.45| 0.673| 8   | 0.344|
| 9   | 7.37| 0.677| 2.08| 0.688| 2.78| 0.990| 8.31| 0.266|
Now, grey relational coefficient for each response is computed on the basis of equation (3). The value of distinguishing coefficient is taken as 0.5 for each response [14, 15]. The values of grey relational coefficient are presented in table 5.

| S.No. | BW    | BH    | P    | HAZ   |
|-------|-------|-------|------|-------|
| 1     | 0.729411 | 0.416215 | 0.366197 | 0.333333 |
| 2     | 0.6631  | 0.333333 | 0.619047 | 0.554634 |
| 3     | 0.62   | 0.905882 | 1     | 0.582003 |
| 4     | 0.950108 | 0.538461 | 0.559139 | 0.576978 |
| 5     | 1      | 1     | 0.504854 | 1     |
| 6     | 0.63589 | 0.472392 | 0.333333 | 0.458286 |
| 7     | 0.939391 | 0.793814 | 0.452173 | 0.66281 |
| 8     | 0.333333 | 0.416216 | 0.60465  | 0.432578 |
| 9     | 0.608082 | 0.615999 | 0.98113  | 0.4056 |

After computing grey relational coefficients the grey relational grade is calculated with the help of equation (4). The values of grey relational grades are presented in table 6.

| S.No. | Grey Relational Grade (GRG) |
|-------|-----------------------------|
| 1     | 0.461289                    |
| 2     | 0.542529                    |
| 3     | 0.776971                    |
| 4     | 0.656172                    |
| 5     | 0.876214                    |
| 6     | 0.474975                    |
| 7     | 0.712047                    |
| 8     | 0.446694                    |
| 9     | 0.652703                    |

After calculating grey relational grades the welding process parameters are optimized by using Taguchi method corresponding to larger-the-better (LB) criterion. The S/N ratio for each output has been calculated with the help of grey relational grade using equation 5. For the calculation of the S/N ratio, the experimental data from table 6 for grey relational grade is converted into signal to noise ratio and it is presented in table 7.

| S.NO. | Vo | C  | WS | (GRG) | S/N ratio |
|-------|----|----|----|-------|-----------|
| 1     | 26 | 160| 42 | 0.461289 | -6.7205   |
| 2     | 26 | 170| 47 | 0.542529 | -5.3115   |
| 3     | 26 | 180| 52 | 0.776971 | -2.1919   |
| 4     | 27 | 160| 47 | 0.656172 | -3.6596   |
| 5     | 27 | 170| 52 | 0.876214 | -1.1479   |
| 6     | 27 | 180| 42 | 0.474975 | -6.4665   |
| 7     | 28 | 160| 52 | 0.712047 | 2.94982   |
| 8     | 28 | 170| 42 | 0.446694 | 6.99979   |
| 9     | 28 | 180| 47 | 0.652703 | 3.70568   |
The maximum signal-to-noise ratio is the optimum level, because a high value of signal-to-noise ratio indicates that the signal is much higher than the random effects of the noise factors. Table 7 shows the calculation of the average S/N ratios for welding current, arc voltage and welding speed. The effect of largest S/N$_{avg}$ ratio for parameters is shown in the figure 6. Table 8 shows the optimum level for input welding parameters. The optimal bead width, bead height, welds penetration and HAZ is obtained by applying current 170 A, arc voltage 27 V, and welding speed 52 cm/min, for a plate of 6 mm thickness.

| Parameter     | Arc Voltage | Welding Current | Welding Speed |
|---------------|-------------|-----------------|---------------|
| Level         | 2           | 3               | 3             |

TABLE 8: The optimum values for input parameters

![Figure 6: Effect of controllable factor on S/N ratio](image)

6. Analysis of Variance
ANOVA is a standard statistical technique to interpret the experimental results. The percentage contribution of various process parameters to the selected performance characteristic can be estimated by ANOVA. Thus information about how significant the effect of each controlled parameter is on the quality characteristic of interest can be obtained. ANOVAs for raw data has been performed to identify the significant parameters and to quantify their effect on the performance characteristic [16]. The ANOVA based on the raw data identifies the factors which affect the average response rather than reducing variation. In ANOVA, total sum of squares (SS$_T$) is calculated by:

$$SS_T = \sum_{i=1}^{N} (Y_i - \bar{Y})^2$$

Where N is the number of experiments in the orthogonal array, N=9, $Y_i$ is the experimental result for the $i^{th}$ experiment and $\bar{Y}$ is given by:

$$\bar{Y} = \frac{1}{N} \sum_{i=1}^{N} Y_i$$

The total sum of the squared deviations SS$_T$ is decomposed into two sources: the sum of the squared deviations SS$_p$ due to each process parameter and the sum of the squared error SS$_e$. SSP can be calculated as:

$$SS_P = \sum_{j=1}^{t} \left( \frac{(SY_j)^2}{t} - \frac{1}{N} \left( \sum_{i=1}^{N} Y_i \right)^2 \right)$$
Where \( p \) represent one of the experiment parameters, \( j \) the level number of this parameter \( p \), \( t \) the repetition of each level of the parameter \( p \), the sum of the experimental results involving this parameter \( p \) and level \( j \). The sum of squares from error parameters \( SS_e \) is:

\[
SS_e = SS_T - SS_A - SS_B - SS_C
\]

The total degrees of freedom is \( D_T = N - 1 \), and the degrees of freedom of each tested parameter is \( D_p = t - 1 \). The variance of the parameter tested is \( V_p = SS_p/D_p \). Then, the \( F \)-value for each design parameter is simply the ratio of the mean of squares deviations to the mean of the squared error \( (F_p = V_p/V_e) \). The percentage contribution \( \rho \) can be calculated as:

\[
\rho_p = \frac{SS_p}{SS_T}
\]

### TABLE 9: ANOVA for bead geometry

| Source            | DOF | Sum of Squares | Mean Square | F-ratio | Contribution (%) |
|-------------------|-----|----------------|-------------|---------|------------------|
| Voltage           | 2   | 1.633          | 0.8166      | 0.97    | 4.55             |
| Welding current   | 2   | 0.2390         | 0.1195      | 0.14    | 0.66             |
| Welding speed     | 2   | 32.2757        | 16.1378     | 19.23   | 90.08            |
| Error             | 2   | 1.6782         | 0.8391      |         | 4.68             |
| Total             | 8   | 35.8261        |             |         |                  |

According to Table 9, ANOVA shows that welding speed and arc voltage are the most significant welding process parameters that affect bead width, bead height, penetration and heat affected zone (HAZ). While welding current is the least significant process parameter.

**Figure 7:** Percentage contribution of process parameters
7. Results and Discussion

In this research the effects of welding process parameters on weld bead geometry were investigated. It was predicted that the effect of welding speed is most significant. It was also observed that current has almost no effect on bead geometry.

After finding all the optimum levels of welding process parameter, the next step is to verify the values of responses by optimal setting of parameters. On doing optimal parameter setting on GMAW setup we get following values of bead width, bead height, weld penetration and HAZ presented in table 10.

| Vo | C | WS | BW (mm) | BH (mm) | P (mm) | HAZ (mm) |
|----|---|----|--------|--------|--------|----------|
| 27 | 180 | 52 | 6.42   | 1.78   | 2.92   | 5.26     |

Above obtained results shows applicability of Grey coupled with Taguchi method to perform a multi-objective problem of parameter design. A robust design could be obtained for three levels and three factors by using an orthogonal array and problem could be analyzed. It was found that Taguchi based grey method provides a simple, systematic and efficient methodology for multiple response optimization of GMA welding parameters.

Welding speed and arc voltage have significant effect on the weld bead geometry whereas welding current has decreasing effect on the weld bead geometry.

8. Conclusion

This paper deals with the use of Taguchi based Grey relational analysis to optimize gas metal arc welding parameters. The multiple response optimization process employs orthogonal array to conduct experiments along with GRA and Taguchi method. The optimal setting of welding parameters simultaneously minimizes bead width, bead height HAZ and maximizes weld penetration. It has been proven that multiple responses in gas metal arc welding are improved by grey based Taguchi method.

It was obtained that the percentage contribution of welding speed, voltage, and welding current was 90.08 %, 4.55 % and 0.66 % respectively on weld bead geometry. Error also contributes 4.68% which is mainly due to machine vibration and human error. The optimum values of welding parameters based on GRA are voltage 27 V, current 180 A and welding speed 52 cm/min.

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