OPTIMIZATION OF MECHANICAL PROPERTIES OF WIRE ARC ADDITIVE MANUFACTURED SPECIMENS USING GREY-BASED TAGUCHI METHOD

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Abstract
In present work, the optimization of mechanical properties of specimens accumulated by Wire Arc Additive Manufacturing (WAAM) process is done using Grey-based Taguchi method. ER4043 MIG wire of 1.2mm diameter specimen material and 6061 aluminium substrate are selected for analysis. Initially, the specimens are fabricated by using Cold Metal Transfer (CMT) welding machine with a linear manipulator by changing process parameters like Gas pressure, Current, Nozzle to tip distance by following L9 Orthogonal Array (OA). Mechanical tests are conducted on specimens like, Micro tensile test and Micro Hardness test. From the output responses (test data) Grey-based Taguchi analyses and Grey based ANOVA test is performed. Finally, Maximization of Ultimate tensile strength (UTS) and Hardness of the WAAM specimens by Grey based Taguchi analysis and identified the percentage of contribution of each process parameters by using Grey based ANOVA.

Keywords: Wire Arc Additive Manufacturing (WAAM), Orthogonal Array (OA), Grey based Taguchi method, ANOVA (Analysis of Variance)

INTRODUCTION
In the past few years, Wire Arc Additive Manufacturing (WAAM) technology got attraction of manufacturing industries, due to the capability of manufacturing complex and large metal components with a high deposition rate with approximately 100% material utilization. WAAM is a process of deposition of molten metal on a layer by layer form to achieve the final object, and this development is carried out with an electric arc as a heat source to melt the metal wire. Due to increasing demand in today’s market to develop new designs with large productivity with less material waste and low equipment cost, WAAM for dissimilar alloys is one of the trending topics. WAAM components of dissimilar alloys are mostly used in special applications.

Karmuhilan et al. [1] done their research on Artificial Neural Network (ANN) in the WAAM process and introduced the ANN for bead geometry prediction for WAAM. Mainly focused on the bead geometry by selecting appropriate parameters for the welding process and also developed a reverse model for selecting the welding parameters based on the user-specified geometry. The results show that, in the WAAM method, the significant parameters with variable welding and the ANN model predict welding process parameters for specified bead geometry. Michel et al. [2] done their research and introduced a new path planning technique for WAAM called Modular Path Planning (MPP), which can help to fabricate a large variety of complex geometries. Knezovic et al. [3,4] studied the WAAM process for depositing material in a layer by layer manner like Additive Manufacturing (AM) technique, a similar technique like LENS, a Laser Engineered Net Shaping process, used to fabricate a fully dense metal parts and large near-net-shape products, especially in modern industries, like aerospace and automobile etc. They concluded that by introducing some improvements, WAAM could replace conventional manufacturing processes, like casting and forging, in particular applications. Ganzi Suresh et al. [5] reviewed about the role of medical implants fabricated by Additive manufacturing technique as biomaterials which shows the similar features like fully dense and near net shaped components. Like as WAAM process. Chen et al. [6] experimented to study the stability of aluminum alloy formed by using the WAAM-CMT system through different models. The forming system WAAM based on CMT is a high build rate system to manufacture a near-net-shape components by layer by layer. Different shapes are printed via arc forming method to examine the arc stability for 3D metal additive formation, and to investigate the formation consistency of metal parts and the accuracy of forming measurements in different welding modes under various welding parameters. Lu et al. [7] designed a cost-effective metal WAAM system and high production performance. The three aspects like formability, microstructure, and mechanical properties are evaluated, by optical microscopy (OM), SEM, Microhardness, and Micro tensile test. By using a compulsory cooling system, the formability of metal parts fabricated by open-source WAAM system improved with better-quality; whereas microstructures exhibited as granular structure and the better mechanical property was observed in the specimen along weld bead direction. P Suresh Babu et al. [8,9] conducted mechanical, microstructural and tribological analysis to predict the corrosion rate, microhardness value and microstructure of stir casted magnesium alloy added with different weight percentages of calcium silicate under specified test conditions. The results reveal that magnesium alloy added with 4% calcium silicate shows less corrosion rate and lower wear rate compared to other specimens. Kumar et al. [10] performed experimental studies on the WAAM process effect on Inconel 825 material. Using the Taguchi method mainly based on the effect of weld parameters on the deposited layer width by additive manufacturing. MIG welding and Inconel 825 are used for this investigation. Parameters like waviness, weld cracks, porosity, and discontinuity of weld bead of a surface mostly...
reduced by the selection of materials otherwise it leads to the irregular shape formation during the manufacturing process. Analyzed input parameters welding speed, wire feed speed, and voltage. Carried out several confirmation tests for the obtained optimized parameters by the linear regression model and obtained results are compared. Kohei Oyama et al. [11] conducted their work on heat source control in the Al-Mg and Al-Si alloy wire + arc+ additive manufacturing cycle. Modeling they conducted indicates that the most efficient way to reduce metrological variations is to process. Al alloys with short intervals and with appropriate heat source adjustment for each material. Gong et al. [12] conducted their analysis to detect and compare defects on Ti-6Al-4V specimens with SLM and EBD processes, and also investigated the porosity of specimens using an optical image microscope. Cunningham et al. [13] carried out their work on cost modeling and sensitivity analysis of wire and arc additive production. And results show that the substantial cost savings for two sections of the Ti-6Al-4V case study can be achieved. Y Pratapa Reddy et al. [14] predicted about the electro-chemical behavior of commercially available conventional materials like Al copper, and mild steel under the influence of selected electrolyte as media which covers Alonso et al. [15] WAAM specimens are produced as wall-like structures with Ti-6Al-4V in this research and are primarily based on the tensile strength of WAAM specimens at different locations. Also, the impact of cutting speed and chip feed morphology in WAAM specimens during drilling. Tian et al. [16] in this research mainly focuses on WAAM specimens fabricated with Ti-6Al-4V and AlSi alloy using CMT welding machine and studied the interface layer microstructure, hardness, and tensile strength. The interface layers observed between Ti and Al alloys involved as a continuous and discontinuous layer. The continuous layer was composed of Ti₅Al₄Si₁₂ and the discontinuous layer contains Ti₅(Al₃₋ₓSiox₃₋y). From this experiment observed that element Si was rich in the continuous layer. Zhou et al. [17] investigated the effect of the electric arc travel speed (TS) on the macro-morphology, microstructure, and mechanical properties. Concluded that the tensile resistance increased, the equiaxed grain size and volume fraction decreased. When the tensile strength was 350 and 250 mm/min the volume fraction reached maximum. They also measured the alloy’s micro-hardness and tensile strength which indicates that samples manufactured at a tensile strength of 350 mm/min show better-equiaxed grain and a higher overall tensile strength and yield strength than those manufactured at 250 mm/min. Yunpeng Nie et al. [18] done their macro-structure, microstructure of 4043 Al alloy parts by varying polarity of CMT welding. Mechanical properties of these structures are analyzed and found the best processing parameter which has a strong effect on the geometry, microstructures, roughness, and hardness of a WAAM specimen. Zhong et al. [19] investigated the influence of post-deposited heat treatment of the WAAM specimen on the microstructure. A special AA2050 Al-Li alloy wire was prepared and working in the manufacture of straight-walled components, based on the variable polarity GTAW process. The mechanical behaviors like hardness and tensile properties were tested. Finally concluded that the microstructures of AA2050 aluminum deposits varied with their location layers and the upper layers and bottom layers grains are oriented in fine equiaxed grains and coarse column structure respectively. Mechanical properties observe a significant enhancement after post-deposited heat treatment. Kumar et al. [20] predicted about the best process parameters by MIG preheating welding on AISI 1018 mild steel using grey-based Taguchi method. Experimental analysis of UTS and percentage of elongation was carried out, later performed ANOVA for GRG with MINITAB software. From ANOVA it was conformed that each process parameter contributes to the output responses. M Kedar Mallik and K I Narayana [21] conducted mechanical tests like impact strength and fracture analysis on LENS deposited additive manufacturing samples with Co-Cr-W alloy material with selected process parameters and concluded that the specimen shows more brittleness in impact strength. Hasani et al. [22,23,24] investigated by Grey Relational Analysis (GRA) to determine the optimum process parameters for Open-End Spinning Yarns and on Co-Cr-W alloy samples fabricated by Additive manufacturing technology by following Taguchi L9 orthogonal array, and concluded that optimization of process parameters, and the grey relational analysis plays a key role and shows a significant impact to determine multiple output characteristics.

**METHODOLOGY**

**Fabrication**

In this work, the specimens are fabricated with the help of a CMT welding machine with a linear manipulator for WAAM. It involves a linear translation manipulator with the aid of a lead screw, servomotor configuration, for a moment of base plate substrate plate in forward and backward direction. Moving to the specifics of the Device, this is the Trans Plus Synergic 4000 CMT System with Kuhlgerat FK 4000-R FC style wire feeder. 99.99 percent pure Ar is used for weld pool shielding to avoid oxidation and weld pool porosity from the surroundings.

**Base material and specimen preparation**

ER4043 Aluminium MIG wire was taken as the filler material, and Al 6061 is taken as a substrate plate. It is an important filler wire widely used to connect two separate plates of aluminum, and wire having 1.2 mm diameter has been used as filler wire. In general, it offers good fluidity and less crack sensitivity than other filler wires for aluminum. This welding wire suitable with pure Ar. It offers good seam welding, less spatter, and excellent welding properties.

| Table 1: Chemical composition of ER4043 in weight percentage |
|--------------|---|---|---|---|---|---|---|---|
| Al | Si | Fe | Cu | Mn | Mg | Zn | Ti | Others |
| Remaining | 4.5-6.0 | max 0.6 | max 0.3 | max 0.5 | max 0.5 | max 0.1 | max 0.2 | 0.05-0.2 |

| Table 2: Chemical composition of Aluminium 6061 plate in weight percentage |
|--------------|---|---|---|---|---|---|---|---|
| Al | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Others |
| Remaining | 0.4-0.8 | 0.7 | 0.15-0.4 | 0.15 | 08-1.2 | 0.04-0.35 | 0.25 | 0.15 | 0.5-0.2 |

The base plate is 80 mm wide and 12 mm thick and the length of the plate is cut into 150 mm long parts based on the length of the weld run we needed as these 9 base plates were prepared. Whereas Table 1&2 indicates the chemical composition of the substrate plate and the wire materials.
Recognition of input parameters
The input process parameters can affect the average and response variability. In the WAAM process, the specimen quality depends on the process parameter selection. These parameters mainly affect the durability of the specimen and its strength. This device consists mainly of 7 process parameters such as gas pressure, current, voltage, diameter of the wire, nozzle to tip distance, number of runs, gas flow rate. The arrangements for the selected OA, number of process parameters, and levels are L9 and selected the one with 9 experimental trials and its arrangement is shown in Table 2. Therefore, process parameters mainly affect on mechanical properties of WAAM specimens. In this research gas pressure, current and nozzle to tip distance were selected according to literature. Pure Ar was used as the gas for shielding. The metal deposition rate was kept steady at 0.75 kg/hr.

Selection of level values
Three levels of process parameters for the design of the experiment are shown in Table 3. The values of the nozzle to tip distance have been chosen based on experience and gas pressure, the current has been taken from the literature review. In this research gas pressure, current and nozzle to tip distance were selected according to literature. The L9 orthogonal array was selected with 3 levels as shown in Table 3.

| Table 3: Process parameters and their levels |
| Symbol | Process parameter | Unit | Level 1 | Level 2 | Level 3 |
|--------|-------------------|------|---------|---------|---------|
| A      | Gas pressure      | bar  | 10      | 12      | 14      |
| B      | Current           | Amps | 55      | 60      | 65      |
| C      | Nozzle distance   | mm   | 6       | 8       | 10      |

| Table 4: Experimental trails and its arrangement |
| Sample | GasPressure (MPa) | Current (Amps) | Tip distance (mm) |
|--------|-------------------|----------------|-------------------|
| 1      | 10                | 55             | 6                 |
| 2      | 10                | 60             | 8                 |
| 3      | 10                | 65             | 10                |
| 4      | 12                | 55             | 8                 |
| 5      | 12                | 60             | 10                |
| 6      | 12                | 65             | 6                 |
| 7      | 14                | 55             | 10                |
| 8      | 14                | 60             | 6                 |
| 9      | 14                | 65             | 8                 |

Experimental procedure
Recognition of response parameters
Here in this research work, UTS and Hardness were considered as parameters of response and how they affect the performance of WAAM specimens. UTS provides the strength and hardness gives the WAAM specimen hardness.
Micro Tensile testing:

Fig 2: Tensile testing Specimen as ASTM B557

To evaluate the tensile strength of ER4043 WAAM specimens, a Micro tensile testing machine used. Where the specimen was cut into the ASTM B557 standard with the help of EDM as shown in figure 2. This cutting process is divided into two directions as Horizontal and vertical as shown in the figure.

Tensile tests were performed on Micro Tensile Testing Machine to determine the quality of various specimens based on UTS. All of the tests undergo tensile loading until the specimen fails.

Micro Hardness testing

The Hardness test was conducted with Vicker's Hardness testing machine, it consists of the diamond indenter, 10X, and 40X lenses used to measure indentation length.

Fig 3: (a) Micro Vickers hardness tester, (b) macro view of indenter and specimen setup, (c) 9 specimens

GREY REGRESSION ANALYSIS

In the Taguchi method, generally, three standard signal-to-noise (S/N) ratios are used to optimize response parameters. There are three different S/N ratios, i.e. larger-the-better, nominal-the-better, and lower-the-better. The Taguchi method only able to optimize for one objective function only. Julong Deng, a Chinese researcher, is using the Taguchi method combined with grey relational analysis for optimization problems involving more than one objective. Minitab 17.0 software has been used to apply the statistical approach according to the chosen technique. The following expressions show the Grey based Taguchi analysis.

For Larger-the-better criterion, the normalized values of experimental data are calculated using the formula

\[ x_i^*(k) = \frac{x_i(k) - \text{max}_x(k)}{\text{max}_x(k) - \text{min}_x(k)} \]  

(1)

Where,

\( x_i^*(k) \) = Comparability sequence

\( k = 1, 2, ..., 9 \)

\( x_i(k) \) = Experimental data

\( x_{i0}^*(k) \) = The definition of the GRG in the grey relational analysis to show the relational degree between the nine sequences

\[ \Delta_i(k) = \left| x_{i0}^*(k) - x_i^*(k) \right| \]  

(2)

Where,

\( \Delta_i(k) \) is the deviation sequence of the reference sequence \( x_{i0}^*(k) \) and the comparability sequence is \( x_i^*(k) \),

\( \theta \) = Identification coefficient (theta) and in general it is taken as 0.5.
The grey relational coefficient for each experiment of the L9 OA can be calculated using Eq. (4).

\[ Y_i = \frac{2 - d_i(k)}{n} \]

**ANOVA for GRG**

In 1926 Ronald Fisher proposed ANOVA. It is a statistical technique that uses the mean sum of squares calculated from the data of the response and divides the variability among the parameters of the output. Calculating the percentage contribution of the individual input parameter to the response parameters is helpful. The ANOVA table was formulated using GRG values.

**RESULTS AND DISCUSSIONS**

This result shows the evaluation and optimization of the tribological properties of the WAMM specimens. Initially, the WAAM process fabricates nine specimens in 3 levels with L9 OA, as shown in the table. The final fabricated WAAM specimens have shown in figure 4.

![Fig 4: WAAM specimens fabricated based on L9 OA](image)

**Results of Micro-Tensile test**

To check the quality of different specimens based on UTS tests have been performed on micro tensile at room temperature. All the test specimens have been prepared as per the ASTM B557 standards and subjected to tensile loading until the specimen failed. The UTS of specimens has been noted in Table 3. From tensile test data, horizontal specimen-7 have higher UTS 116.19 MPa, among all vertical and horizontal tensile specimens. From this, it can be stated that specimen-7 has higher average UTS 97.36 MPa, corresponds to Gas pressure = 14 bar, current = 55 Amps, nozzle to tip distance = 10 mm, the load vs displacement graph is shown in figure 6.

![Fig 5: Tensile specimen at failure](image)

**Table 5: Experimental UTS results for horizontal and vertical specimens and average UTS**

| Sample | UTS(MPa) | Average UTS |
|--------|----------|-------------|
| 1      | 1V       | 38.98       | 55.25       |
|        | 1H       | 71.52       |             |
| 2      | 2V       | 43.82       | 66.515      |
|        | 2H       | 89.21       |             |
| 3      | 3V       | 83.21       | 93.4        |
|        | 3H       | 103.07      |             |
| 4      | 4V       | 56.6        | 71.405      |
|        | 4H       | 86.21       |             |
| 5      | 5V       | 46.48       | 75.9        |
Results of Micro-Hardness test
To check the quality of different specimens based on hardness tests that have been performed on the Vickers Hardness testing machine, all the tests have been performed Hardness testing at 200gr load for 10 sec. The hardness of specimens has been noted in Table 6. The hardness is calculated by using the Eq. (5). And also the diamond indentation after loading, the microscopic view at 40X as shown in figure 6.

\[
\text{Vickers hardness} = 1854.4 \frac{P}{d^2} \tag{5}
\]

Where,
\( P = \) test load (gf)
\( d = \) average diagonal length (μm)

![Diamond indentation view with a 40X microscope.](image)

Table 6: Experimental results for UTS and Hardness as per Taguchi L₉ OA

| Sample | Gas Pressure | Current | Nozzle to tip distance | UTS (MPa) | Vickers Hardness |
|--------|--------------|---------|------------------------|-----------|------------------|
| 1      | 10           | 55      | 6                      | 55.25     | 1629.9           |
| 2      | 10           | 60      | 8                      | 66.515    | 2081.8           |
| 3      | 10           | 65      | 10                     | 93.4      | 1980.1           |
| 4      | 12           | 55      | 8                      | 71.405    | 471.9            |
| 5      | 12           | 60      | 10                     | 75.9      | 772.9            |
| 6      | 12           | 65      | 6                      | 76.52     | 1030             |
| 7      | 14           | 55      | 10                     | 97.36     | 1438             |
| 8      | 14           | 60      | 6                      | 79.46     | 2357.4           |
| 9      | 14           | 65      | 8                      | 84.335    | 2220.7           |
Grey based Taguchi analysis
Initially, the original sequence is normalized from Equation (1) and tabulated in Table 7. A detailed explanation of the normalized series is shown below,

For UTS, \( x_1^* = \frac{97.36 - 55.25}{97.36} = 1.000 \)

For Hardness, \( x_1^* = \frac{2357.4 - 1629.9}{2357.4} = 0.386 \)

Table 7: Normalized values of UTS and Hardness

| UTS   | Hardness |
|-------|----------|
| 0.000 | 0.614    |
| 0.268 | 0.854    |
| 0.906 | 0.800    |
| 0.384 | 0.000    |
| 0.490 | 0.160    |
| 0.505 | 0.296    |
| 1.000 | 0.512    |
| 0.575 | 1.000    |
| 0.691 | 0.927    |

Table 8. is the sequence of each performance characteristics after pre-processing. Further, the derivative sequence is evaluated from Equation (2) and tabulated in Table 8. A detailed explanation of the evaluation of the derivative sequence is given below.

For UTS, \( \Delta_u(1) = |1 - 0| = 1 \)

For Hardness, \( \Delta_u(1) = |1 - 0.614| = 0.386 \)

Table 8: Derivative sequence of UTS and Hardness

| UTS   | Hardness |
|-------|----------|
| 1.000 | 0.386    |
| 0.732 | 0.146    |
| 0.094 | 0.200    |
| 0.616 | 1.000    |
| 0.510 | 0.840    |
| 0.495 | 0.704    |
| 0.000 | 0.488    |
| 0.425 | 0.000    |
| 0.309 | 0.073    |
After the derivation sequence evaluation, Grey regression coefficients are evaluated by using the Eq. (3) and tabulated in Table 9. A detailed explanation of the process of evaluation of grey regression coefficients are shown below.

For UTS, \( \xi_1(k) = \frac{0.4 + 0.5(1)}{1 + 0.5(5)} = 0.333 \)

For Hardness, \( \xi_2(k) = \frac{0.4 + 0.5(1)}{0.8 + 0.5(5)} = 0.564 \)

After the Grey regression coefficients evaluated Grey relational Grade is obtained from Equation (4) and tabulated in Table 9. And is given from maximum value to the minimum value.

\[
Y_1 = \frac{0.333 + 0.564}{2} = 0.449
\]

### Table 9: Grey regression coefficients and GRG

| Grey relational coefficients | Grey relational grade | Rank |
|-----------------------------|-----------------------|------|
| UTS \( \xi_1(1) \)          | Hardness \( \xi_2(2) \) | \( Y_1 = \frac{\xi_1(1) + \xi_2(2)}{2} \) |
| 0.333                       | 0.564                 | 0.449 | 7 |
| 0.406                       | 0.774                 | 0.590 | 5 |
| 0.842                       | 0.714                 | 0.778 | 1 |
| 0.448                       | 0.333                 | 0.391 | 9 |
| 0.495                       | 0.373                 | 0.434 | 8 |
| 0.503                       | 0.415                 | 0.459 | 6 |
| 1.000                       | 0.506                 | 0.753 | 3 |
| 0.540                       | 1.000                 | 0.770 | 2 |
| 0.618                       | 0.873                 | 0.746 | 4 |

### Table 10: Response table for GRG values

| Symbol | Process parameters | Level-1 | Level-2 | Level-3 | Delta | Rank |
|--------|--------------------|---------|---------|---------|-------|------|
| A      | Gas pressure       | 0.606   | 0.428   | 0.756*  | 0.328 | 1    |
| B      | Current            | 0.531   | 0.598   | 0.661*  | 0.130 | 2    |
| C      | Nozzle to tip distance | 0.559   | 0.575   | 0.655*  | 0.096 | 3    |

Total mean values of GRG \( Y_{m} = 0.597 \), *Levels for optimal GRG

The values of S/N ratios corresponding to GRGs have been computed using Eq. (4) and values are shown in Table 9. From GRG values, mean GRG values have been calculated for significant parameters as shown in Table 10. The S/N ratio main effects plot for mean GRG is shown in Fig. 8. A larger S/N ratio means better quality characteristics, no matter what quality characteristics are selected.

### Table 11: S/N ratios corresponding to GRGs

| A   | B  | C  | UTS | Hardness | SNR1 | MEAN1 |
|-----|----|----|-----|---------|------|-------|
| 0.493 | 0.564 | 0.565 | 55.25 | 294.7 | 37.7069 | 174.97 |
| 0.493 | 0.614 | 0.541 | 66.515 | 1704.8 | 39.4621 | 885.66 |
| 0.493 | 0.621 | 0.693 | 93.4 | 1318.2 | 42.3955 | 705.8 |
| 0.566 | 0.564 | 0.541 | 71.405 | 1811.3 | 42.7678 | 941.35 |
| 0.566 | 0.614 | 0.693 | 75.9 | 2033.8 | 40.609 | 1047 |
| 0.566 | 0.621 | 0.565 | 76.52 | 2073.8 | 40.6797 | 1055.16 |
| 0.739 | 0.564 | 0.693 | 97.36 | 2013.2 | 42.7678 | 1055.28 |
| 0.739 | 0.614 | 0.565 | 79.46 | 2572.5 | 41.0091 | 1325.98 |
| 0.739 | 0.621 | 0.541 | 84.335 | 1832.5 | 41.5213 | 958.42 |
Fig 8: Main effect plot for S/N ratios

Hence, the optimal combination of process parameters corresponds to the combination having the largest S/N ratio. From the analysis of the S/N ratio, A3B1C3 is the optimum combination of parameters i.e. Gas pressure = 14 bar, current = 55 Amps, and Tip distance = 10mm.

ANOVA for GRG

Table 12: ANOVA for GRG and percentage of contribution of each parameter

| Source                  | DF | Adj SS  | Contribution | Adj MS   | F-Value | P-Value |
|-------------------------|----|---------|--------------|----------|---------|---------|
| Gas pressure            | 2  | 0.16216 | 73.91%       | 0.081082 | 10.07   | 0.090   |
| Current                 | 2  | 0.02534 | 11.55%       | 0.012668 | 1.57    | 0.389   |
| Nozzle to tip distance  | 2  | 0.01578 | 7.19%        | 0.007889 | 0.98    | 0.505   |
| Error                   | 2  | 0.01611 | 7.34%        | 0.008054 |         |         |
| Total                   | 8  | 0.21939 | 100%         |          |         |         |

From the Table-12[ANOVA for GRG], it is observed that Gas Pressure is the dominant factor on the response variable with a contribution of 73.91% followed by Current and Nozzle to tipdistance.

Table 13: Model summary

| S          | R-Sq  | R-Sq(adj) | R-Sq(pred) |
|------------|-------|-----------|------------|
| 0.0897459  | 92.66%| 70.63%    | 0.00%      |

The value of R-Sq indicates 92.66% of the variation in response. S indicates the standard deviation between fitted value and data values.

By conducting the experiments using the L9 Taguchi technique, the DOF can be minimized, robustness increases with the minimization of experiments. For the values of the S/N ratio, larger is better property is best to minimize the response. The statistical analysis is conducted for WAAM specimens as mentioned above.

CONCLUSIONS

Specimens are made by using the WAAM technique. And UTS and hardness properties of the specimens are evaluated by using an experiment. Further, optimization is done by using the grey-based Taguchi method. The following key points are drawn from this work.

i. From tensile test data, observe that UTS of the WAAM specimen in a vertical direction (along deposition direction) is less when compared to the horizontal direction (along with weld bead).

ii. Multi-response optimization by grey-based Taguchi method provided A3-B3-C3 as the optimal combination of parameters for the responses considered and easy understanding from main effect plot for S/N ratios shown in figure 6, i.e. Gas pressure = 14 bar, current = 65 Amps and nozzle to tip distance = 10 mm. Then UTS at optimal condition is 93.4 MPa, and Hardness at optimal condition is 1980.1 VH.

iii. Out of Gas pressure, current and Nozzle to tip distance, Nozzle to tip distance is the most influential parameter affecting the tensile properties of WAAM specimens followed by Gas pressure and current. And Current is the most influential parameter affecting the Hardness properties of WAAM specimens followed by Gas pressure and Nozzle to tip distance.

iv. GRG based ANOVA has been done with the help of MINITAB-17.0 software and also mentioned the percentage of contribution of each process parameter.

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