**Grey Relational Analysis for Multi Objective Optimization of Weld Bead Geometry in Double Pulsed Gas Metal Arc Welding**

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**Abstract.** In Manufacturing Industry, there is a need to estimate/predict values for performance measures for a set of input parameters and vice versa, for various machining operations which consume lot of operational time and money. This paper presents grey relational analysis method with full factorial design of experiments conducted on double-pulsed GMAW of AA5083 H111, for multi output optimization. The welding parameters namely, wire feed rate, wire feed rate/travel speed, amplitude (variation of wire feed rate) and double pulse frequency are measured each at three levels for the multiple performance measures of bead geometry considered to be bead penetration, bead reinforcement, bead width and convexity index. Grey relational grade is used to correlate multi responses to a single response called all-inclusive component output measure called the grey relational grade. Also, analysis of variance technique ANOVA is implemented to get the most influential multi response DP-GMAW parameter. The results conclude that the wire feed rate of 5.5 m/min, wire feed rate/travel speed of 30, amplitude of 0.4 Amp and frequency of 2 Hz are the most favorable welding parameters for double-pulsed GMAW of AA5083 H111.

Keywords: Gas Metal Arc Welding (GMAW), fractional factorial method, S/N ratio, Grey relational grade

1. **Introduction**

Welding is one of the most widely used manufacturing process in industries. The study of welding process mainly focuses on weld bead geometry, mechanical properties and welding parameters that influence the efficiency and quality of the process. An improvement in process efficiency can be obtained by optimizing the process parameters which are identified and determined using regions of critical process control which result in output responses with acceptable variations. The simplest systems can be modelled using single response optimization. However, welding process is too complex to be categorized into individual responses. [1] This problem can be solved by the grey system theory introduced by Deng. [10]. Chen et al. [11] proposed the integration of grey relational analysis and the Taguchi Method to resolve multiple quality characteristics. This method transforms multiple quality characteristics into single grey relational grades. By comparing the computed grey relational grades, the arrays of respective quality characteristics are obtained in accordance with response grades to select an optimal set of process parameters. Optimal process parameters can then be determined by the Taguchi method using the grey relational grade as the performance index.

This present study on the application of Taguchi-GRA Multi output optimization is used as a well-organized approach to resolve the optimal welding parameters in double-pulsed GMAW of AA5083 H111 using fractional factorial design of experiments. In this process, Taguchi models of signal for noise (S/N) ratio, ANOVA and grey relational analysis to optimize the double-pulsed GMAW process parameters for a single comprehensive output measure called grey relational grade. As a final point, the analysis of variance is used to find out the most influential welding parameter for optimization problems of single and multiple responses.

1. **Experimental data Generation**

Welding of AA5083 H111 is considered for experimental work. A plate of 6mm thickness is used as base material. Wire feed rate, travel speed, amplitude i.e variation in wire feed rate and double pulse frequency are considered as input parameters. Depth of penetration, reinforcement, bead width and convexity index are considered as performance measures. Table 1 shows the levesl of the input parameters. Full factorial design of experiments comprising of 81 experiments is chosen for predicting the process parameters effect on bead geometry and experiments are conducted accordingly.

**2.1** **Experimental set-up**

The experiment work is carried out on PROMIG welding machine shown in the Figure 1. It is comprised of gas metal arc welding machine, automatic feeding weld bed, DC motor, and a rheostat. The weld bed is connected to lead screw and lead screw is turn connected to DC motor to get movement, when DC Motor is powered. As the lead screw moves forward the weld bed automatically feeds in opposite direction. The amount of current passage to the DC Motor is monitored by varying rheostat such that the speed of the DC motor varies.

The travel speed of the weld bed facilitates to calculate the wire feed rate. Welding is done on the weld plate by keeping the welding torch fixed at a position and giving movement to the weld bed by varying the position of pointer on rheostat and the wire feed rate. After welding the weld plate, it is cut to metallurgical finish and then the depth of penetration, reinforcement, bead width and convexity index are calculated.

## **2.2 Fractional factorial design of experiments**

One-third of the fractional factorial design is considered for carrying out the experiments. The fraction is selected to make use of the sparity-of-effects principle, to interpret information about the significant features of the problem. In the present work 27 such experiments are considered by taking generator as I=ABCD, out of suggested 81 experiments and is shown in Table 2.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **TABLE 1.** Welding parameters at different levels   |  |  |  |  |  | | --- | --- | --- | --- | --- | | **Parameter** | **Symbol** | **Level 1** | **Level 2** | **Level 3** | | Wire feed rate (m/min) | A | 4.0 | 5.5 | 7.0 | | Wire feed rate/  Travel speed | B | 20 | 25 | 30 | | Amplitude (Amp) | C | 0.4 | 1.2 | 2.0 | | Frequency (Hz) | D | 1.5 | 2.0 | 2.5 | | IMG_20150224_104732.jpg  **Figure 1.** PROMIG3200 welding machine |

TABLE 2: Fractional factorial design of experiments

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Expt. No.** | **A** | **B** | **C** | **D** | **Expt.**  **No.** | **A** | **B** | **C** | **D** | **Expt. No.** | **A** | **B** | **C** | **D** |
| 1 | 4 | 20 | 0.4 | 1.5 | 10 | 5.5 | 20 | 0.4 | 2 | 19 | 7 | 20 | 0.4 | 2.5 |
| 2 | 4 | 20 | 1.2 | 2 | 11 | 5.5 | 20 | 1.2 | 2.5 | 20 | 7 | 20 | 1.2 | 1.5 |
| 3 | 4 | 20 | 2 | 2.5 | 12 | 5.5 | 20 | 2 | 1.5 | 21 | 7 | 20 | 2 | 2 |
| 4 | 4 | 25 | 0.4 | 2 | 13 | 5.5 | 25 | 0.4 | 2.5 | 22 | 7 | 25 | 0.4 | 1.5 |
| 5 | 4 | 25 | 1.2 | 2.5 | 14 | 5.5 | 25 | 1.2 | 1.5 | 23 | 7 | 25 | 1.2 | 2 |
| 6 | 4 | 25 | 2 | 1.5 | 15 | 5.5 | 25 | 2 | 2 | 24 | 7 | 25 | 2 | 2.5 |
| 7 | 4 | 30 | 0.4 | 2.5 | 16 | 5.5 | 30 | 0.4 | 1.5 | 25 | 7 | 30 | 0.4 | 2 |
| 8 | 4 | 30 | 1.2 | 1.5 | 17 | 5.5 | 30 | 1.2 | 2 | 26 | 7 | 30 | 1.2 | 2.5 |
| 9 | 4 | 30 | 2 | 2 | 18 | 5.5 | 30 | 2 | 2.5 | 27 | 7 | 30 | 2 | 1.5 |

1. **Experimental results**

The experimental results shown in Figure 2(a) to 2(d) show the ranges of depth of penetration PD (0.31 mm to 5.67 mm), reinforcement RH(2.65 mm to 4.62 mm), bead width BW (5.193 mm to13.408 mm) and convexity index CI (0.242 to 0.68) respectively .

|  |  |
| --- | --- |
|  |  |
| (a) | (b) |
|  |  |
| (c ) | (d) |

## Figure 2. Experimental results for the response variables

1. **Optimization of DP-GMAW parameters**

Taguchi method is used in combination with Grey relational analysis for the optimal welding parameters in Double-Pulsed GMAW process [1].The deviation between experimental value and desired value are approximated by Taguchi’s loss function. The characteristics of performance by signal-to-noise ratio is analyzed under three classes namely-‘lower-the-better’, ‘higher-the-better’ and ‘nominal-the-best’.[1] “Lower-the-better” is preferred in obtaining optimal welding performance with the minimum reinforcement and convexity index. “Higher-the-better” characteristic is preferred for achieving optimal welding performance maximum depth of penetration and bead width.

S/N ratio values are tabulated in Table 3 for each experimental parameter combinations for depth of penetration, reinforcement, bead width and convexity index and are used for single and multi characteristic optimizations.

1. **Single output parameter optimization**

When a single-response problem is considered then Taguchi method is used. The largest S/N ratio is used for the quality characteristic. Besides, the influence of every factor is estimated through ANOVA. In GMAW, a smaller value of reinforcement and convexity index is normally essential. Consequently, the smaller-the-better approach of S/N ratio is applied for the above mentioned responses. The higher-the-better approach of S/N ratio is used to calculate the depth of penetration and bead width.

## **5.1 Optimization for Depth of penetration**

The factor combination A3B3C1D2 is recommended as per ANOVA response table of S/N ratios of depth of penetration shown in Table 3. It is observed that the contribution factor A to the depth of penetration is the largest (36.9%) followed by factor D (20.03%). Thus, wire feed rate is the most important factor followed by frequency to the extent that depth of penetration is concerned

## **5.2 Optimization for Reinforcement**

Factor combination A2B1C2D2 is recommended as per S/N ratios of reinforcement shown in Table 4. Also it is observed that the contribution of factor D to the reinforcement is the largest (29.183%) followed by factor B (12.893%). Thus, frequency is the most important factor followed by wire feed rate/travel speed as far as reinforcement is concerned.

## **5.3 Optimization for Bead width**

From the ANOVA response table of S/N ratios of bead width shown in Table 5, factor combination A2B3C1D2 is recommended. Also it is observed that the contribution of factor A to the bead width is the largest (38.548%) followed by factor B (17.321%). Thus, wire feed rate is the most important factor followed by wire feed rate/travel speed as far as bead width is concerned.

TABLE 3. ANOVA analysis of S/N ratios of depth of penetration

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Variable** | **Average level** | | | **DOF** | **SS** | **MS** | **F** | **Contribution (%)** |
| **1** | **2** | **3** |
| A  B  C  D  Error  Total | 0.697  4.32  **7.788**  6.868 | 7.384  5.995  5.641  **8.511** | **9.368**  **7.134**  4.02  2.07 | 2  2  2  2  3  11 | 371.516  36.065  64.306  201.621  333.103  1006.611 | 185.76  18.033  32.153  100.81  111.035 | 1.673  0.163  0.29  0.908 | **36.908**  3.583  6.389  20.03  33.092  100 |

TABLE 4. ANOVA analysis of S/N ratios of reinforcement

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Variable** | **Average level** | | | **DOF** | **SS** | **MS** | **F** | **Contribution (%)** |
| **1** | **2** | **3** |
| A  B  C  D  Error  Total | -10.631  **-9.864**  -10.508  -11.211 | **-9.935**  -10.706  **-10.354**  **-9.598** | -10.884  -10.881  -10.589  -10.642 | 2  2  2  2  3  11 | 4.348  5.322  0.257  12.047  19.307  41.281 | 2.174  2.661  0.129  6.024  6.436 | 0.338  0.414  0.021  0.936 | 10.533  12.893  0.623  **29.183**  46.77  100 |

**TABLE 5.** ANOVA analysis of S/N ratios of bead width

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Variable** | **Average level** | | | **DOF** | **SS** | **MS** | **F** | **Contribution (%)** |
| **1** | **2** | **3** |
| A  B  C  D  Error  Total | 17.174  18.081  **19.062**  19.168 | **19.77**  18.602  18.755  **19.52** | 19.758  **20.018**  18.884  18.014 | 2  2  2  2  3  11 | 40.25  18.086  0.428  11.171  34.482  104.417 | 20.125  9.043  0.214  5.586  11.494 | 1.751  0.787  0.019  0.486 | **38.548**  17.321  0.41  10.699  33.024  100 |

## **5.4 Optimization for Convexity index**

From the ANOVA response table of S/N ratios of convexity shown in Table 6, factor combination A2B3C1D2 is recommended. Also it is observed that the contribution of factor A to the convexity index is the largest (29.522%) followed by factor D (18.47%). Thus, wire feed rate is the most important factor followed by frequency as far as convexity index is concerned. We can conclude that a study of all the four ANOVAs reveals the optimal factor/level combination, or the most significant factor. It reveals that one quality is generally different from another.

1. **Multi characteristic optimization by Grey Relational Analysis method**

Grey relational analysis is performed to obtain the optimal level/factor combination of DP-GMAW process,

when a multi-response problem is considered. In a multi-response case, grey relational grade is employed to transform the four correlated responses to a single response called comprehensive output measure. The following are the steps followed for performing grey relational analysis.

**TABLE 6.** ANOVA analysis of S/N ratios of convexity index

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Variable** | **Average level** | | | **DOF** | **SS** | **MS** | **F** | **Contribution (%)** |
| **1** | **2** | **3** |
| A  B  C  D  Error  Total | 6.547  8.223  **8.556**  7.958 | **9.836**  7.899  8.406  **9.927** | 8.875  **9.136**  8.296  7.374 | 2  2  2  2  3  11 | 51.482  7.407  0.307  32.208  82.983  174.387 | 25.741  3.704  0.154  16.104  27.661 | 0.931  0.134  0.006  0.583 | **29.522**  4.248  0.177  18.47  47.586  100 |

**6.1 Normalizing Signal to Noise (S/N) ratio**

In this step, pre-processing of the data was first performed for normalizing the raw data for analysis. Signal to noise ratio responses obtained in table 4.16 are used for finding normalized signal to noise ratio and are tabulated in table 4.17

= (higher the better)

= (lower the better)

**6.2 Calculating Grey Relational Coefficient and Grey Relational Grade**

The grey relational coefficient is calculated to express the relationship between the ideal (best) and actual normalized experimental results. Before that, the deviation sequence for the reference and comparability sequence were found out.

**Deviation Sequences: Grey Relational Coefficient:**

 

Where,  is the deviation sequence of the reference sequences

is distinguishing or identified coefficient. The value of is the smaller and the distinguished ability is larger. = 0.5 is generally used. Grey Relational Grade was determined by averaging the Grey Relational Coefficient corresponding to each performance characteristic. The overall performance characteristic of the multiple response process depends on the calculated Grey Relational Grade. The Grey Relational Grade , can be expressed as

**6.3 Determining of the optimal factors**

From the graph shown in figure3, experiment No.26 has the highest grade to obtain the best multi-response characteristics of minimum bead height, maximum depth of penetration, maximum bead width and minimum convexity index. Thus the multi response optimal parameters obtained at A3B3C1D2 represents the best multi-performance characteristics amongst the 27 experimental run conditions. In addition, the mean response which refers to the average value of the grey relational grades on each parameter at different levels are calculated and have been shown in Table 7. The optimal welding parameters are the wire feed rate at level 2 (5.5 m/min), wire feed rate/travel speed at level 3 (30), amplitude at level 1 (0.4 Amp) and frequency at level 2 (2 Hz) i.e. A2B3C1D2 are the most favorable welding parameters for double-pulsed GMAW of AA5083 H111.

## Figure 3. Grey relational grade for the response variables

Table 7 Response table for grey relational grades Table 8 - Improvements in grey relational

grade with optimized DP-GMAWelding parameters

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Para  meter | Level 1 | Level 2 | Level 3 | Max-Min |
| A | 0.500419 | **0.575417** | 0.5432 | 0.074998 |
| B | 0.544292 | 0.519077 | **0.555666** | 0.036589 |
| C | **0.561398** | 0.551482 | 0.506156 | 0.055242 |
| D | 0.527976 | **0.597812** | 0.493248 | 0.104564 |

|  |  |  |
| --- | --- | --- |
| Condition description | 26th Expt. Result | Grey theory prediction results |
| Levels | A3B2C1D2 | A2B3C1D2 |
| Penetration depth | 5.67 | 4.7 |
| Bead height | 3.39 | 2.92 |
| Bead width | 13.24 | 14.11 |
| Convexity index | 0.257 | 0.207 |
| Grey relational grade | 0.7989 | 0.8656 |
| Improvement in grey relational grade=0.067 | | |

**6.4 Confirmation Experiments**

Confirmation experiments are conducted and the observed output characteristics obtained at the optimal setting of the process parameters are compared with the characteristic values obtained at the initial setting of the process parameters. It can be observed from Table 8, that there is significant improvement in all the performance characteristics at the specified optimal levels of welding parameters for double-pulsed GMAW of AA5083 H111parameters obtained by application of Taguchi grey relational analysis (TGRA).

1. **Conclusions**

In this study, to optimize the DP-GMAW of AA5083 H111 the Taguchi is used with grey relational analysis approach. In contradiction to full factorial design, the welding parameters optimization is activated through experiments with minimum number of trials using Fractional factorial design of experiments. The results are as follows:

(1) The factor/level combination A3B3C1D2 for depth of penetration, A2B1C2D2 for reinforcement, A2B3C1D2 for bead width and A2B3C1D2 for convexity index are the suggested optimum parameters, for DP-GMAW when all four responses are considered independently.

(2) In the multi-response problem, all the four depth of penetration, reinforcement, bead width and convexity index are simultaneously considered and A2B3C1D2 is the suggested optimum condition with reference to the Taguchi-GRA approach.

(3) It can be seen that middle level of wire feed rate (5.5 mm) and frequency (2 Hz), lower level of amplitude (0.4 amp) and higher level of wire feed rate/travel speed (30) yield the optimal result.

(4) Both single response and multi-response optimization analysis prove that middle level of frequency (D2) is favorable in increasing depth of penetration, bead width and reducing reinforcement, convexity index compared to higher (D3) and lower (D1) levels of frequency.

This present paper familiarizes the use of fractional factorial method with Grey relational analysis to the Taguchi method in optimization of the DP-GMAW with multiple performance characteristics and a four performance characteristics namely depth of penetration, reinforcement, bead width and convexity index can be enhanced. Hence, it can be thus concluded that the optimization methodology extended in this study is useful in enriching the multi performance characteristics in DP-GMAW.

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