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Optimisation of the weld bead geometry in gas tungsten arc welding of AISI 904 L super austenitic stainless steel by TOPSIS method

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ABSTRACT:

Gas Tungsten arc welding (GTAW) process is an arc welding process which uses a non-consumable tungsten electrode to produce the weld. Selection of the levels of the input parameters plays a very significant role in determining the quality of a weld joint. AISI 904 L Super austenitic stainless steels are preferred in many applications as they are relatively cheaper than austenitic stainless steel. Super austenitic stainless steels (SASS) consist of a fully austenitic structure in the solution-quenched condition. This works mainly focused on the Gas Tungsten arc welding (GTAW) parameters optimization of AISI 904 L super austenitic stainless steel joints using Technique for Order Preference by Similarity to Ideal Solution Method (TOPSIS). Bead on plate GTA welding was performed based on taguchi L9 orthogonal array. The input process parameters considered for this work were current, voltage, travel speed and shielding gas flow rate. The quality of the weld was analysed by measuring the bead width, depth of penetration and hardness of the weld. Multi-response characteristics were optimised using TOPSIS. Consequently, the TOPSIS method was found to be promising technique to obtain the optimum conditions for such studies. Moreover, the experimental results obtained confirm the adequacy and effectiveness of this approach.

Keywords: super austenitic stainless steel; weld bead profile; weld hardness; TOPSIS.

1. Introduction:

Super austenitic stainless steel (AISI 904 L) is a highly alloyed austenitic low carbon stainless steel having good weldability. Due to its high molybdenum content and specially designed welding consumables with low impurity level, hot crack formation during welding can be avoided despite the fully austenitic filler metal. Super austenitic stainless steel (AISI 904 L) is primarily characterized by its excellent ductility, even at low temperatures. Ferrite free, fully austenitic stainless steel with high nitrogen content has very good impact strength and is therefore very suitable for cryogenic applications. Gas tungsten arc welding process provides greater control over other welding processes. It provides higher quality of welds in a wide variety of metal and alloys. Therefore, it is most commonly used to join stainless steel and other ferrous metals.

The weld bead geometry plays an important role in determining the mechanical properties of the welded joints. Therefore, the selection of the welding process parameters is very essential for obtaining optimal weld bead geometry [1-3]. The main challenge for the manufacturer is how to choose the process input parameters that would produce an excellent weld joint. Conventionally, defining the weld input parameters for newly welded products with the required specifications is a time consuming trial involving error development effort and the skill of the welding engineer or welding machine operator in choosing the right weld input parameters. Then the weld is inspected to determine whether it meets the specification or not. Eventually the chosen parameters would produce a welded joint close to the required specification. Also, what are often not considered, or achieved are optimized welding parameters combinations. In other words, there are many other alternative ideal welding parameter combinations that can be used if they could be determined. To predict the welding parameters accurately without consuming time, materials and labor effort, various optimization methods are available. In the last two decades, the use of design of experiment (DOE) has grown rapidly and been adapted for many applications in different areas. Design of experiments (DOEs) and statistical techniques are widely used to optimize process parameters. Basically, the classical process parameter design is complex and not easy to use. This is particularly true when the number of the process parameters increases, the number of experiments that are to be carried out also increases. To solve this task, Taguchi method with a special design of orthogonal arrays is used to study the entire process parameter with equal level with a small number of experiments only [4].

Sathiya et al. [5] in their work used Artificial neural network to predict the weld bead geometry such as depth of penetration (DP), bead width (BW) and tensile strength (TS) of the laser welded butt joints of AISI 904L super austenitic stainless steel and it was observed that the results obtained from this neural network with several different configurations are then compared to find the one that yields the best performance [5]. Juang et al. [6] explored the back-and counter-propagation networks to associate the process parameters with the features of the bead geometry, and concluded that the counter-propagation network has better learning ability for the tungsten inert gas (TIG) welding process than the back propagation network. Juang and Tarng

[7] adopted a modified Taguchi method to analyze the effect of each TIG welding process parameters such as gas flow rate, arc gap, welding current and welding speed on the weld pool geometry i.e. front height, back height, front width, back width and found an optimal combination of the process parameters associated with the optimal weld pool geometry. The base metal was used as AISI 304 stainless steel plates with a thickness of 1.5 mm. Experimental results showed that the front height, front width, back height, back width of the weld pool in the TIG welding of S304 stainless steel were greatly improved by using this approach. Dutta and prathihar [8] used conventional regression analysis and neural network to find out input-output relationships for TIG welding process. For that purpose one thousand training data for neural networks were created at random, by varying the input variables within their respective ranges and the responses were calculated for each combination of input variables by using the response equations. It was concluded that the neural network based approaches could yield predictions that were more adaptive in nature compared to those of the more conventional regression analysis approach. The authors also concluded that the Genetic Algorithm-Neural Network was found to perform better in most of the test cases. Kumar et al. [9] successfully investigated the enhancement of mechanical properties and effective optimization of pulsed GTAW process parameters on aluminum alloy 6061 using sinusoidal AC wave with argon plus helium gas mixtures. Modified Taguchi Method (MTM) was employed to formulate experimental layout and to study effects of process parameter optimization on mechanical properties of the weld joints. Microstructural characterization of weld joint was carried out to understand the structural property correlation with process parameters.

In most studies, authors have used grey relational techniques for optimizing the process parameters in welding processes. But the usage of TOPSIS in predicting the optimized welding parameters is very much limited. Thus, in this work TOPSIS is employed for determining the optimized parameter combination. Technique for Order Preference by Similarity to Ideal Solution Method (TOPSIS) is one of the Multi Criteria Decision Making Method (MCDM) which is used to solve the type of decision making problem. This method is based on the concept that the chosen alternative should have the shortest euclidean distance from the ideal solution, and the farthest from the negative ideal solution. The ideal solution is a hypothetical solution for which all attribute values correspond to the maximum attribute values in the database comprising the satisfying solutions; the negative ideal solution is the hypothetical solution for which all attribute values correspond to the minimum attribute values in the database. TOPSIS thus gives a solution that is not only closest to the hypothetically best, that is also the farthest from the hypothetically worst [10]. Hwang and Yoon developed TOPSIS to assess the alternatives before multiple attribute decision making. TOPSIS considers simultaneously the distance to the ideal solution and negative ideal solution regarding each alternative and also selects the most relative closeness to the ideal solution as the best alternative [11]. Generally MCDM was used to solve problem involving selection from among a finite number of alternatives. For a decision making problem among the various alternatives TOPSIS is one of the higher potential tool [12].TOPSIS is a decision making technique. It is a goal based approach for finding the alternative that is closest to the ideal solution. In this method, options are graded based on ideal solution similarity. If an option is more similar to an ideal solution, it has a higher grade [13].

Based on the above literature, the present mainly focused on bead on plate GTA welding of Super austenitic stainless steel with different combinations of welding current, voltage, travel speed and shielding gas flow rate on the weld bead geometry i.e. bead width, depth of penetration and weld microhardness and then to determine optimal combination of the process parameters associated with the optimal weld bead geometry.

2. Experimental Procedures:

The welding trials were carried out on a 6 mm thick sheet of AISI 904L super austenitic stainless steel. The chemical composition of the base material is presented in Table 1.

Table 1 Base material chemical composition

Material (%)	Si	Mn	P	S	Cr	Ni	Mo	C	Cu
Base Material	0.369	1.5	0.017	0.005	19.923	25.418	4.113	0.017	1.59

Bead on plate welding trials were conducted on 100 X 50 X 6 mm sheets. Joints prior to welding surfaces were cleaned with wire brush followed by acetone swabbing. Bead on plate welding was carried out using electrode negative polarity with a 2% thoriated tungsten electrode of 2.4 mm diameter. GTA welding was carried out on these plates using a fixture to hold the parts in proper alignment. Experiment was carried out based on L9 taguchi design. The welding parameters and their levels are shown in Table 2.

Table 2 welding parameters and their levels

Welding parameters	Notations	Level 1	Level 2	Level 3
Current (Amps)	A	150	170	190
Voltage (Volts)	B	15	17	19
Travel speed (mm/min)	C	50	60	70
Gas flow rate (lpm)	D	13	15	17

The experimental details with the measured bead width, depth of penetration and hardness are presented in Table. 3. Argon shielding gas was used to protect the weld from oxidation. The purity of argon gas was 99.9 %.

Table. 3 Experimental details with measured output parameters

Exp.No.	Current (A)	Voltage (V)	Travelling speed (mm/min)	gas flow (lpm)	Depth of Penetration (mm)	Bead Width (mm)	Hardness (HV)
1	150	15	50	13	2.42	4.43	198
2	150	17	60	15	2.08	4.99	191
3	150	19	70	17	2.67	4.78	187
4	170	15	60	17	2.74	5.44	212
5	170	17	70	13	2.65	5.17	202
6	170	19	50	15	2.83	5.54	208
7	190	15	70	15	3.31	5.12	210
8	190	17	50	17	3.23	5.23	223
9	190	19	60	13	3.18	5.34	231

The bead-on-plate welds were processed and the photographic views of the weld sample are presented in Figure 1.

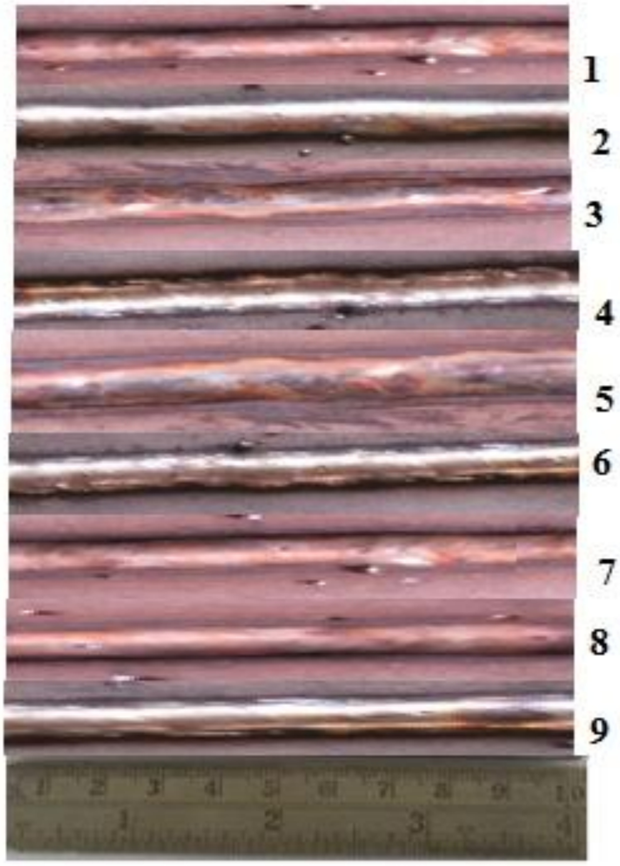
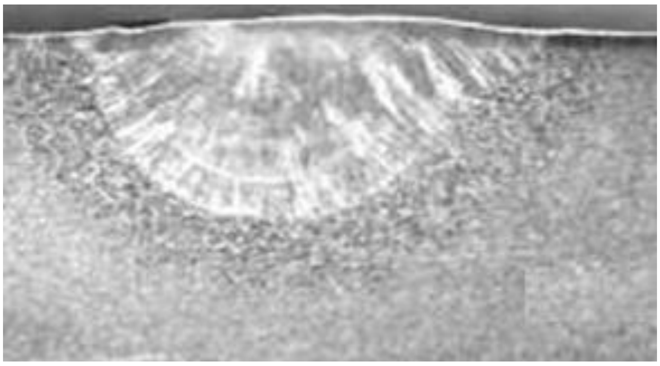
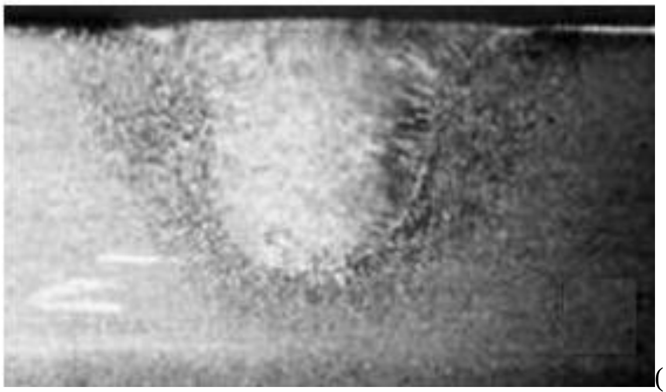


Figure 1 Photographicview of bead on plateGTAweld

A smooth bead finish as observed from the top view. Using optical microscopy, the bead profiles were measured and their values are presented in Table 2. Weld profiles were obtained by sectioning and polishing with suitable abrasive and diamond paste. Weld samples were etched with 10% oxalic acid an electrolytic to state and increase the contrast of the fusion zone with the base metal. Typical bead profiles are presented in Figure 2.



(a) Experiment No. 4



(b) Experiment No. 9

Figure 2. Typical bead Profiles

Micro-hardness surveys were carried out using a Zwick Vickers hardness tester at 500 grams load for 10 s. The microhardness tests were performed on a transverse section of the weld bead center.

3.0 RESULTS AND DISCUSSIONS:

3.1. TOPSIS

Step 1: First step in TOPSIS method is the normalization of performance of different criterion.

This step provide path for comparing different criterion by converting various attributes dimension into non dimensional attribute.

Normalize scores or data as follows:

$R_{ij} = x_{ij}/ (\Sigma x^2_{ij})$ for i = 1… m; j = 1… n

Normalized Matrix

$$R_{9*3} = \left| \begin{matrix} 0.027359 & 0.027664 & 0.03378 \\ 0.020211 & 0.0351 & 0.031434 \\ 0.033304 & 0.0322208 & 0.030131 \\ 0.035073 & 0.041716 & 0.038726 \\ 0.032807 & 0.037678 & 0.035159 \\ 0.037415 & 0.043263 & 0.037278 \\ 0.051183 & 0.036952 & 0.037999 \\ 0.048739 & 0.038557 & 0.042849 \\ 0.047242 & 0.040196 & 0.045978 \end{matrix} \right|$$

STEP 2: Allocating weights for the entire criterion which are considered for optimization. The weights considered for this research were: depth of penetration=0.33, bead width=0.33, hardness=0.33. The sum of weight should be equal to one.

STEP 3: Construct the weighted normalized decision matrix.
Suppose we have weights for each criteria w_j for j = 1…n.
On multiplying each column of normalized decision matrix by its respective weight.the element obtained is:
$V_{ij} = W_j R_{ij}$

Weighted normalized decision matrix

$$V_{9*3}=\begin{vmatrix} 0.027359 & 0.027664 & 0.03378 \\ 0.020211 & 0.0351 & 0.031434 \\ 0.033304 & 0.032208 & 0.030131 \\ 0.035073 & 0.041716 & 0.038726 \\ 0.032807 & 0.037678 & 0.035159 \\ 0.037415 & 0.043263 & 0.037278 \\ 0.051183 & 0.036952 & 0.037999 \\ 0.048739 & 0.038557 & 0.042849 \\ 0.047242 & 0.040196 & 0.045978 \end{vmatrix}$$

STEP 4: The next step is determination of ideal and negative ideal solution
Ideal solution.
$A^+ = \{ V_1^+, \ldots, V_n^+ \}$, where
$V_j^+ = \{ \max (V_{ij}) \text{ if } j \in J \, ; \min (V_{ij}) \text{ if } j \in J' \}$
Negative Ideal solution.
$A^- = \{ V_1^-, \ldots, V_n^- \}$, where $V^- = \{ \min (V_{ij}) \text{ if } j \in J \, ; \max (V_{ij}) \text{ if } j \in J' \}$
$V^+ = 0.051183$ $V^+ = 0.027664$ $V^+ = 0.045978$
$V^- = 0.020211$ $V^- = 0.043263$ $V^- = 0.030131$

STEP 5: Separation measure determination is the fifth step in TOPSIS method. The value obtained is given below in Table 4

The separation from the ideal alternative is:
$S_i^+ = [\Sigma (V_j^+ - V_{ij})^2]^{½}$ i = 1, …, m
Similarly, the separation from the negative ideal alternative is:
$S_i^- = [\Sigma (V_j' - V_{ij})^2]^{½}$ i = 1, …, m

Table 4 Separation Measure for all the experimental run

Experiment no	S^+	S^-
1	0.026765	0.017543
2	0.035016	0.008267
3	0.02432	0.017136
4	0.022574	0.017238
5	0.023559	0.014667
6	0.022552	0.018629
7	0.012246	0.032573
8	0.011595	0.031587
9	0.013138	0.031483

Step 6: The relative closeness of a particular alternative are calculated and presented in Table 5.
$P_i = S_i^- / (S_i^+ + S_i^-)$, $0 < P_i < 1$

Select the option with P_i closest to 1

Table 5. Relative closeness value

Symbol	Input Weldiing parameter current	1	2	3	Optimum level	Max-Min	Rank
A	Current	0.3334	0.423	0.7212	3	0.3878	1
B	voltage	0.5185	0.4353	0.527	3	0.0883	2
C	Travel speed	0.5265	0.4431	0.5079	1	0.0834	3
D	Shielding Gas flow Rate	0.495	0.4567	0.5259	3	0.0692	4

From the Table 5, it is understood that, 8th experimental run resulted in maximum closeness value. The variation of the closeness value for each experimental run is presented in Figure.3.

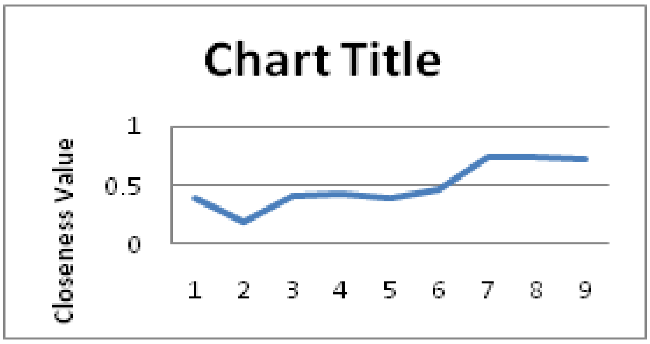


Figure 3. Closeness value for all the experimental run

The response table for mean closeness value was calculated and presented in Table 6. The parameters combination of the 8th experimental run didn't match the parameter combinations of the mean response table parameter combination which indicate that the closeness value obtained in the 8th experimental run is not the optimised value. The parameter combinations obtained in the response table will result in better closeness coefficient.

Table 6. Response Table for Closeness value

Exp.No.	Relative Closeness	Rank
1	0.39593	7
2	0.191003	9
3	0.413355	6
4	**0.432975**	**5**
5	0.383689	8
6	0.452365	4
7	0.726772	2
8	0.731488	1
9	0.70557	3

From the response table for closeness value it is understood that the optimised parameter combination is A3B3C1D3. The mean effect plot for closeness value is presented in Figure. 4

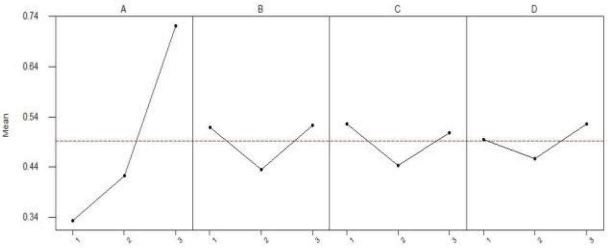


Figure 4. Mean response value of GTA welding process parameters

3.2. Analysis of Variance (ANOVA):

In the present study ANOVA was carried out at a confidence level of 95% and significance level of 5 %. Table 7 shows the results of ANOVA for the influence of input parameters on the multiresponse parameters.

Table 7 ANOVA Results and Percentage of Contribution

Sl. No.	Welding parameters	DOF	Sum of squares	Mean Square	F value	% of Contribution
1	Current	2	0.247	0.124	26.440	88.085
2	Voltage	2	0.015	0.007	1.577	5.252
3	Travel Speed	2	0.011	0.006	1.229	4.094
4	Shielding gas flow rate	2	0.007	0.004	0.771	2.569
5	Error	0				
6	Total	8	0.281			
7	Pooled error	4	0.019	0.005		

It was found that current was most influential parameter on the multiresponse parameters followed by voltage, travel speed and shielding gas flow rate. The percentage contribution of individual parameter on multiresponse parameters is presented in Figure 5.

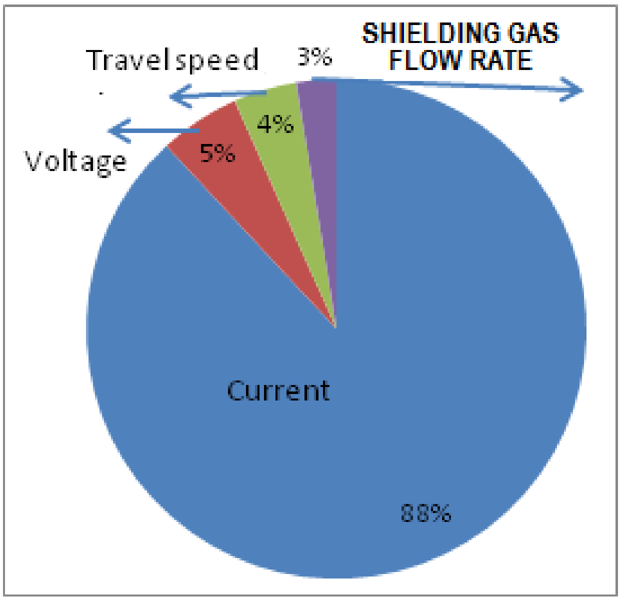


Figure 5. Percentage contribution of individual parameters on Multi-response characteristics

3.3. Confirmation Test:

The comparative test results for initial and optimal selection of GTA welding parameters (predicted and experimental conditions respectively) are shown in Table. Once the optimal level of welding parameters was determined, confirmation tests were carried out to validate improvement of the multi-response of GTA welding. Using the optimal level of GTA welding parameters, predictive response value can be estimated from the following equation.

The estimated GRG $\hat{\beta}$ is calculated using Equation (1)

$$\hat{\beta} = \beta_m + \sum_{i=1}^{Q} (\bar{\beta} - \beta_m) \qquad (1)$$

Where β_m is grey relational grades average value, $\bar{\beta}$ is the mean of the grey relational grade at optimum level and Q is the number of welding parameters that had a major influence on multiple response characteristics. Experimental confirmation results are shown in Table 8.

Table 8 Experimental confirmation results

	Initial level	Optimized parameters	
		Prediction	Experiment
Setting level	$A_1B_1C_1D_1$	$A_3B_3C_1D_3$	$A_3B_3C_1D_3$
Depth of penetration (mm)	2.42	-	3.4
Bead width (mm)	4.43	-	4.56
Hardness (Hv)	198	-	240
Closeness value	0.39593	0.788982	0.94

The confirmation test results indicated that the overall closeness value of the optimal parameter combination ($A_3B_3C_1D_3$) is higher than that of the initial setting parameter condition (Table 8)and also that the predicted response value is close to the experimental value.

4. CONCLUSIONS:

In the present work, TOPSIS Method with orthogonal array was utilised to optimise the process parameters in the GTA welding of AISI 904 L super austenitic stainless steel for multi-response characteristics. Based on the results, the following conclusions are drawn,

- An optimal combination of welding parameters and their levels was identified for achieving better depth of penetration, bead width and hardness. The optimised parameter combination is welding current: 190 A, voltage: 19 V, Travel speed: 50mm/min and shielding gas flow rate: 17 litre/min.
- The corresponding optimised output parameter values were identified according to the response of closeness coefficient values and the values are Depth of penetration: 3.4 mm, width: 4.56mm, Hardness: 240 HV
- ANOVA was conducted to calculate the important parameters for the multi-response characteristics of TIG welded super austenitic stainless steel. From the above analysis, it was found that current (88%) as the most influential parameter followed by voltage (5%), travel speed (4%) and shielding gas flow rate (3%). It was understood that the proposed combination of TOPSIS and ANOVA was more effective in solving GTA Welding multiresponse problems than previously used methods.

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