The Role of Nanoparticle Based Coating in Optimizing TIG Welding Parameters for EN31 Steel

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Abstract. This study investigates the optimization of process parameters in TIG welding of EN31 steel alloys, incorporating nano-enhanced materials to improve performance in sustainable manufacturing and energy-efficient applications. The three key input variables considered are welding current (CT), welding speed (WD), and gas flow rate (GF), while tensile strength (TS) and hardness (HS) are taken as output responses. The experiment was designed using the Central Composite Design (CCD) under the Response Surface Methodology (RSM) framework, with 20 experiments conducted. Nanoparticle ($TiO2$ & B4C) were coated with EN31 steel to enhance chemical reactions, improve weld quality, and promote energy efficiency. Results indicate that the optimal conditions for tensile strength (TS) were achieved at 120 Amps CT, 70 mm/min WD, and 11 lpm GF. For hardness (HS), the optimal conditions were 100 Amps CT, 70 mm/min WD, and 11 lpm GF. Analysis of variance revealed that the welding current (CT) significantly impacts both TS and HS, while the integration of nano materials further improved these mechanical properties by enhancing microstructural refinement and energy efficiency. The experimental data closely aligned with the normal probability plot, confirming the reliability of the results. This study highlights the potential of nano-enhanced TIG welding as a sustainable solution for improving the mechanical properties of steel alloys while promoting energy-efficient manufacturing practices

Keywords: TIG welding, Nano materials, optimization, energy-efficient and sustainable manufacturing

1. Introduction

When pressure parts for oil refining vessels or other items with extraordinary quality standards are required, TIG welding is always a highly sought-after process [1]. Its fluxless functioning and inert gas shielding are the reasons behind this. For dissimilar welded parts without welding flaws, the TIG welding method is also successfully used [2]. By combining RSM with a cutting-edge Heat Transfer Search optimisation algorithm, J. Vora et al. [3] have reported optimizing the machining variables of the A-TIG welding process, specifically for achieving full penetration in 6 mm thick carbon steels. In the experiments, penetrating depth, depths-to-width ratio, heat input, and width within the HAZ were taken into consideration as output variables, while welding current, length of the arc, and torch travel speed were chosen as input process parameters.

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For the response characteristics, statistical models are formed using the experiment data. Minh et al. [4] examined the effects of welding parameters on the geometry and mechanical characteristics of TIG orbital welding on 304 stainless steel pipe. The factors including welding angle, current, speed, duration of pulse, and also height of torch. The Taguchi method is used to optimise the manufacturing process. The findings may be used to enhance the SUS Stainless Steel 304 pipe's TIG orbital welding quality. the welding of 316 L steel plates was examined by Lothongkum et al. [5]. It has been demonstrated that a higher welding speed results in a higher pulse current. Slag formation occurs when the welding speed is increased to a rate greater than 6 mm/s. Under the observation of high-dynamic-range videography, Riffel et al. [6]autonomously welded a SUS 304 L stainless steel pipe at a speed of 500 mm/min.

Without any porosity, discontinuities, or lack of fusion, the welded junction was successfully created. Using the Taguchi approach, Natrayan et al. [7]adjusted three TIG welding parameters to determine which one contributed most to the tensile strength. utilising the GMAW process, Ramarao et al. [8] evaluated which parameter had the most influence on the welding of two different metals by utilizing the Taguchi method. Using the mechanical characteristics of the weld bead as output parameters, Vinoth et al. [9] optimised the input parameters for the TIG welding of stainless steel. S. Prasath et al.'s study [10]looked into ways to maximize the tensile strength of dissimilar the ZM21 and AZ31 magnesium alloy joints by optimizing the pulsed TIG welding parameters, notably the welding current, pulsing frequency, and welding speed. To optimize the TIG process parameters, one uses the Taguchi L9 orthogonal array. To confirm the weldment's mechanical strength, the tensile strength of the joints was assessed. The influence of input factors on the tensile strength was examined. The greatest SN ratio is considered at a greater value when the study's quality characteristic lies closer to the intensification function. The micro and macrostructure of the various weld zones were used to do the metallurgical characterization. The results established that the dissimilar joints of ZM21 and AZ31 were effectively created by pulsed TIG weld, which are free from porosity and cracking flaws. To maximize the tensile strength of different magnesium alloy joint, welding parameters were to be optimized. The joint that was formed using a 160 A of welding current, 100 HZ of pulse frequency, and 160 mm/min of welding speed showed a maximum UTS of 178 MPa. V. Mohanavel et al. [11] studied the numerical and experimental outcomes of AA6061 TIG welding. The Taguchi technique was applied to optimize the welding parameters, such as gas flow rate, current, and speed to combine AA6061 plates. In order to make a weld joint with the highest impact strength, the parameter combinations were carefully chosen. Four parameter levels were used for the experimental experiments, in accordance with the L16 orthogonal array. ANOVA and SN ratio were employed to evaluate the experimental findings. According to the findings, welding speed and welding current are the next most important parameters that affect the strength of the weld connections, after gas flow rate.In this work, The EN31steel plates are joined togetr with aid og TIG welding. The input variables can be analysed through optimization technique and also find the which variable contributes to improve tensile strength and hardness of weld joints.

2. Materials and methods

The EN31 steel plates are chosen because of their cross-sectional measurements of 140 mm in length, 50 mm in width, and 5 mm in thickness. The substance for the electrode is tungsten. The experimental specimen must first have its edges prepared in order to achieve maximum fusion at the weld root with the least amount of weld metal. Achieving full welding penetration and minimising component deformation throughout the welding process depend on this. After that, the two workpieces are placed on the bed and fused together with a TIG welding equipment. The levels of the three input variables—CT, WD, and GF—that have been chosen are shown in the table.1. Twenty welding operations are completed in accordance with the CCD-RSM approach, and the combination of all variables for all tests is displayed in the table.2. The welded joints are cut in accordance with ASTM standard specifications in order to perform the tensile test. The ball indenter is used to measure hardness at intervals of 15 seconds when the load is 250 grammes. The table displays the TS and HS readings for each weld joint.2.

Table 1. TIG variables and their levels

Variables	**Units**	Level-1	Level-2	Level-3
Current (CT)	Amp	100	120	140
weld speed (WD)	mm/min	50	60	70
Gas Flow Rate (GF)	lpm	10	12	14

Table 2. combination of variables for experimentation

EXP.NO	CT	WD	GF	TS	HS
1	100	50	12	250.2	88.5
2	120	60	11	260.4	95.6
3	120	60	11	302.1	94.2
4	100	50	10	229.3	84.3
5	120	60	12	245.8	81.6
6	140	50	12	294.2	78.9
7	120	60	11	288.9	79.6
8	120	50	11	278.5	81.2
9	120	60	10	261.9	77.6
10	140	70	10	302.6	84.3
11	140	70	12	305.6	89.5
12	100	60	11	312.5	91.2
13	140	60	11	208.6	71.5
14	140	60	10	279.5	79.5
15	120	70	11	315.5	88.5
16	140	50	10	294.5	83.6
17	100	70	10	258.4	84.9
18	100	70	12	246.8	79.5
19	120	60	11	310.6	91.6
20	120	50	11	288.9	90.2

Fig. 1. TIG welded samples

3. Result ad discussion

Fig. 2 displays a 3D plot illustrating the relationship between input variables (CT, WD, and GF) and TS (tensile strength). The plot indicates that TS increases as both CT and WD rise, as depicted in Fig. 2a. The elevation of CT at the point of contact, across different scenarios, potentially contributes to the enhanced strength of the plates.Fig.2b and 2c revealed that the interaction of CT vs GF and WD vs GF in which TS is increased due to increasing of WD and reducing of GF. Fig.3 illustrated the 3d plots between input variables (CT, WD and GF) on HS. it is concluded that HS is increasing by increasing CT and GF and decreased by WD. From overall experiment results of TS and HS, the higest TS and HS are observed at Experiment : 15 and 2 respectively.

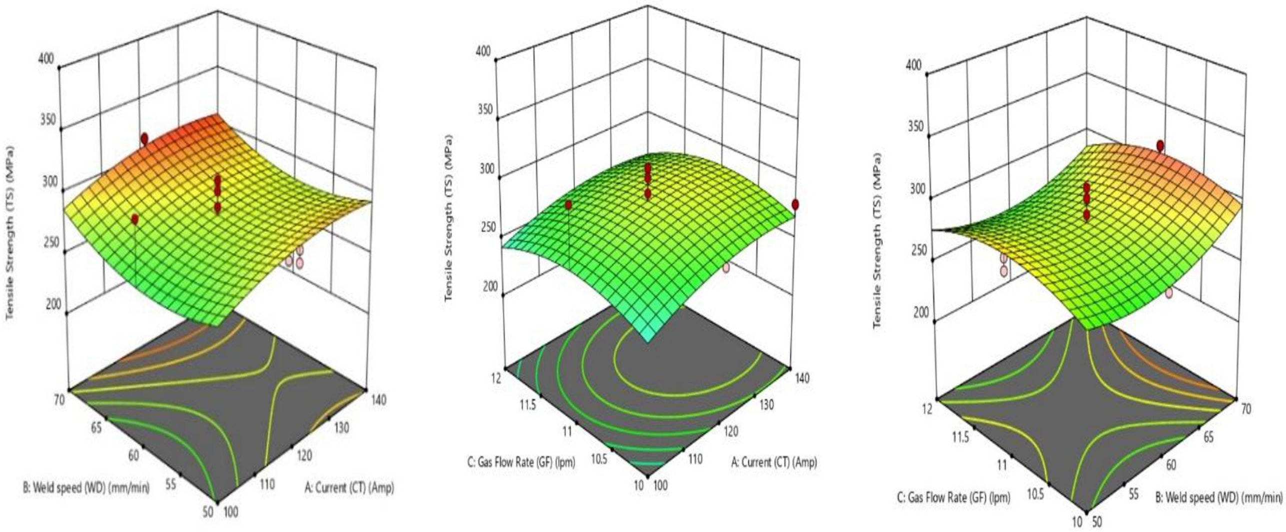

Fig. 2. 3D Interaction plots for tensile strength

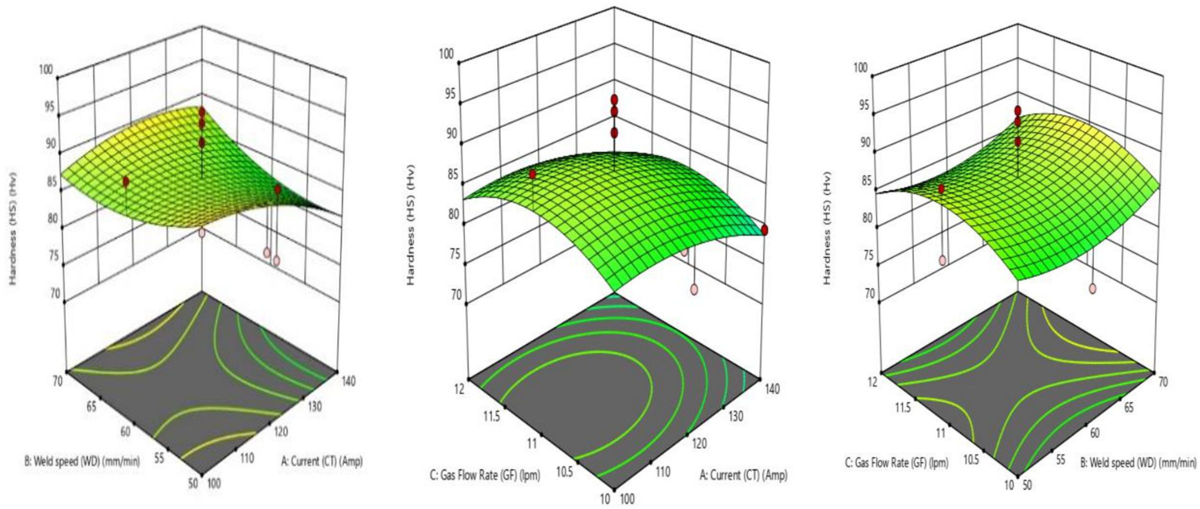

Fig. 3. 3D Interaction plots for Hardness

A CCD-RSM provides an L20 orthogonal array, selected for experimentation involving three unique welding configurations. Utilizing the S/N ratio, a logarithmic function representing the desired outcome serves as the objective function for optimizing process parameters. This approach is recommended for data analysis. Moreover, employing this method facilitates data analysis and the prediction of optimal levels during the welding process [12][13][14][15]. according to plot graph for the S/N ratios (Fig.4 and 5). The optimal values for maximizing tensile strength are CT of 120 Amps, WD of 70mm/min and GF of 11 lpm and he optimal values for maximizing hardness are obtained at CT of 100 Amps, WD of 70mm/min and GF of 11 lpm.

ANOVA is a statistical technique that looks at the averages of multiple groups in order to determine if there are any statistically significant differences between the groups. Analyzing the F-statistic and p-value that go along with it is necessary to understand the meaning of the ANOVA table. If the value of the p-value is lower than the chosen significance level, which is usually 0.05, the idea of a null is to be rejected and it is concluded that the mean of at least one group varies from the others. The ANOVA results indicate that the current has the greatest impact on the advancement of TS and HS. since the P value is below 0.05. The mechanical characteristics (TS and HS) of Tig weld EN 31 plates are enhanced by gas flow, which is the second significant variable.

Table 3. Tensile strength ANOVA result

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**
Model	4488.40	9	498.71	0.3900	0.00913
Current (CT)	1507.52	1	1507.52	1.18	0.0030
Weld speed (WD)	783.72	1	783.72	0.6130	0.0045
Gas Flow Rate (GF)	23.41	1	23.41	0.0183	0.0089
CT* WD	4.81	1	4.81	0.0038	0.0095
CT* GF	40.61	1	40.61	0.0318	0.0086

WD* GF	106.58	1	106.58	0.0834	0.0077
CT ²	383.91	1	383.91	0.3003	0.0059
WD ²	1249.94	1	1249.94	0.9776	0.0034
GF ²	973.98	1	973.98	0.7618	0.0040
Residual	12785.95	10	1278.60		
Lack of Fit	11284.73	6	1880.79	5.01	0.00703
Pure Error	1501.22	4	375.31		
Cor Total	17274.35	19			

Table 4. Hardness ANOVA result

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**
Model	217.98	9	24.22	0.4615	0.008700
Current (CT)	42.21	1	42.21	0.8043	0.003909
Weld speed (WD)	7.27	1	7.27	0.1385	0.007175
Gas Flow Rate (GF)	0.7287	1	0.7287	0.0139	0.009085
CT* WD	48.51	1	48.51	0.9244	0.003590
CT* GF	0.1398	1	0.1398	0.0027	0.009598
WD* GF	0.0113	1	0.0113	0.0002	0.009886
CT ²	11.53	1	11.53	0.2197	0.006493
WD ²	18.11	1	18.11	0.3451	0.005699
GF ²	41.33	1	41.33	0.7876	0.003957
Residual	524.76	10	52.48		
Lack of Fit	324.79	6	54.13	1.08	0.004919
Pure Error	199.97	4	49.99		
Cor Total	742.74	19			

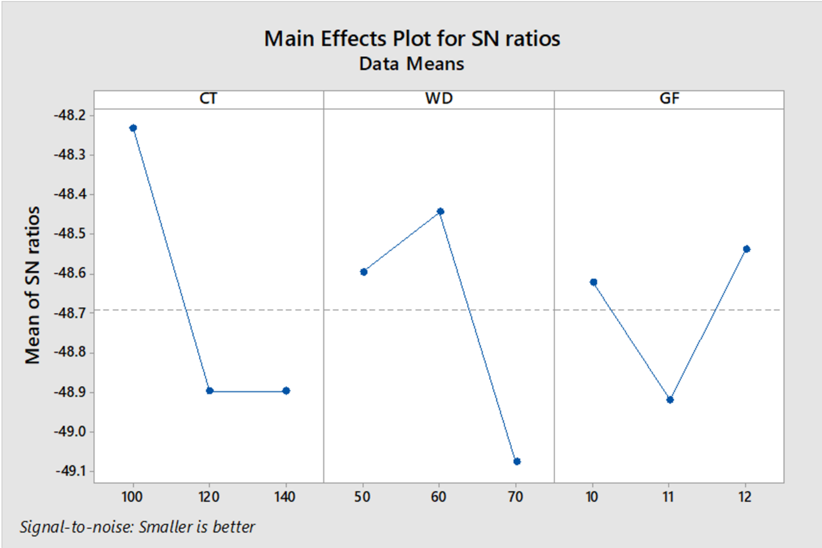

Fig. 4. SN ratio for TS

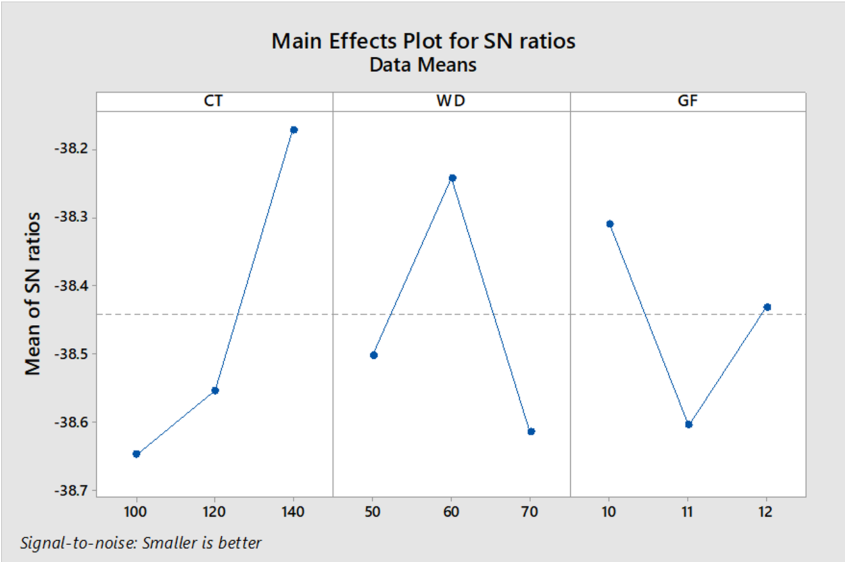

Fig. 5. SN ratio for HN

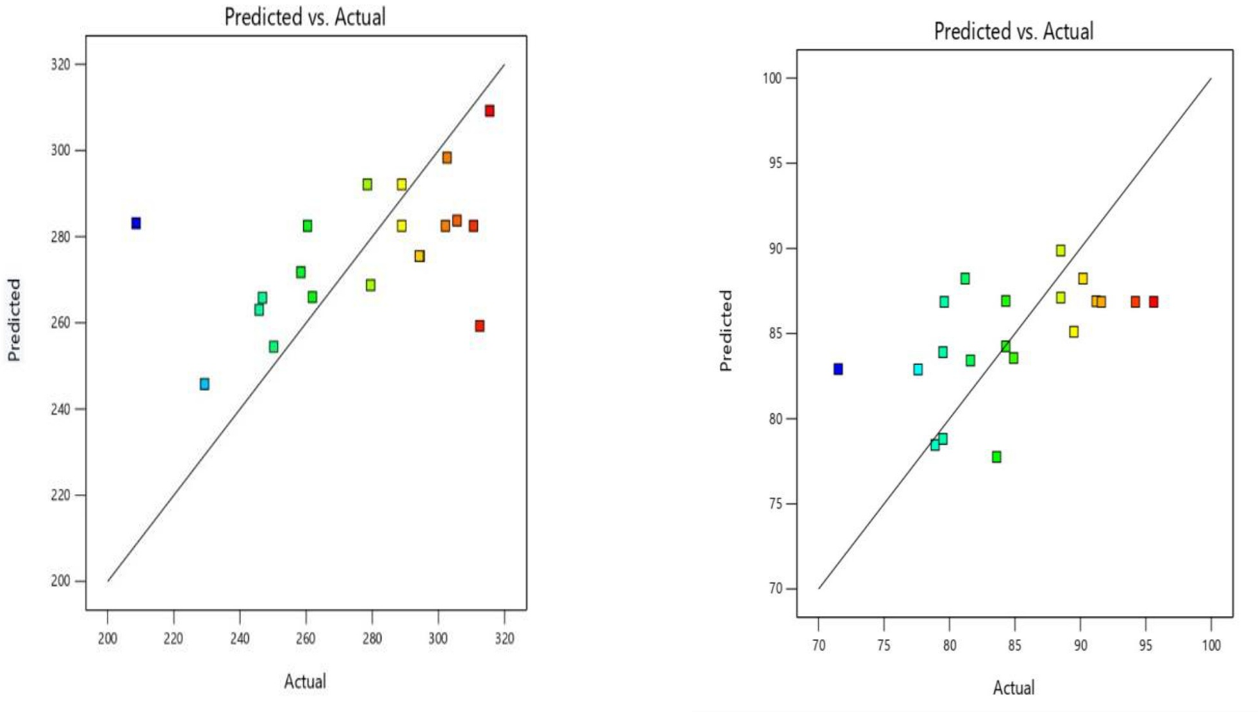

Fig. 6. Predicted vs actaul value for TS and HS

Normal probability plots are useful for visually assessing the normality assumption, which is often required for many statistical analyses such as t-tests, ANOVA, and linear regression. If the data are not normally distributed, transformations or non-parametric methods may be necessary to analyze the data appropriately. scatter plot of predicted versus actual values, is a graphical tool used to assess the performance of a predictive model. It is commonly used in regression analysis to visually examine how well the model's predictions match the actual values of the dependent variable. From the Fig.6 , the predicted data is represented in y-axis and actual data is represented in X-axis in which both values are very close to each other in tensile strength and hardness plots.

4. Conclusion

- This study addresses the TIG welding technique for EN31 steel joints in the structural application of industries. The process variables in TIG was found by the CCD-RSM method, and ANOVA was used to evaluate the which variables affects the tensile and hardness of the joint. The following results were concluded from the present study.
- From overall experiment results of TS and HS, the highest TS and HS are observed at Experiment: 15 and 2 respectively.
- The optimization result revealed that The optimal conditions for maximum TS is obtained at CT of 120 Amps, WD of 70mm/min and GF of 11 lpm and optimal conditions for HS is also obtained at CT of 100 Amps, WD of 70mm/min and GF of 11 lpm.
- From the analysis of variance, Current is most important variable which increase the tensile strength and hardness of EN31 steel joint and the experimental data for TS and HS align closely with a straight line from normal probability plot.

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