Optimization of mechanical properties of ER-4043 specimens fabricated by WAAM process through Grey Relational Analysis

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Abstract

Wire Arc Additive Manufacturing (WAAM) is the process of used to fabricate material samples by deposition of material which is in wire form at high temperature. ER-4043 Aluminium wire is deposited on substrate steel plate and predicted the properties by following Taguchi orthogonal Array. It reduces the complexity occurs by conventional process in fabricating a large size, complex shape components.

In the present investigation, the optimized multi-responses by Orthogonal Array (OA) which are strength and hardness values obtained during WAAM process for nine samples are evaluated to presage the influence of process parameters through Grey Relational Analysis (GRA) followed by Taguchi method.

Keywords: ES-4043 Aluminium, WAAM Process, GRA, Orthogonal Array, Taguchi Method.

1. Introduction

1.1. Additive Manufacturing

Manufacturing process plays a predominant role in fabrication of components in all fields. Especially, Additive Manufacturing (AM) plays a vital role which fabricates the components in an easy method which reduces the involvement of manpower, vast usage of tools etc.

AM technologies differ in their production methods based on the material to be processed, the manner in which individual layers are created, and the methods by which layers are fused together[1].
1.2 Wire and Arc Additive Manufacturing
WAAM process is preferred in modern industries like aerospace with its ability to fabricate a near net shape and fully dense components. In WAAM process, the wire acts as feed stock melted by electric energy as the heat source and deposits the required 3-D object. It has an advantage of utilization of material at full extent and reduces the cost of production.

![Figure 1.1 Schematic representation of WAAM Setup](image)

Wire and Arc Additive Manufacturing (WAAM) comes under DED technique has unique efficiency and cost advantages. Hence many researchers doing lot of researches for this WAAM process and they yield successive results.

1.3 Taguchi GREY Relational Analysis
Poovalingam Muthu [2] investigated about the optimized wear parameters of dry sliding LM25 metal matrix Composites with reinforcements Silicon carbide and Copper which are fabricated using stir casting process. The wear test was done using pin on disc apparatus to find the wear rate and coefficient of friction and by using ANOVA L9-orthogonal array the number of samples are fabricated. Grey relational analysis was carried out with an objective of minimisation of wear rate and coefficient of friction of fabricated samples. The results are compared by experimentation results with GRA analysis. To study the wear mechanism during wear test SEM analysis was done.

Guofu Lian et al [3] investigated about the influence of process parameters on multi-track laser cladding using Taguchi orthogonal method and employed multi-response grey relational analysis to identify the flatness ration of coating and cladding efficiency and validated the results with experimental results, and found that the flatness ratio and cladding efficiency are closely correlated to the laser power.

Soutrik Bose and Titas Nandi [4] presented a novel optimised desirable algorithm with multi objective optimization to measure the process parameters which influences machining of hybrid titanium composite part fabricated by Laser Engineered Net Shaping (LENS) process.

G Suresh et al [5] deposited Co-Cr-W alloy specimens by LENS process by following L9 orthogonal Array and predicted the tribological, mechanical properties of specimens, and investigated about the influencing parameters of deposition of samples using Grey Relational Grade Analysis (GRGA).

K Teja et al. [6] fabricated ER-4043 MIG wire deposited samples on Aluminium substrate using Taguchi L9 Orthogonal Array and investigated about the mechanical properties by various tests like microhardness, micro-tensile test etc., Later the output responses are evaluated by Grey Rational Analysis to achieve the objectives as maximization of tensile strength and hardness of samples.

Amlana Panda et al. [7] investigated about parametric optimization of multi-response of machining hardened AISI steel 52100 with mixed ceramic insert by Grey Relational Analysis (GRA).

Kedar M Mantrala et al. [8] deposited the Co-Cr-Mo alloy specimens on steel substrate using LENS process with various combinations of process parameters like laser power, scan rate and powder feed rate using L9 orthogonal array nad further GRGA and Analysis of Variance (ANOVA) were applied to discover optimal process parameters.
Rani M G et al.[9] investigated the process parameters of wire electrical discharge machining (WEDM) in metal matrix composites, and result reveal were analysed and optimal conditions are derived using ANOVA technique.

Satyanarayana G et al. [10,11] forecast about weld pool geometry generated and temperature enhancement around the weld pool during the CFD simulation process. The results are equated by optimization technique using Taguchi method.

Sanjay Krishna et al. [12] attempted a Taguchi method and grey relational analysis on Stainless Steel 310 material with optimised process parameters in wire electrical discharge machining (WEDM) technique.

A V S Ram Prasad et al. [13] worked with unconventional machine process which is Wire Electrical Discharge Machining with various input data to predict the material removal rate and Surface roughness of titanium alloy material and multi response optimization is used along with Taguchi method to compare optimization results with experimental results.

Amit H Karwande and Seeram Srinivas Rao [14] applied Friction Stir Welding (FSW) to weld AZ31 and AZ91 magnesium alloys specimens with various process parameters by applying L9 Orthogonal Array of Taguchi method, to predict the effect of process parameters on weld zone and observed the microstructure with microscope at weld zone.

Dharmendra B V et al. [15] adopted the multi-objective optimization technique to presage the combination of process parameters of Abrasive Water Jet Machining (AWJM) in Inconel 718 material, followed by Taguchi method. Manikyam Sandeep and P Jamaleswara Kumar [16] applied a grey relational analysis and Taguchi method to get the updated material removal process parameters in Wire EDM while working on EN31 hardened steel.

The review of the literature survey revealed the application of Taguchi and Grey Relational Analysis is successful one in manufacturing whether that may be a conventional, Non-conventional or Additive Manufacturing.

Present work concentrated on application of Taguchi and Grey Relational Analysis in Wire and Arc Additive Manufacturing of ER 4043 Alloy. Multi response optimisation was performed in order to obtain better mechanical properties.

2 Experimentation
2.1 WAAM Apparatus

In this work, a CMT welding machine with a linear manipulator for WAAM, is used for fabrication of specimens according to L9 orthogonal array shown in Figure 2.1.

![Wire Arc Additive Manufacturing (WAAM) Apparatus](image)

Figure-2.1 Wire Arc Additive Manufacturing (WAAM) Apparatus

2.2 Orthogonal Array

Taguchi method optimization is used to minimize the fabrication of samples using L9 orthogonal Array. The array is shown in Table-1. The process parameters considered are gas pressure, nozzle to tip distance in mm. The selected process parameters to conduct experiment are mentioned in Table-2. Three levels of work are carried out with OA.
Table 2.1 L9 Orthogonal Array

| Experiment | A  | B  | C  |
|------------|----|----|----|
| 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  |

Table-2.2: Selected Process Parameters and their Levels

| Symbol | Parameter              | Level-1 | Level-2 | Level-3 |
|--------|------------------------|---------|---------|---------|
| A      | Gas Pressure(bar)      | 10      | 12      | 14      |
| B      | Current (Ampere)       | 55      | 60      | 65      |
| C      | Nozzle tip distance(mm)| 6       | 8       | 10      |

2.3. Sample preparation using WAAM

ER4043 Aluminium MIGwire was selected for experimentation purpose and Al6061 is taken as a substrate plate. A total of 9 samples are fabricated by using WAAM process show in Figure 2. Pure Ar was used as the gas for shielding. The metal deposition rate was kept steady at 0.75kg/hr.

![Figure-2.2 Specimens Fabricated using WAAM process](image)

After deposition of samples using WAAM process, they are separated from the substrate plate using Wire EDM. Different tests viz Ultimate Tensile Strength, Hardness were performed on the samples and the results were tabulated in the following Table 2.3.
3. Grey Relational Analysis (GRA) and its Implementation: (from Ref-7)

In prediction of results, when multiple responses are occurred or predicted, the influence and relationship between input variables and outcomes are cross checked, and when these are observed as grey indicates that those are not fair and complex in nature. This GRA analysis maintains a uncertain values as multi-responses, then these are optimized by using grey relational grade which exhibits a single response grade.

This process is done in following steps

- Step-1: To predict the Normalised Sequence (NS)
- Step-2: To find the Grey Relational Coefficient (GRC)
- Step-3: To find the Grey Relational Grade (GRG)
- Step-4: To determine the Higher Grey Relational Grade (HGRG)
- Step-5: Application of Analysis of Variance (ANOVA)
- Step-6: Improvement of Grey Relational Grade

Step-1: To find the normalised sequence of the outcome of experiment, first the data is normalised to predict the suitable value from the original value by converting the original data to compare which lies between 0 to 1. When the output response is to be minimised, then smaller -the-better feature is implemented to normalise the value to acceptable range, which is done with the following Eq-1.

\[
x_i^* (k) = \frac{\max_i X_i (k) - X_i (k)}{\max_i X_i (k) - \min_i X_i (k)}
\]

(1)

Where, \(i = 1 \) to \(m \) … (m is the number of total count of data) and \(k = 1 \) to \(n\) … (n is the total outcomes or responses)

\(X_i\) is the original data before processing the sequence

\(X_i^*\) is the sequence after processing is done

\(\max.\ X_i (k)\) indicates the maximum value of \(X_i (k)\)

\(\min.\ X_i\) is the required outcome response

Step-2: After implementation f above step, next step is to calculate the Grey Relational Coefficient (GRC, \(\xi_i (k)\)), which will obtain by using the Eq-2
\[ \xi_i(k) = \frac{\Delta \min + \xi \Delta \max}{\Delta \min(k) + \xi \Delta \max} \]  

(2)

Where, \( \Delta o_i(k) \) is deviation sequence of the main referred sequence which is equal to \( \Delta o_i(k) = ||X_0(k) - X_i(k)|| \), and \( X_0 \) is reference sequence and \( X_i \) is comparability sequence, and \( \Delta \min \) and \( \Delta \max \) are the minimum value and maximum value of \( \Delta o_i \). and \( \xi \) is the symbol indicates the grey relational coefficient which ranges from 0 to 1, but this value is generally taken as 0.5.

Step-3: Grey Relational Grade (GRG) is determined by following Eq-3.

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

Where, \( \gamma_i \) is the required grey relational grade for the \( i^{th} \) experiment, and \( n \) is number of responses, and this GRG always represents the overall representation of quality of the optimization values obtained, which is converted to Taguchi analysis and made as single response optimization.

Step-4: In this step the obtained optimized values are again processed to find the higher grey relational grade (HGRG) values which indicates the better product quality. The optimal parametric level combinations are determined.

Step-5: Application of Analysis of Variance is used to judge the obtained responses to presage the significant process parameters which effect the outcomes of the experiment. This should make the result of 95\% confidence level but this ANOVA process provides the percentage of contribution level. Later the Fisher Ratio (F-value) is calculated and depending upon the F-value the P-Value is calculated depending the obtained significance value is less than 0.05.

Step-6: The obtained value of GRG are improved by optimal combination of process parameters by using the relation mentioned in Eq-4.

\[ \hat{\gamma} = \gamma_m + \sum_{i=1}^{0} (\bar{\gamma}_i - \gamma_m) \]  

(4)

Where \( \gamma_m \) is the total mean grey relational grade, \( \bar{\gamma}_i \) is the mean grey relational grade at optimal value and 0 indicates the number if significant process parameters.

4 Results and Discussions

The results obtained after computing the analysis with MINITAB software (V16.0), the normalising sequence, GRG, GRC, ANOVA application results and % contributions are mentioned from Table-4 to Table-7.

| Expt. No | Normalising Sequence |
|----------|----------------------|
|          | Tensile Strength     | Vickers Hardness |
| 1        | 0                    | 0.6141607       |
| 2        | 0.267513655          | 0.853831875     |
| 3        | 0.903585847          | 0.799893927     |
| 4        | 0.383638091          | 0               |
| 5        | 0.490382332          | 0.159639353     |
| 6        | 0.505105676          | 0.295995757     |
| 7        | 1                    | 0.512383983     |
| 8        | 0.574922821          | 1               |
| 9        | 0.690691047          | 0.927499337     |

Table-4: Normalising sequence Values
| Expt. No | Deviation Sequence | Tensile Strength | Vickers Hardness | Tensile Strength | Vickers Hardness |
|----------|--------------------|------------------|-----------------|------------------|-----------------|
| 1        | 1                  | 0.3858393        | 0.333333333     | 0.564436        |
| 2        | 0.732486           | 0.146168125      | 0.405684008     | 0.773792        |
| 3        | 0.096414           | 0.200106073      | 0.838343619     | 0.714177        |
| 4        | 0.616362           | 1                | 0.447883429     | 0.333333        |
| 5        | 0.509618           | 0.840360647      | 0.495236975     | 0.373034        |
| 6        | 0.494894           | 0.704004243      | 0.502565939     | 0.415281        |
| 7        | 0                  | 0.487616017      | 1               | 0.50627         |
| 8        | 0.425077           | 0                | 0.540495443     | 1               |
| 9        | 0.309309           | 0.072500663      | 0.617811033     | 0.873361        |

**Table 6: Analysis of variance for GRG**

| Source             | DF  | Seq SS       | Adj SS       | Adj MS        | F    | P    |
|--------------------|-----|--------------|--------------|---------------|------|------|
| Gas pressure       | 2   | 0.162134     | 0.162134     | 0.081067      | 10.17| 0.09 |
| Current            | 2   | 0.025121     | 0.025121     | 0.012561      | 1.58 | 0.388|
| Nozzle tip distance| 2   | 0.015582     | 0.015582     | 0.007791      | 0.98 | 0.506|
| Error              | 2   | 0.015943     | 0.015943     | 0.007971      | 0.98 | 0.506|
| Total              | 8   | 0.21878      |              |               |      |      |

\[ S = 0.0892826 \quad R-Sq = 92.71\% \quad R-Sq(adj) = 70.85\% \]

**Table 7: Percentage contribution of Parameters**

| Source                | %contribution | Rank |
|-----------------------|---------------|------|
| Gas pressure          | 74%           | 1    |
| Current               | 11%           | 2    |
| Nozzle tip distance   | 7%            | 3    |
| Error                 | 7%            | -    |
| Total                 | 100%          | -    |

Based on the values tabulated the process parameters, their interactions and their effects on hardness and tensile strength were plotted and it was shown in figure 3.1
5 Conclusions:

After experimentation and by GRG analysis, the following conclusions are derived under selected process parameters,

- Gas pressure plays a crucial role which has 74% contribution in fabrication of samples compared to other parameters and occupied top rank as 1 by WAAM process.
- The process parameter, Current engaged the second rank with 11% in deposition of samples
- Nozzle tip distance occupies the least role in the process of deposition
- By ANOVA analysis, the gas pressure has Fisher ratio (F Value) as 10.17
- From the main effects plots, Fig-3.1(a), the response value of gas pressure for level-1 lies between 0.7 to 0.8.
- Similarly, the response value of current and nozzle to tip distance both with their average values lies between 0.6-0.7 at level-2.
- The average values of gas pressure at first level is approximately at 0.601, and at second level is 0.43 and at third level it raised to 0.73.
- The Gas Pressure at 10 bar, Current at 55 Amperes and Nozzle to Tip distance of 6 mm shows optimum result in deposition of samples by WAAM process.

These conclusions reveal that whenever, for ER4043 Tensile strength and Hardness are the major properties needed in for the specimens fabricated in WAAM, Gas pressure plays a vital role. Along with that current occupies a vital role. Here multi objective optimisation is done to obtain the properties like hardness and tensile strength, which are the major mechanical properties.

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