

SELECTION OF APPROPRIATE PROCESS PARAMETERS FOR ENHANCEMENT OF PENETRATION IN TIG WELDING OF 304H STAINLESS STEEL FLATS: AN AHP-BASED APPROACH

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ABSTRACT

Weldability is a critical factor in the fabrication of various grades of stainless steel used in industries. Tungsten Inert Gas (TIG) welding, known for its precision and high-quality results, is frequently employed in industrial applications. However, one of the common challenges with TIG welding is achieving adequate penetration of weld joints, despite the flexibility to modify welding parameters. A suitable combination of welding parameters such as current, inert gas flow rate and root gap can increase heat input and improve penetration depth, leading to a significant enhancement in the quality of weld joints and its productivity for fabricating mechanical components made of steel. This, in turn, ensures better performance and long-term reliability. In this work, we attempted to optimize the welding process of 304H austenitic stainless steel, which is known for its strength and corrosion resistance in boiler components. The experiment was designed

using Response Surface Methodology (RSM) with Central Composite Design (CCD), considering three factors: heat input, root gap and gas flow rate. Each factor was tested at three different levels to understand the effect on the quality of the weld, aiming primarily for full penetration, which is crucial for creating a strong joint. A total of 14 samples of 8mm thick 304H stainless steel plates, each measuring 50 mm by 50 mm, were welded using Gas Tungsten Arc Welding (GTAW), popularly known as TIG welding, with similar filler material to improve the overall weld quality. In this study, the Analytical Hierarchy Process (AHP), a multi-criteria decision-making tool which is widely used in various fields of work, was employed to validate the optimal values determined. The results obtained from the research align well with the AHP results.

Keywords: AHP; welding; bead geometry; penetration; Gas Tungsten Arc Welding; Tungsten Inert Gas Welding

1. Introduction

The Analytical Hierarchy Process (AHP), introduced by T.L. Saaty, is a multi-criteria decision-making tool that aids decision-makers in addressing complex problems with multiple criteria through step-by-step or pairwise comparison matrices (Saaty, 1977; Saaty, 1980; Vargas, 1990). Since its introduction, the AHP has found broad applications, as noted by Vargas (1990), and has been particularly successful in manufacturing and related fields. The main idea behind the AHP is to divide a complex problem into a hierarchy of smaller, easier-to-handle components, allowing each part to be evaluated individually. These smaller components typically represent criteria that are important in assessing various options. The AHP allows for a structured comparison of these options based on the importance of each criterion. The process involves three key steps. First, the problem is structured into a hierarchy, starting with the main goal, followed by criteria and alternatives. Next, pairwise comparisons are made to prioritize these elements using a scale of 1 to 9. Finally, a consistency check ensures the reliability of the comparisons, leading to a priority ranking that identifies the best option. The AHP's ability to integrate both qualitative and quantitative factors makes it highly valuable in fields such as engineering, information technology, construction, transportation, mathematics and management, etc. In welding, it effectively balances key considerations like strength, cost, and environmental impact, leading to more informed and effective decision-making (Saaty, 1977; Saaty, 1980; Vargas, 1990).

Amenta et al. (2021) introduced a Frobenius norm-based approach using the AHP to evaluate suitable coefficients that reflects large variations in the opinions of the decision makers for aggregating the individual judgments into a common group preference matrix where the assigned weights were non-negotiable. Munier and Hontoria (2021) presented a critical review of the AHP by examining multiple shortcomings, using reasoning, examples, and literature insights rather than mathematical analysis.

Darko et al. (2018) reviewed an application of the AHP in construction management where sustainable construction and risk management were found as common application areas. The authors found that the AHP was used widely due to its flexibility to function as a stand-alone tool and was preferred due to high consistency and simplicity.

Han et al. (2020) applied the AHP for selection of a road in topographic map generalization. Outcomes suggested that the AHP was more accurate than manual selection maintaining global connectivity, demonstrating its feasibility and efficiency for small-scale road generalization.

Saaty and Vargas (2001, 2012, 2013a, 2013b) evaluated the methods, concepts and applications of the AHP, focusing on broad areas such as economics, social sciences and technical domains. However, the AHP has also been widely used in manufacturing especially welding.

Different arc welding processes are prevalent in various industries and used to join metallic components. TIG (Tungsten Inert Gas) welding is an arc welding process which offers accuracy with high precision. However, the productivity of TIG is quite low, primarily due to its low material deposition rate. When a weldability study of a new material is undertaken, the main focus is determining the appropriate process parameters. Here, process optimization plays a key role.

Kaur et al. (2021) demonstrated the use of the AHP to optimize welding parameters for TIG welding of mild steel. The study focused on optimizing key parameters, such as voltage, current, and travel speed, to improve weld quality. This research demonstrates how the AHP can effectively prioritize these factors to achieve optimal results in the welding process.

Gupta et al. (2019) applied the AHP to compare the performance of different welding processes, specifically for dissimilar material joints. The authors emphasized the importance of evaluating factors like weld strength, thermal distortion, and cost when selecting the most appropriate welding technique. This approach allowed for more informed decision-making in industries where specific criteria had to be met.

Manohar et al. (2020) integrated the AHP with the Taguchi method to optimize welding parameters for mild steel and stainless-steel joints. By combining these two methods, they were able to assess parameters like tensile strength and toughness more comprehensively. This combined approach led to improvements in both weld quality and efficiency, making the process more effective and reliable.

Prasad et al. (2021) utilized the AHP to assess the environmental sustainability of welding processes. Their study took into account factors such as energy consumption, emissions, and material waste, highlighting the importance of incorporating sustainability into welding parameter optimization. This approach ensured that welding practices could align with environmental goals while still maintaining high-quality results.

Bhatti and Tharwat (2018) employed the AHP to select welding parameters for Metal Inert Gas (MIG) welding. Their research emphasized the use of multi-criteria decision-making in determining the most suitable welding parameters. The study showcased how the AHP could effectively be used to balance various factors, ensuring that welding processes were optimized for quality and efficiency. The AHP has been effectively used to assess suitable welding processes and optimize parameters for materials like aluminum and steel by researchers such as Ravisankar et al. (2006) and Sabiruddin et al. (2013).

These studies demonstrated the technique's effectiveness in selecting the right welding parameters to improve the overall quality of welds.

Saaty (2009) highlighted the distinction between decision-making based on judgment and quantitative measurements when applying the AHP to solve various problems. This distinction emphasizes the flexibility of the AHP, allowing it to be applied to a wide range of complex decision-making scenarios.

Numerous researchers have employed the AHP in manufacturing, welding, and other areas of management. For example, Lai et al. (2009) used the AHP to determine appropriate welding parameters for resistance spot welding, ensuring better quality and efficiency in the process.

Liu and Gong (2011) demonstrated the successful application of the AHP to select edge preparations for welding, aiming to improve the fatigue life of welded joints. Their work highlights the potential of the AHP to optimize welding techniques for better long-term performance.

Capraz et al. (2015) combined the AHP with the TOPSIS method to select the best welding process and optimize parameters for welding a storage tank made of plain carbon steel. Their hybrid approach improved the selection process by combining the strengths of both methods. Saaty and Vargas (2013a) applied a variant of the AHP, namely the Analytic Network Process (ANP), to solve various economic socio-political and technological decision-making problems

Jayant and Dhillon (2015) successfully implemented the AHP to identify the most appropriate welding technique among five widely adopted methods suitable for high-pressure welding applications. The selection was based on a comprehensive evaluation of several critical factors, including design requirements, joint type, welding position, initial investment, deposition rate, part thickness, weld quality, material category, welding procedures, operator-related considerations, filler metal efficiency, and equipment mobility.

Bhattacharya et al. (2021) applied the AHP to identify optimal welding parameters for high carbon steel flats using GMAW. They considered several criteria, including spatter, penetration depth, blowhole absence, deposition, cracks, and bending load, to determine the best welding conditions.

Acharya et al. (2023) successfully used the AHP to validate the optimal values of criteria and responses in ATIG welding against experimental results. This application of the AHP helped confirm the effectiveness of the optimized welding parameters in real-world conditions.

In summary, the AHP is proven to be a versatile and effective multi-criteria decision-making tool in various fields including welding technology. By providing a clear and systematic framework for evaluating multiple factors, it improves the selection of welding parameters, resulting in better weld quality, cost savings and sustainable practices across various applications.

The literature review provides limited insight into systematic optimization methods for TIG welding parameters specific to 304H stainless steel, a material known for its high strength and corrosion resistance in elevated-temperature environment. To address this gap, the present work investigated the relationship between key welding parameters and weld bead geometry parameters by providing a structured approach via the AHP to optimize them, thus ensuring stronger weld joints with improved performance. Unlike prior studies that primarily focused on materials such as mild steel or other dissimilar joints, the present work systematically applied the AHP specifically to optimize TIG welding parameters for SS 304H stainless steel used in high-temperature applications.

Experiments were planned on TIG welding of SS 304H austenitic stainless steel considering three process variables, namely heat input, root gap and gas flow rate. Heat input was varied from 1.323 kJ/mm to 1.660 kJ/mm. Root gap was varied at three levels having the values of 1.2 mm, 1.6 mm and 2.0 mm. Gas flow rate was varied at three levels having the values of 10, 12 and 14 L/min.

2. Materials and method

This investigation focused on optimizing the parameters of weld bead geometry such as minimization of height of reinforcement, bead width and primarily the increase in depth of penetration of welded joints, by varying key input parameters of the Gas Tungsten Arc Welding (GTAW) process. Optimization of input parameters used in welding has multiple benefits. Economically, it leads to high productivity with faster rate, lower cost of production and maintenance, and less consumption of raw materials and weld consumables. Environmentally, weld parameter optimization also has some benefits such as reduced greenhouse gas emission due to less production of fumes thereby reducing energy usage. The input parameters used in this work include supply current, root gap, and gas flow rate. The current and voltage directly influence the heat input, which is a critical factor affecting the optimization of the parameters of weld bead geometry and increasing the strength and quality of the weld joints. However, despite the widespread industrial application of TIG welding, achieving consistent and adequate penetration remains a challenge due to the difficulty of finding a suitable combination of multiple welding parameters.

The welding was carried out using a KEMPPi K2 TIG 200 AC/DC machine on 14 304H stainless steel samples, each 8 mm thick and 50 mm x 50 mm in size, which ensured precise control over the current and arc stability. A MOGRA CWF 04 Cold Wire Feeder was employed to ensure a constant supply of 1.2 mm diameter filler wire made of 304H grade austenitic stainless steel, maintained at a consistent feed rate of 20 mm/s. The welding speed was fixed at 1.22 mm/s after conducting sample welds at various speeds, as this speed provided the most optimal results for deposition and control of heat input. Figure 1 depicts the representation of the welding setup used.

Experiments were conducted with the torch held at a 75° angle, maintaining a constant arc gap length of 5 mm, and welding speed of 1.22 mm/s. Various current and voltage settings were tested in initial test runs to evaluate their impact on weld quality. The key varied input parameters were current, root gap, and gas flow rate. Each of these parameters was evaluated at three different levels. The current values were set at 130 A, 140 A and 150 A, with the voltage adjusted accordingly. The root gap was varied at 1.2

mm, 1.6 mm and 2 mm and the argon gas flow rate was controlled at 10, 12 and 14 L/min. In welding process optimization, key input parameters such as heat input, root gap and gas flow rate significantly affect both weld quality and productivity. Higher heat input generally improves penetration but may lead to defects like excessive reinforcement or distortion if not controlled properly. The root gap influences joint quality, where too small a gap may cause lack of fusion and too large a gap may increase the risk of poor bead geometry and instability. Gas flow rate plays a critical role in shielding the weld pool; inadequate flow leads to oxidation, while excessive flow can destabilize the arc. These parameters highlight the necessity of a systematic approach like the AHP to carefully balance multiple criteria in parameter selection for efficient and reliable TIG welding.

Each of the 14 samples were welded under these varying conditions, allowing a detailed analysis of the optimization parameters. The joints were non-autogenous butt joints, welded with a 3.2 mm non-consumable Thoriated tungsten electrode. After welding, the specimens were air-cooled. The chemical composition of the 304H stainless steel and filler material is provided in Table 1. To assess weld quality, welded specimens were polished and etched with Carpenter's Etchant, and the bead geometry was measured using a Tool Maker's Microscope. The welded specimens were first polished using a polishing machine equipped with flat disk wheels. The specimens were progressively polished by fixing abrasive papers on the disk with finer grits one after the other to achieve a smooth, mirror-like finish. The specimens were then cleaned with water and alcohol. Finally, the specimens were etched using Carpenter's reagent, which consisted of a mixture of 50 ml of hydrochloric acid, 100 ml of water, and 1 g of copper chloride. Parameters such as weld bead width, reinforcement, and penetration depth were measured. Reinforcement form factor (RFF), penetration shape factor (PSF), and heat input (HI) were calculated using the following Equations (1), (2) and (3).

$$\text{RFF} = W/R \quad (1)$$

$$\text{PSF} = W/P \quad (2)$$

$$\text{HI} = (V \times I \times \eta) / (1000 \times S) \quad (3)$$

HI is the heat input in kJ/mm, V is the voltage in V, I is the current in A, S is the welding speed in mm/s, and η is the efficiency of the welding process (0.75 taken for GTAW).

Figure 1 shows the welding setup used during the experiments.

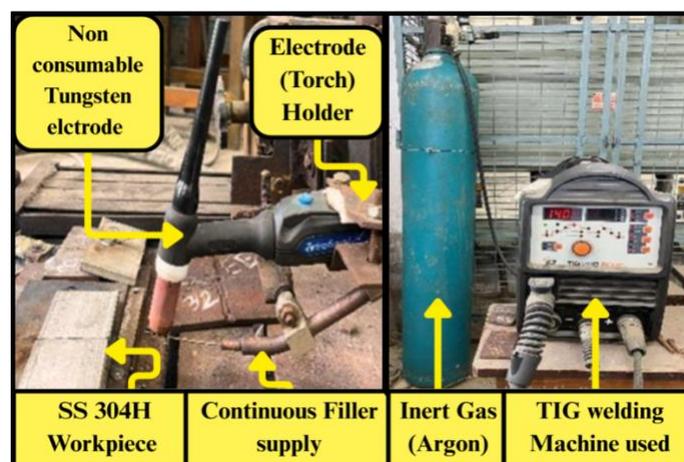


Figure 1. GTAW setup used (torch angle 75°)

Table 1
Constituents of SS304H flats and filler

Element	C	Si	Mn	P	S	Cr	Ni	Fe
Wt.%	0.06	0.48	1.4	0.03	0.03	18.11	8.48	Balance

2.1. Design of experiment by central composite design (CCD)

In this investigation, Central Composite Design (CCD), a popular method in Response Surface Methodology (RSM), was utilized to examine how three critical factors affect welding outcomes. These factors are welding current, root gap and gas flow rate. Each factor was tested at three levels, which were determined through initial trials to identify the most effective welding settings for achieving a high-quality weld. CCD, as a type of RSM, was selected due to its efficiency in estimating both linear and quadratic relationships between process parameters and outcomes, while reducing the number of required experiments compared to full factorial designs. This approach is especially useful in welding applications where process optimization and understanding of interaction effects are essential for improving weld quality and ensuring full penetration.

Gas flow rate was chosen as 10, 12 and 14 L/min, while the root gap was set at 1.2, 1.6 and 2.0 mm. For the welding current, values of 130, 140 and 150A were selected. The corresponding voltage was adjusted to ensure the correct heat input for the process.

Figure 2 presents sample images of the welded specimens and Figure 3 showcases cross-sectional cuts of few welded specimens, revealing instances of full penetration when welded from both ends.



Figure 2. Sample images of few welded specimens

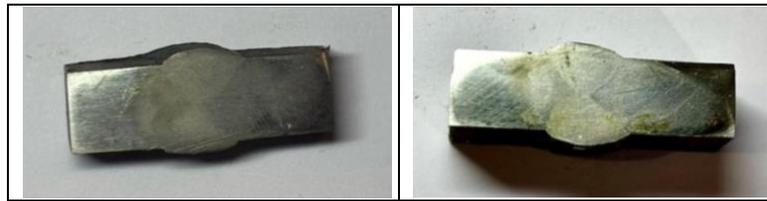


Figure 3. Cross sectional cuts of few welded specimens revealing full penetration.

The experimental parameters which include details of heat input are summarized in Table 2. Here, Numbers 1 and 2 denote butt welds done on top and bottom side of the metal plates.

Table 2
Experimental parameters during welding

Sl. No.	Gas Flow Rate (L/min)	Root Gap (mm)	OCC (A)	CCC (A)	CCV 1 (V)	CCV 2 (V)	HI1 (kJ/mm)	HI2 (kJ/mm)	Avg HI (kJ/mm)
1	10	1.2	130	130	16.8	16.6	1.343	1.327	1.335
2	14	1.2	130	130	16.5	16.6	1.319	1.327	1.323
3	10	2.0	130	129	16.9	16.8	1.340	1.332	1.336
4	14	2.0	130	129	17.0	17.2	1.348	1.364	1.356
5	10	1.2	150	148	18.3	17.6	1.665	1.601	1.633
6	14	1.2	150	148	18.1	17.9	1.647	1.629	1.638
7	10	2.0	150	148	18.2	18.1	1.656	1.647	1.651
8	14	2.0	150	148	18.3	18.2	1.665	1.656	1.660
9	12	1.6	140	138	17.7	16.8	1.502	1.425	1.463
10	12	1.6	140	138	17.8	17.6	1.510	1.493	1.502
11	12	1.6	140	138	17.5	16.9	1.485	1.434	1.459
12	12	1.6	140	138	17.4	16.8	1.476	1.425	1.451
13	12	1.6	140	138	18.0	17.9	1.527	1.519	1.523
14	12	1.6	140	138	18.5	17.6	1.569	1.493	1.531

Note: OCC = Open Circuit Current, CCC = Closed Circuit Current, CCV = Closed Circuit Voltage, HI = Heat Input

3. Experimental results and discussion

Top views of some typical specimens having a butt joint made using double-sided TIG welding with filler material are shown in Figure 2. In all the specimens, a continuous uniform weld bead was observed without any visible defect. Cross-sectional cuts of a few welded specimens are shown in Figure 3 which clearly show full penetration of the weld joint. Also, in these specimens, no visible weld defects were found.

For the 14 experimental runs, different combinations of input parameters such as gas flow rate, root gap and heat input were varied for which the weld bead geometry parameters such as depth of penetration, height of reinforcement and bead width were observed as shown in Table 3. Additionally, derived parameters like RFF and PSF were computed and included in Table 3. In the specimens Sl. Nos. 3 –10 and 14, there was full penetration of 8 mm, whereas in other experimental runs full penetration could not be achieved. In specimen Sl. No 4, minimum bead width of 7.76 mm was found; however, for specimen Sl. No. 13 a maximum bead width of 12.62 mm was found. The maximum reinforcement was found in specimen Sl. No. 4 with a value of 2.46 mm. The minimum reinforcement was found in specimen Sl. No. 10 with a value of -0.67 mm. The PSF was found to have a maximum value of 4.344 for specimen Sl. No. 11, whereas, it was found to be minimum value of 0.969 for specimen Sl. No. 4. The RFF was found to have a maximum value of 31.066 for specimen Sl. No. 12, whereas, it was found to be minimum value of -13 for specimen Sl. No. 10. An increase in heat input increases the melt volume. In some cases, this increased melt volume can contribute to deep penetration, and in other cases this can cause increased reinforcement and bead width.

Table 3
Observed bead geometry

Sl. No.	Gas Flow Rate (L/min)	Root Gap (mm)	Heat input (kJ/mm)	Penetration (mm)	Widht h (mm)	Reinforcement (mm)	PSF (W/P)	RFF (W/R)
1	10	1.2	1.335	2.83	8.11	1.61	2.869	5.034
2	14	1.2	1.323	4.63	8.61	1.18	1.860	7.297
3	10	2.0	1.336	8	8.3	1.14	1.037	7.276
4	14	2.0	1.356	8	7.76	2.46	0.969	3.159
5	10	1.2	1.633	8	9	1.32	1.124	6.836
6	14	1.2	1.638	8	9.65	0.67	1.206	14.511
7	10	2.0	1.651	8	9.71	0.51	1.213	19.029
8	14	2.0	1.660	8	9.14	0.49	1.142	18.835
9	12	1.6	1.463	8	8.19	1.05	1.024	7.837
10	12	1.6	1.502	8	8.62	-0.67	1.077	-13
11	12	1.6	1.459	2.73	11.86	0.69	4.344	17.188
12	12	1.6	1.451	3	11.81	0.38	3.961	31.066
13	12	1.6	1.523	3.25	12.62	0.83	3.881	15.290
14	12	1.6	1.531	8	9.63	1.59	1.203	6.056

4. Procedure of the AHP

In this work, the AHP involved structuring the problem into a hierarchy, with the main goal at the top, followed by criteria and alternatives in subsequent levels as shown in Figure 4. The matrix used for pairwise comparisons is represented in Equation (4).

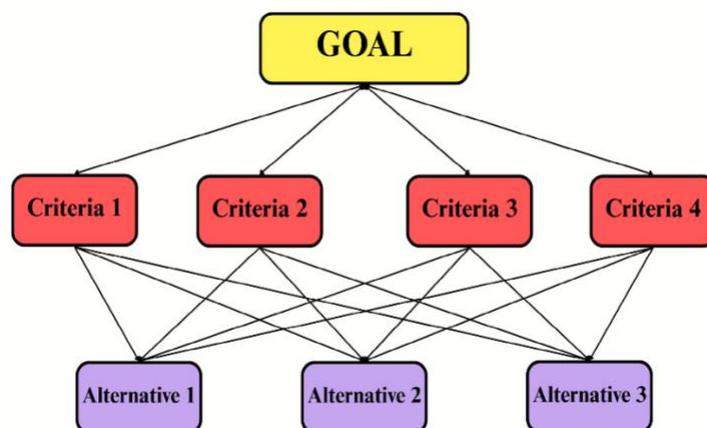


Figure 4. Basic AHP hierarchy

$$M = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} \quad (4)$$

Here m_{ij} represents the strength of preferences of element m_i over m_j concerning a specific goal or criterion ($m_{ij} = m_i/m_j$). Saaty's ratio scale (Saaty, 1977; Saaty, 1980) was employed to determine the values of m_i and m_j for pairwise judgments, which is given in Table 4. Consistency of the comparison matrix was then checked following the standard procedure of determining a Consistency Ratio (CR) after Saaty (1977) and Saaty (1980).

Table 4
Ratio scale comparison matrix

Preference	Scale
Extremely Preferred	9
Very Strongly to Extremely Preferred	8
Very Strongly Preferred	7
Strongly to Very Strongly Preferred	6
Strongly Preferred	5
Moderately to Strongly Preferred	4
Moderately Preferred	3
Equally to Moderately Preferred	2
Equally Preferred	1

Local priority weights of the comparison matrix for criterion were integrated with local weights of pairwise comparison matrices for alternatives to determine global weights. The alternative with the highest global weight is typically considered the most suitable choice in the decision-making process. The hierarchy structure constructed for the present case is shown in Figure 5.

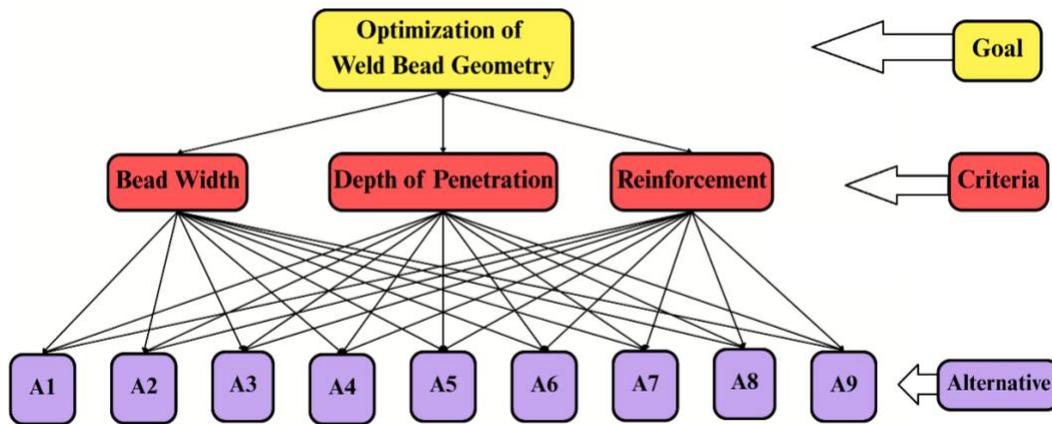


Figure 5. Hierarchy structure of the AHP Process used

5. Results obtained from the AHP

The goal of the multi-criteria process optimization was to optimize weld bead geometry, with a primary focus on achieving full depth of penetration. The criteria considered for this purpose included bead width, depth of penetration, and height of reinforcement. Data corresponding to experimental runs from serial numbers 1 to 9 were used in the optimization, as the input parameters for runs 9 to 14 were found to be similar. The hierarchical structure adopted for the optimization procedure is schematically illustrated in Figure 5.

The criteria for the AHP selection, depth of penetration, bead width, and reinforcement were chosen because of their significant impact on weld quality and joint strength, as supported by previous studies (Kaur et al., 2021; Gupta et al., 2019; Bhatti & Tharwat, 2018). Depth of penetration is critical for ensuring mechanical strength and avoiding incomplete fusion; bead width affects weld appearance and mechanical properties, while nominal value of reinforcement influences structural stability and stress distribution.

HI, calculated by Equation (3) plays a key role in welding performance, as it governs the melting of base material and filler, thereby controlling penetration depth and bead formation. Excessive or insufficient heat input may lead to poor weld quality. Therefore, optimizing these criteria via the AHP enables a balanced decision-making process for selecting ideal process parameters to improve weld quality and performance.

Priority weights for the AHP were calculated manually rather than with software after discussions with welding experts and academic guidance. Brainstorming sessions helped create a more customized approach, ensuring that the weight assignments were based on expert comments and the unique complexities of the welding parameters.

Table 5 represents the AHP model, where weights of various criteria were chosen based on the goal of optimizing weld parameters. Then, the maximum Eigen value was calculated from a 3×3 matrix. It was calculated as $\lambda_{\max} = 3.103$; finally, the consistency ratio (CR) was calculated. This value was calculated as 8.8% which is less than 10%; therefore, it is accepted. Furthermore, the pairwise comparison matrix for the alternatives was constructed for run orders 1 to 9, as the operating parameters were identical for

multiple trials from run order 9 to 14, such as gas flow rate 12 L min, root gap 1.6 mm and current 140 A. For this reason, the value from run order 9 was considered for evaluation.

Table 6 shows the calculation of the comparison matrix between alternatives for criterion 1 (depth of penetration) keeping in mind the goal, i.e., optimization of weld bead geometry. The maximum Eigen value of $\lambda_{\max}= 9.0689$ was calculated from a 9×9 matrix and the CR was calculated as 5.9% which is below 10% and therefore accepted.

Table 5
Pair wise comparison matrix for criteria

Criteria	Depth of penetration	Bead width	Reinforcement	Geometric mean	Local weight
Depth of penetration	1	4	3	2.27	0.62
Bead width	0.25	1	2	0.79	0.21
Reinforcement	0.33	0.5	1	0.55	0.15

$\lambda_m= 3.103$, C.R.= 0.088

Table 6
Pair wise comparison matrix for alternatives for depth of penetration

Alternative	A1	A2	A3	A4	A5	A6	A7	A8	A9	Geometric mean	Local weight
A1	1	1/3	1/5	1/5	1/5	1/5	1/5	1/5	1/5	0.256	0.0246
A2	3	1	1/4	1/4	1/4	1/4	1/4	1/4	1/4	0.388	0.037
A3	5	4	1	1	1	1	1	1	1	1.39	0.134
A4	5	4	1	1	1	1	1	1	1	1.39	0.134
A5	5	4	1	1	1	1	1	1	1	1.39	0.134
A6	5	4	1	1	1	1	1	1	1	1.39	0.134
A7	5	4	1	1	1	1	1	1	1	1.39	0.134
A8	5	4	1	1	1	1	1	1	1	1.39	0.134
A9	5	4	1	1	1	1	1	1	1	1.39	0.134

$\lambda_m= 9.0689$, C.R.= 0.059

Table 7 shows the calculation of the comparison matrix between alternatives for criterion 2 (bead width) keeping in mind the goal, i.e., optimization of weld bead geometry. The maximum Eigen value of $\lambda_{\max}= 9.657$ was calculated from a 9×9 matrix and the CR was calculated as 5.6 % which is below 10% and therefore accepted.

Table 7
Pair wise comparison matrix for alternatives for bead width

Alternative	A1	A2	A3	A4	A5	A6	A7	A8	A9	Geometric mean	Local weight
A1	1	3	2	1/2	3	4	4	4	3	2.270	0.19
A2	1/3	1	1/2	1/3	3	4	4	4	1/2	1.190	0.10
A3	1/2	2	1	1/3	3	4	4	4	1/2	1.462	0.13
A4	2	3	3	1	4	5	5	5	3	3.070	0.27
A5	1/3	1/3	1/3	1/4	1	3	4	2	1/3	0.747	0.06
A6	1/4	1/4	1/4	1/5	1/3	1	2	1/2	1/3	0.415	0.04
A7	1/4	1/4	1/4	1/5	1/4	1/2	1	1/2	1/3	0.345	0.03
A8	1/4	1/4	1/4	1/5	1/2	2	2	1	1/2	0.530	0.05
A9	1/3	2	2	1/3	3	3	3	2	1	1.415	0.12

$\lambda_m = 9.657$, C.R. = 0.056

Table 8 shows the calculation of the comparison matrix between alternatives for criterion 2 (reinforcement) keeping in mind the goal, i.e., optimization of weld bead geometry. The maximum Eigen value of $\lambda_{max} = 9.445$ was calculated from a 9×9 matrix and the CR was calculated as 3.8% which is below 10% so it is acceptable.

Table 8
Pair wise comparison matrix for alternatives for height of reinforcement

Alternative	A1	A2	A3	A4	A5	A6	A7	A8	A9	Geometric mean	Local weight
A1	1	1/2	1/2	3	1/2	1/3	1/3	1/3	1/2	0.576	0.054
A2	2	1	1/2	3	2	1/3	1/3	1/3	1/2	0.782	0.073
A3	2	2	1	3	2	1/3	1/3	1/3	1/2	0.911	0.085
A4	1/3	1/3	1/3	1	1/3	1/4	1/4	1/4	1/3	0.343	0.032
A5	2	1/2	1/2	3	1	1/3	1/3	1/3	1/2	0.671	0.063
A6	3	3	3	4	3	1	1/2	1/2	2	1.750	0.164
A7	3	3	3	4	3	2	1/2	1/2	2	2.030	0.190
A8	3	3	3	4	3	2	1	1	2	2.370	0.220
A9	2	2	2	3	2	1/2	1/2	1/2	1	1.220	0.114

$\lambda_m = 9.445$, C.R. = 0.038

The role of the AHP in this work is to systematically prioritize multiple criteria (depth of penetration, bead width, and reinforcement) by assigning relative weights through expert judgment, constructing pairwise comparison matrices, and calculating consistency ratios. For example, a criterion such as “depth of penetration” is given the highest local weight (0.62), reflecting its greater importance, and alternatives are evaluated accordingly to identify the optimal welding condition.

In Table 9, the local weights for each parameter are considered and global weights are calculated for all individual alternatives. The maximum global weight of 0.144 for run order 4 represents the suitable alternative which may be considered as the optimized condition.

Table 10
Local and global weights for alternatives and local weights for criteria

Alternative No.	Local Weights			Global Weights	Rank
	Depth of penetration	Bead Width	Reinforcement		
	0.62	0.21	0.15		
A1	0.0246	0.19	0.054	0.063	VIII
A2	0.037	0.10	0.073	0.054	IX
A3	0.134	0.13	0.085	0.123	IV
A4	0.134	0.27	0.032	0.144	I
A5	0.134	0.06	0.063	0.105	VII
A6	0.134	0.04	0.164	0.116	VI
A7	0.134	0.03	0.19	0.117	V
A8	0.134	0.05	0.22	0.126	II
A9	0.134	0.12	0.114	0.125	III

In this work, the AHP was applied to identify the optimal depth of penetration while maintaining productivity and determining the associated process parameters for TIG welding. Global weights of all alternatives were calculated based on multiple criteria reflecting weld quality, and the highest value of 0.144, corresponding to alternative 4 (gas flow rate of 14 L/min, root gap of 2.0 mm, and heat input of 1.356 kJ/mm), was identified as the optimal condition. This alternative was also found to produce experimentally confirmed full penetration and optimal bead geometry, demonstrating a close agreement between the AHP predictions and experimental results. This validates the strength of the AHP as a data-driven, systematic decision-making tool that effectively predicts optimal welding parameters and guides experimental planning in TIG welding.

However, the AHP applied in this process is exclusive to this set of experiments only. Therefore, for other sets of experiments, the hierarchy structure of the AHP would need to be constructed again to suit the specific application.

6. Conclusion

The welding experiments confirm that most parameters tested resulted in fully penetrated joints, which are essential for achieving strong and reliable connections. Run orders 4, 5, 6, 7, 8, and 14 produced particularly promising results. Full penetration was achieved in these cases by welding from both sides, ensuring strong joint formation. Specifically, run orders 4, 7 and 8, which used a 2 mm root gap and gas flow rates of 10–14 L/min, resulted in highly stable welds with minimal reinforcement and full penetration.

These experimental results align closely with the AHP findings, which identified alternative 4 as the optimum condition, achieving the highest global weight of 0.144. The second-highest global weight of 0.126, corresponding to alternative 8, also aligns with the experimental observations. The agreement between the AHP predictions and experimental data demonstrates the effectiveness of the AHP in identifying optimal

welding parameters. Both approaches confirmed that sample 4, characterized by a 2 mm root gap, gas flow rates of 14 L/min, and appropriate heat input, is the most favorable condition for achieving reliable and robust welds.

Weldability studies of SS 304H austenitic stainless steels using a multi-criteria decision-making tool such as the AHP have not been extensively carried out in the literature. The results of this study using the AHP confirm the state of the art in welding optimization by demonstrating a data-driven methodology which aligns well with experimental results and establishes the utility of this multi-criteria decision-making tool. This work not only identifies parameter combinations that produce a superior weld quality but also confirms the predictive accuracy of the AHP for welding applications. For researchers, the key takeaway is that combining experimental validation with a structured decision-making tool such as the AHP improves the parameter selection which enhances the weldability of high temperature application material such as SS 304H. For practitioners, the study provides concrete parameter ranges and validated settings that may be directly applied in further studies to achieve full penetration and consistent weld quality. Appropriate process parameters determined by the AHP such as gas flow rate of 14 L/min, root gap of 2.0 mm and heat input of 1.356 kJ/mm may be adopted in relevant industries to achieve full penetration of 8 mm thick SS 304H austenitic stainless steels which are used in high temperature applications.

Building on the current study, future research could expand the AHP-based decision-making framework by incorporating additional welding parameters such as welding speed, electrode type, and filler material composition, which may influence weld quality and productivity. Moreover, integrating the AHP with other systematic multi-criteria decision-making methods such as the Analytic Network Process (ANP), TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), Weighted Sum Model (WSM), Weighted Product Model (WPM), or similar methods could enhance its predictive capability and flexibility. These hybrid approaches would enable more robust, data-driven optimization of welding quality and corresponding process parameters, improving efficiency, and performance in high-temperature applications like SS 304H stainless steel.

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