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Parametric optimization for hardness of tig welded duplex stainless steel

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ABSTRACT

Achieving optimal mechanical properties in welding joints hinges on employing precise parametric conditions. This is particularly crucial for Tungsten Inert Gas (TIG) welding of ASTM/UNS 2205 Duplex Stainless Steel (DSS), where attributes like hardness, ultimate tensile strength, and yield strength are paramount. Maintaining high Hardness Value (HV) demands proper welding parameters such as welding current, gas flow rate, and welding speed. To enhance DSS welding quality, especially hardness, this study utilizes the Taguchi method to optimize welding process parameters. The importance of each factor is assessed through Annova statistical analysis. The outcomes highlight the positive impact of parametric optimization on HV, as evidenced by the analysed data. Parametric optimization proves to be a potent approach for refining industrial processes like welding, with particular relevance in TIG welding of duplex stainless steel due to its mechanical robustness and corrosion resistance. Nevertheless, challenges arise due to the material's elevated hardness and low thermal conductivity, resulting in potential defects like cracks and porosity. The identification of optimal welding parameters, encompassing current, voltage, speed, and gas flow rate, helps address these challenges and advances high-quality welds. Through systematic variations and analysis of these parameters, researchers and engineers can pinpoint the optimal combination that mitigates defects while maximizing desired joint attributes. Within the realm of TIG welding of duplex stainless steel, metric optimization holds the potential to elevate welding quality, curtail costs and waste, and heighten productivity and safety. Consequently, organizations can attain enhanced performance, efficiency, and profitability within their welding processes.

INTRODUCTION

Parametric optimization is a powerful tool for improving the hardness of TIG welded duplex stainless steel. The hardness of TIG welded duplex stainless steel is affected by various welding parameters, including welding current, welding speed, shielding gas, electrode type, and post-weld heat treatment.

A Design of Experiments (DOE) approach is used to optimize these parameters for maximum hardness. This approach involves creating a matrix of experiments that systematically vary each parameter over a range of values. The results of each experiment are then analyzed statistically to determine the optimal combination of parameters that produce the desired hardness.

Once data are collected from the DOE experiments, statistical techniques viz. Analysis of Variance (ANOVA) is used to analyse the results and create a model that predicts the hardness of the welded joint based on the welding parameters. This model can then be used to identify the optimal welding parameters for maximum hardness. It's important to note that optimizing for hardness may not be the only goal in TIG welding. Other factors, such as the welded joint's strength, ductility, and corrosion resistance, may also need to be considered. Therefore, balancing these factors is important when choosing the optimal welding parameters.

DSS exhibits a remarkable fusion of ferrite and austenite in a double-phase arrangement. The austenite structure offers a special combination of strength and corrosion resistance. For Duplex stainless steel, the ferrite phase structure provides local corrosion resistance. The usage of DSS is widespread in the chemical and oil industries.

Numerous researchers have looked into various facets of Duplex Stainless Steel which are described here. A mathematical model for the five levels factorial approach was created by Murugan et al. The bead geometry of welding 316L stainless steel into IS2062 structural steel had been examined and graphical representations had been provided using this method. To achieve the necessary quality for the welded result, they looked for the best values of process parameters to choose [1]. Phase structure configuration and other 2205DSS material parameters were examined by Badji et al. They used temperatures between 8000C and 10000C to anneal the DSS materials as part of the heat treatment process. They demonstrated that the HAZ zone was where the majority of ferritic phase structures were found [2]. Sotomayor et al. noted duplex stainless steel's adhesive quality on a thermoplastic. They also explored the rupture failures of the material. Factors that include humidity have been employed to assess the success of surface treatment [3]. Palani and Murugan looked examined the weld bead geometry's impact of cladding by utilising several parameters, including welding current, welding speed, and nozzle-to-plate distance [4]. Using finite element methods, including the birth and death approach, J. J. Del Coz Diaz et al. demonstrated the critical importance of the material properties in the final deformed shape of two distinct stainless-steel sheets. They also looked at the possibility that welding these steels using a comparable TIG method result in opposite angular deformation and longitudinal bending [5]. To predict the tensile properties of dissimilar AA6061-T6 to Cu welds, Pandya and Menghani created a mathematical model. They employed a Zn interlayer and a friction stir welding technique [6]. Tarng and Yang used the Taguchi technique to optimise the weld pool configuration [7]. Using the modified Taguchi technique, Tarng et al. analysed the ideal stainless steel TIG weld bead structure to identify the process parameters [8]. To determine the best-submerged arc welding process variables, Tarng et al. looked into relevant grey-based Taguchi approaches [9]. To forecast mechanical qualities in the production of rebar, Murta et al. devised a mathematical model [10]. They demonstrated how an artificial neural network can help determine the most appropriate parameters for achieving the desired steel qualities. According to Badjia et al.'s observation, the textures of both phases in the received metal are mixes of textures from recrystallization and deformation, which typically distinguish between the material's single-phase BCC and FCC structure [11]. Ul-Haq et al. studied the duplex stainless steel's microstructures and texturing. Additionally, they demonstrated how the microstructure of duplex stainless steel developed its rolling texture [12]. Researching and fabricating structural materials is one of the most difficult concerns for existing and future advanced fusion reactors such as ITER and DEMO [13,14]. Austenitic stainless steels have great weldability, outstanding corrosion resistance, and superior mechanical qualities at higher operating temperatures. Stainless steels such as SS 304, 316, and 316L(N), as well as some special grades such as 316LN(IG), are employed in the production of vacuum containers,

10.12928/ijio.v4i2. 7756

plasma-facing components, support structures, and other diverse subsystems in fusion reactors. These parts are typically made by joining plates in a range of shapes, such as plane plates, curved plates, and T-joints, in line with the design criteria [15,16]. To study the practicality and specify the manufacturing paths for merging thick plates, several procedures are proposed, including Tungsten Inert Gas (TIG) welding, Narrow Gap TIG welding, Electron Beam welding, and Hybrid Laser MIG welding [17, 18]. Various research have chosen weld process ways for combining thick austenitic stainless steel plates for vacuum vessel fabrication to standardise the welding procedures and characterisation [19]. One of the common methods for connecting stainless steel plates is TIG (tungsten inert gas) welding with numerous passes. Depending on the type of weld joint required, such as shell joints or ribs, the joint design has numerous potential options, such as narrow grooves, double V grooves (X), or J-type grooves [20,21]. In order to increase oil production, gas lift operations include injecting compressed gas into underperforming or low-performing wells. The gas injection rate affects how much oil a gas lift well produces. Through optimization, the ideal gas injection rate can be reached [22]. Yoghurt's flavour and texture, which may be assessed using an organoleptic test, can be used to gauge its quality. The better the yoghurt's flavour and texture, the higher the quality objective [23]. Austenitic stainless steel (SS) of type 316L(N) is utilised as a key structural component in sodium-cooled fast reactors (SFR). The material was chosen for its excellent strength-to-ductility ratio, good oxidation/corrosion resistance, and low sensitization susceptibility. Fusion welding is frequently employed to create the reactor vessel and pipes due to their intricacy and scale. Cracking in weld joints is the most serious concern for welded components [24]. The tungsten inert gas (TIG) welding operation, both with and without filler metal, is the most often used method for combining this class of materials. The main limitations of TIG welding are its inability to weld thicker chunks of material in a single pass, poor tolerance for some variations in material composition (from casting to casting), and low metal production. When using argon as the shielding gas, the maximum depth of weld that can be achieved in a single pass when TIG welding austenitic stainless steel is roughly 3 mm [25]. Several techniques have been created throughout the years to boost the productivity of joining in the TIG welding process. Applying a flux coating containing specific inorganic compounds to the joint surface prior to welding can considerably improve the arc's ability to penetrate during TIG welding. [26-37]. According to [37], the A-TIG welding method may fully penetrate up to 12 mm in a single pass without the use of filler wire or bevel preparation. The arc's shrinkage has explained this and the reversal of the Marangoni flow in the molten weld pool [34]. Furthermore, the weldment's soundness and mechanical properties are claimed to remain intact. The measured residual stress value was extremely low when comparing the A-TIG weld junction to the traditional multi-pass TIG weld connection [38]. A literature review indicates that additional, in-depth study is necessary in the field of TIG welding of duplex stainless steel since the sound knowledge foundation for TIG welding on Duplex stainless steel has not yet been sufficiently established. A deeper knowledge base that will help better grasp the numerous factors pertaining to Duplex stainless steel welding may result from more in-depth research. Because of this, mathematical modelling, metallographic characterization, parametric optimization of mechanical properties, and investigations into the effectiveness of welding joints, among other things, are particularly important. Examining this area will help to build a solid knowledge basis that will enable TIG welding to be used in the desired manner with the chosen quality of the weld.

The objective of this research is to use the Taguchi approach to optimize the Tungsten Inert Gas (TIG) welding process parameters, such as welding current, gas flow rate, and welding speed, to improve the mechanical qualities of ASTM/UNS 2205 Duplex Stainless Steel (DSS) welding connections, particularly hardness. The study also aims to assess the individual factors' relevance on the welding quality by utilizing statistical tools such as Analysis of Variance (ANOVA). The research contributes to achieving good hardness value (HV) for DSS welding connections by utilizing parametric optimization based on the experimental data obtained from this investigation.

METHOD

In the experimental setup for TIG welding of duplex stainless-steel plates, 75 mm 50 mm 3 mm plates, an IGBT digital welding inverter (400A, III phases) from Electra Engineering (India) Pvt. Limited, and a tungsten electrode with a diameter of 2.4 mm were employed. During the welding procedure, no filler rod was employed. As a shielding gas, argon gas was used. The welding parameters, including current, gas flow rate, and welding speed, were set appropriately for the welding process. The butt-welding joint was completed, and the resulting weld was analysed to evaluate the mechanical and metallurgical properties of the welded material. Figure 1 depicts the arrangement of TIG welding equipment. Then, Figure 2 portrays welding sample number 4 during experimentation. The trial runs of welding joints and final welding joints were successfully completed with the assistance of this welding equipment.

Figure 1. Setup of welding

Figure 2. Sample no. 4 after welding

1. Base Metal

Duplex stainless steel (DSS) is a type of stainless steel with a two-phase microstructure consisting of austenite and ferrite. This microstructure provides a unique combination of high strength and corrosion resistance, making DSS a popular choice in a wide range of applications, including chemical processing, oil and gas, and marine engineering.

The chemical composition of DSS typically includes a high level of chromium, which provides corrosion resistance, as well as significant amounts of nickel, molybdenum, and nitrogen. The specific chemical composition of the DSS material used in the study is shown in Table 1.

The duplex microstructure of DSS provides several advantages over other types of stainless steel. In terms of welding, the duplex microstructure of DSS can present some challenges. Welding parameters must be carefully controlled to prevent the formation of harmful phases, such as the sigma phase, which can reduce the material's corrosion resistance. However, with proper welding techniques, DSS can be successfully welded using a variety of methods, including TIG welding, MIG welding, and stick welding.

 10.12928/ijio.v4i2. 7756

Table 1. Composition of DSS

	C	Si	Mn	P	S	Cr	Mo	Ni	Al
Composition of elements in %	0.0210	0.2800	1.7200	0.0220	0.0140	22.6500	3.1800	4.7300	0.0100
	Co	**Cu**	**Nb**	**Ti**	**V**	**Pb**	**Fe**	**N**	
	0.0780	0.0090	0.0400	0.0080	0.0110	0.0030	67.123	0.1010	

2. Process Parameters and Their Levels

To optimize the welding process for hardness, the researchers conducted several experimental trials using different combinations of welding parameters. Based on the results of these trials, they selected three levels of welding current, gas flow rate, and welding speed to use in the joining process. Table 2 lists the welding process factors and their levels.

Table 2. Welding process factors with their levels

Factors	Units	Notations	Levels		
			1	**2**	**3**
Welding Current	A	C	80	85	90
Gas Flow Rate	l/min	F	7	7.5	8
Welding Speed	mm/s	S	2.3	2.8	3.5

The researchers systematically varied these factors to determine the optimal combination of parameters that would result in the highest hardness of the welded joint. By conducting experiments at each level of each factor, they created a matrix of data that could be analyzed statistically to identify the optimal parameter settings.

RESULTS AND DISCUSSION

Following the X-ray radiography research, Vickers hardness testing samples from TIG welding plates was performed using Electronica Sprint Cut-734 Wire Electrical Discharge Machining (WEDM) technique. This machining method's input power supply is 3 Phases, AC 415 V, 50 Hz, and the associated load is 15 KVA. Figure 3 depicts a photographic representation of WEDM's Vickers hardness specimen preparation.

Figure 3. Vickers hardness specimen preparation by WEDM

Looking Vickers hardness testing is a method used to measure the hardness of a material by indenting it with a diamond-shaped indenter and measuring the size of the resulting impression. This test can provide information about a material's strength and resistance to deformation. The hardness test of samples is performed at the National Institute of Technical Teachers Training & Research (NITTTR), Kolkata.Hardness test is performed by the Micro hardness tester (Auto), manufactured by Micro-mach technologies, model no MMV-A, SR No.-130.

By performing hardness testing, one can assess the material properties and determine if the welding process that has affected the material structure and strength.

A hardness testing was conducted using a Vickers indenter with a face angle of 1360. The testing involves indenting three points in the welding zone, HAZ zone, and base metal, and measuring the diagonal of the resulting indentation using a digital filler micrometre eyepiece with an accuracy of 0.025 microns and a magnification of 50X. The load applied during the test is 1000 grams. The photographic representation of the micro hardness tester is shown in Figure 4.Vickers hardness image of the welding metal area of sample no .4 is shown in Figure 5.

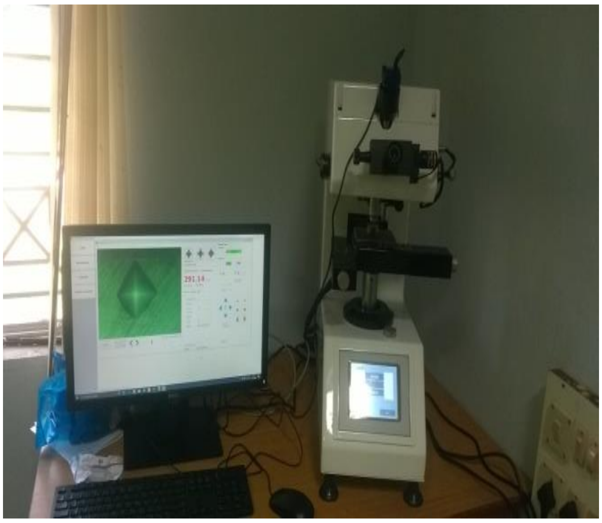

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Figure 4. Photographic view of microhardness tester

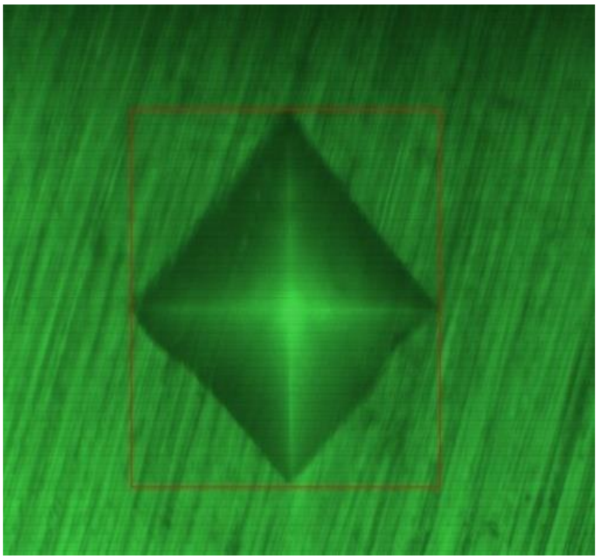

Figure 5. Vickers hardness image of the welding metal area of sample no. 4

The Vickers hardness number (HV) is obtained by dividing the force applied to the Vickers indenter by the surface area of the permanent impression made by the indenter. So, the Vickers hardness, kgf/mm^2 is determined as:

$HV=1.8544 \times P_1/d_1$

Where P_1 is the force in kgf and

d_1 is the length of the long diagonal in mm.

The results of the hardness test with welding parameters are given in Table 3.

 10.12928/ijio.v4i2. 7756

Table 3. The results of the hardness test with welding parameters

Sample no.	Welding Parameter with value			Average hardness (HV)		
	Current (A	Welding speed (mm/s)	Shielding gas flow rate (l/min)	Welding metal	HAZ	Base metal
1	80	2.3	7	285.39	274.53	249.88
2	80	2.8	7.5	255.41	250.88	248.09
3	80	3.5	8	270.43	261.76	248.45
4	85	2.8	7	279.81	270.58	249. 13
5	85	3.5	7.5	270.43	263.22	248.59
6	85	2.3	8	275.06	268.45	248.78
7	90	3.5	7	282.58	273.12	249.61
8	90	2.3	7.5	279.81	271.38	249. 44
9	90	2.8	8	291.14	282.65	250.18

The average hardness of the welding zone of sample no. 2 is 255.41HV which is the lowest hardness and in sample no. 9 the average hardness is 291.14 which is the highest hardness. Here, the satisfactory hardness results come out for TIG welded DSS UNS2205 materials.

1. Parametric Optimization by Taguchi Method

In this study, the objective was to identify the best parametric condition for TIG welding of duplex stainless-steel plates. Single-objective process optimization was performed using Taguchi's orthogonal array method to optimize the Vickers hardness value of the welding zone. Vickers hardness is an important design criterion that indicates the maximum load a welded sample can withstand. The optimization aimed to maximize the Vickers hardness value, which would result in a stronger and more durable welded joint. The Taguchi method is a powerful statistical approach that allows for the optimization of multiple parameters simultaneously while minimizing the number of experiments needed. The selected parametric circumstances were tested, and the resulting Vickers hardness values have been studied for the purpose to establish the optimal parametric condition for TIG welding duplex stainless-steel plates.

1.1. Single Objective Optimization of HV by Taguchi Method

In this study, the Taguchi method was used to perform single-objective optimization of Vickers hardness for TIG welding of duplex stainless-steel plates. The welding process parameters and their corresponding values were given in Table 2, and the optimized parametric condition for HV was obtained using the observed results given in Table 3 with the help of MINITAB 16 software. Two response tables were generated, namely, the Response Table for Signal-to-Noise Ratios Larger is Better and the Response Table for Means, which were described in Tables 4 and Table 5, respectively. The main effects plot for SN ratios and the main effects plot for the mean were given in Figures 6 and Figure 7, respectively. The optimized parametric combination for maximizing the Vickers hardness value (larger is better) was found to be C3 F1 S1, where welding current (C) was set to 90 A, gas flow rate (F) was set to 7 l/min, and welding speed (S) was set to 2.3 mm/s. These results indicate that the chosen welding parameters were optimal for producing a strong and durable welded joint with a high Vickers hardness value.

Table 4. Response Table for Signal-to-Noise Ratios, Larger is better

Level	C	F	S
1	48.63	49.02	48.94
2	48.79	48.57	48.79
3	49.08	48.90	48.77
Delta	0.45	0.45	0.18
Rank	1	2	3

Table 5. Response Table for Means

Level	C	F	S
1	270.4	282.6	280.1
2	275.1	268.6	275.5
3	284.5	278.9	274.5
Delta	0.45	0.45	0.18
Rank	1	2	3

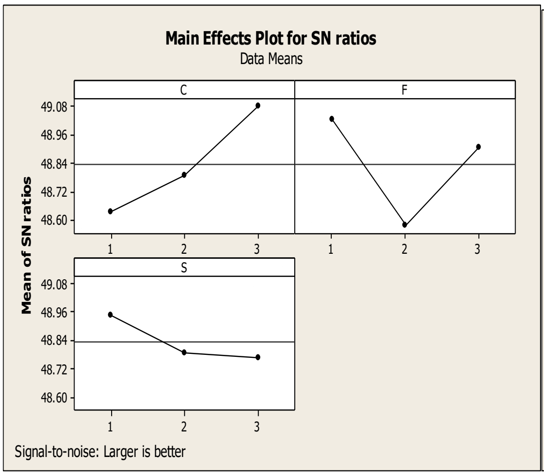

Figure 6. Main effects plot for SN ratios

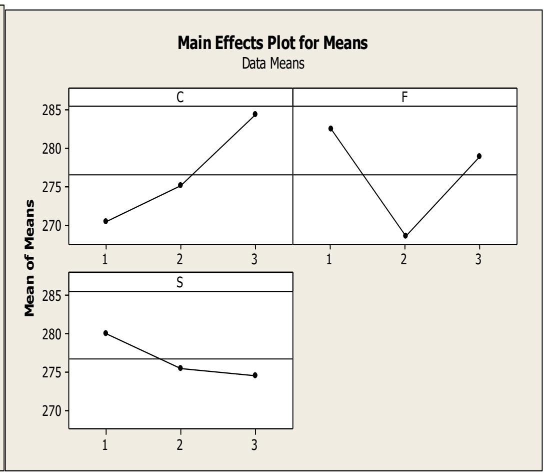

Figure 7. Main effects plot for means

1.2. Analysis of Variance (ANOVA)

In this study, ANOVA was used to analyse the experimental data and draw conclusions about the effects of various factors on Vickers hardness. The main Effects Plot for HV was shown in Figure 8, and the Analysis of Variance for HV was presented in Table 6. The R-Sq score indicated that the experimental model explained at least 78.04% of the variability in the data for the answers.

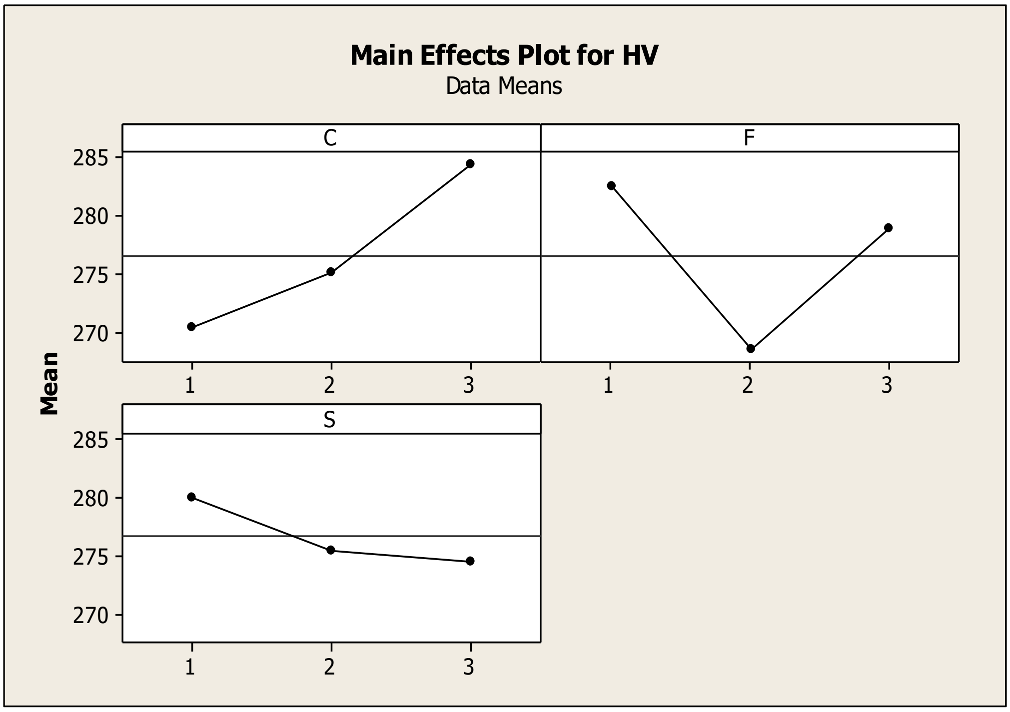

Figure 8. Main effects plot for HV

10.12928/ijio.v4i2. 7756

Table 6. Analysis of variance for HV

Source	DF	Seq SS	Adj SS	Adj MS	F	P
C	2	309.35	309.35	154.68	1.61	0.383
F	2	317.67	317.67	158.83	1.66	0.376
S	2	53.85	53.85	26.92	0.28	0.781
Error	2	191.65	191.65	95.82		
Total	8	872.52				
S = 9.78899 R-Sq = 78.04% R-Sq(adj) = 12.14%						

The significance of the ANOVA components was comparable with the results, where current was ranked first and welding speed was ranked third. These findings suggest that welding current had the most significant effect on Vickers hardness, followed by gas flow rate and welding speed, respectively. Overall, ANOVA was a valuable tool for determining the most important factors affecting the response variable [21, 22] and for identifying the optimal parametric combination for TIG welding of duplex stainless-steel plates.

CONCLUSION

Based on the results of the experiment and analysis, it is possible to conclude that a welding current of 90 A, a gas flow rate of 7 l/min, and a welding speed of 2.3 mm/s are the most effective parametric combinations for TIG welding of Duplex stainless-steel ASTM/UNS: 2205. According to the ANOVA study, welding current has the greatest impact on weld quality and characteristics, whereas welding speed has the least impact. The confirmatory test backs up the findings of the grey-based Taguchi approach. These optimised values were evaluated and resulted in a strong butt joint with good mechanical and metallurgical qualities. Therefore, the use of the Grey-based Taguchi method is an effective approach for optimizing the welding parameters of duplex stainless steel, which can lead to improved weld quality and properties. The optimized parameters resulted in a sound butt joint with good mechanical and metallurgical properties, including high tensile strength and good corrosion resistance. The welding current significantly affects the weld quality and properties of the duplex stainless-steel ASTM/UNS: 2205, while the effect of gas flow rate and welding speed is relatively less significant. Further studies can be conducted to investigate the effect of other parameters, such as electrode type, preheating temperature, and post-weld heat treatment, on the weld quality and properties of duplex stainless-steel ASTM/UNS: 2205.

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