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Prediction of Convective Heat Transfer Coefficient in Tungsten Inert Gas Welding

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ABSTRACT: Tungsten Inert Gas (TIG) Welding is used in pipeline and pipe welding as well as in aviation and aerospace and sheet metal industries when welding particularly thin materials and special materials such as titanium. Thus, the objective of this paper is to predict the convective heat transfer coefficient (CHTC) in Tungsten Inert Gas (TIG) welding using Response Surface Methodology (RSM) was used in the study to optimize welding parameters, such as welding voltage, current, and speed, enhance the understanding of heat transfer during the welding process. The results indicate a robust correlation between the input parameters and the CHTC, and the data is well-fitted by the quadratic model (R^2 = 0.9848). The model's relevance is validated by analysis of variance (ANOVA), showing a P-value of less than 0.05. The results show that welding current and speed have the greatest impact on the CHTC, with voltage having a minor effect. The study concludes that RSM is a useful technique for predicting CHTC in TIG welding, offering insightful insight for improving the welding process and the quality of welded joints. This research makes a noteworthy contribution to the field by showcasing that the predictive model developed can effectively optimize heat management in welding applications, leading to enhanced performance and reliability of welded structures.

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Tungsten electrodes are shielded during the TIG welding process by an inert gas flow, including argon, helium, nitrogen, hydrogen, or combinations. In the fusion, pressure, and soldering processes, heat and pressure are used to fuse the solids in the same or distinct kinds of metal materials (Hashemabad *et al*., 2016; Liu *et al*., 2018; Eboigbe and Ikponmwosa-Eweka, 2021). The fusion process raises the base metal's melting temperature to a degree where it fuses together by forming a heat source with an electrode and an electrical power supply. Two examples of fusion types are gas metal arc welding (GMAW) and shield metal arc welding (Janusas *et al.*, 2012; Narasimhan *et al.*, 2019; Urban, 2017). Among the several forms of fusion welding are gas metal arc welding (GMAW) and shield metal arc welding (SMAW). Urban (2017), Janusas *et al.* (2012), Narasimhan *et al.* (2019). General metal arc welding (GMAW) is a form of arc welding where a plasma arc connects the weld pool to a continuous, consumable filler metall electrode. Magalhaes and associates (2016); Ellen (2002). A thorough grasp of temperature gradients, heat flux, and the cooling process is necessary for investigations on the welding process Magalhaes *et al.* (2016).Conduction within the body, convection, and radiation from the body's surface, and

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conduction of heat to another body are the three main ways that a body loses heat Ellen (2002). The process of welding produces convection, or fluid flow, in the weld pool to re-distribute heat, which can alter the temperature distribution throughout the entire work piece Ellen (2002). Goyal *et al.* (2015) stated in their research work that finding a model equation for the convection coefficient as a function of temperature at a spot on the surface of the structure being welded is the first step towards solving the transient temperature field for a given welding problem. There are one to five parameters in the model equation. An inverse problem involving the computation of the transient temperature in a transient thermal analysis of welding the structure is solved to estimate the parameter values that minimize the difference between the transient temperatures measured at numerous sites. Vinokurov's model equation and the L2 norms of the temperature deviation for the model equation with optimized parameters are compared.

Furthermore, an estimation of the impact of parameter variations from their ideal values on the calculated temperature, distortion, and residual stress is derived from a thermal-microstructure-stress analysis of the structure's welding. The function is validated using experimental findings after being numerically modeled Goyal *et al.* (2015). The thermal influence of heat transmission during the gas tungsten arc (GTA) welding process via radiation and convection was analyzed by Magalhaes *et al.* in their research work titled A GTA Welding Cooling Rate Analysis on Stainless Steel and Aluminum Using Inverse Problems. Using updated internal C++ code that the authors had previously created, the amount of heat transmission by radiation and convection was determined. This software used an iterative Broydon-Fletcher-Goldfarb-Shanno (BFGS) inverse technique to estimate the amount of heat conveyed to the plate once the appropriate sensitivity conditions were determined. The procedure was validated by conducting controlled laboratory tests on AISI 304L stainless steel and aluminum 6065 T5 plates. Due to specific experimental singularities, the forced thermal convection brought on by the thermal-capillary force and electromagnetic field was disregarded. Two prominent instances of these singularities are the very small weld bead in comparison to the sample size and the decreased welding process duration. The local Nusselt number was determined using empirical correlations for flat plates. Thermal emission was one of the primary cooling impacts on the aluminum cooling. But it didn't have the same qualities as the stainless steel ones. The research indicates that convection and radiation heat losses in the weld pool have minimal effect on the cooling process Elisan *et al.* (2017). Researchers like Ikponmwosa-Eweka and Achebo (2023) have previously employed response surface methodology (RSM) to optimize specific welding parameters. In their study, they were able to effectively apply RSM to optimize the heat input during the TIG welding process at steady state conditions. The purpose of this work is to use Response Surface Methodology (RSM) to predict the convective heat transfer coefficient during the TIG welding process under steady state conditions.

MATERIALS AND METHOD

The test piece material was mild steel plate, which was chopped into pieces with a power hack saw. The samples underwent longitudinal cutting, cleaning, grinding, and edge machining. After the edges were machined, the weld specimen was created using tungsten inert gas welding equipment. To create the 100 weldment samples utilized in the studies, 200 mild steel coupons with dimensions of 80 x 40 x 10 mm were employed. Each of the 20 runs of the experiment included 5 specimens. A central composite design matrix was generated, resulting in 20 experimental runs, using the design expert program. Expert Design version 7.01 was utilized to assist in the process of experimental design. The experimental matrix is composed of the input parameters (Current I, welding speed mm/s, and voltage V) and output parameters (convective heat transfer coefficient h W/(m2 ºC)). The data used in the matrix was the responses noted from the weld samples. This research investigation used 100% pure argon gas as a shielding gas. Based on previously published research, Table 1 displays the range and levels of the process parameters that were used to design the experiment.

Table 1: Process parameters and their levels

Process parameters	Unit	Symbol	Low (-)	High (+)
Welding Current	Amp	I	170	190
Welding Voltage	Volts	V	20	22
Welding Speed	mm/Sec	M	2.6	3.0

The data source for the analysis was the gathered experimental results. The RSM prediction model was utilized to determine the convective heat transfer coefficient. First, the statistical design of experiment (DOE) was conducted using the central composite design technique (CCD). The design and optimization were completed using a statistical technique. Design Expert 7.01 was used in this particular instance.

Statistical analysis was done to look at the variability in the experimental design of the model.

RESULTS AND DISCUSSION

Experimental results obtained is presented in table 2. The result was used as data for analysis. To and T_L represents temperature before the welding process started and temperature after the completion of the welding process and they were recorded in ^{0}C.

Modelling for Convective Heat Transfer Coefficient: The applicability of the model was confirmed by creating the goodness of fit tables, the analysis of variance table, and the sequential sum of square table for the convective heat transfer coefficient using RSM. To verify that the quadratic model was suitable for understanding the experimental data, the sequential model sum of squares for the convective heat transfer coefficient were computed.

Table 2: Experimental results

	Input Parameters					
S/N	Current I, Amp	Speed mm/sec	Voltage, Volts	To ºC	T_L ºC	Convective Heat Transfer Coefficient, h W/(m^2 ºC)
1	190	2.63	20.73	35	1610	2.20
2	190	2.63	20.72	32	1592	2.40
3	190	2.63	20.70	33	1598	2.34
4	190	2.63	20.68	29	1625	2.60
5	190	2.62	20.78	36	1720	2.44
6	170	2.80	20.00	35	1672	2.27
7	170	3.00	21.00	34	1658	2.27
8	170	3.00	22.00	36	1586	2.24
9	170	3.00	20.00	38	1615	2.47
10	180	2.60	21.00	30	1710	2.54
11	180	2.60	22.00	35	1672	2.00
12	180	2.60	20.00	31	1545	2.14
13	180	2.80	21.00	37	1640	2.54
14	180	2.80	22.00	36	1655	2.40
15	180	2.80	20.00	38	1632	2.47
16	180	3.00	21.00	32	1610	2.47
17	180	3.00	22.00	37	1698	2.54
18	180	3.00	20.00	36	1668	2.47
19	190	2.60	21.00	34	1628	2.47
20	190	2.60	22.00	32	1646	2.47

Table 3: Sequential Sum of Square for Convective Heat Transfer Coefficient

Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob > F	
Mean vs Total	114.04	1	114.04			
Linear vs Mean	0.043	3	0.014	0.55	0.6541	
2FI vs Linear	0.096	3	0.032	1.30	0.3163	
Quadratic vs 2FI	0.31	3	0.10	149.78	**< 0.0001**	**Suggested**
Cubic vs Quadratic	3.125E-003	4	7.812E-004	1.22	0.3921	Aliased
Residual	3.830E-003	6	6.383E-004			
Total	114.50	20	5.72			

Table 4: ANOVA Table for Convective Heat Transfer Coefficient

Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob > F	
Model	0.45	9	0.050	72.10	**< 0.0001**	**Significant**
A-current	0.011	1	0.011	15.10	0.0030	
B-welding speed	9.720E-003	1	9.720E-003	13.98	0.0039	
C-voltage	0.023	1	0.023	32.72	0.0002	
AB	4.960E-003	1	4.960E-003	7.13	0.0235	
AC	0.055	1	0.055	79.62	< 0.0001	
BC	0.035	1	0.035	51.02	< 0.0001	
A^2	1.198E-003	1	1.198E-003	1.72	0.2186	
B^2	0.30	1	0.30	435.84	< 0.0001	
C^2	1.043E-004	1	1.043E-004	0.15	0.7067	
Residual	6.955E-003	10	6.955E-004			
Lack of Fit	3.236E-003	5	6.473E-004	0.87	0.5587	not significant
Pure Error	3.719E-003	5	7.437E-004			
Cor Total	0.46	19				

The model was determined to be significant, with a P-value of 0.0001, or less than 0.05. Using the sequential sum of squares for the convective heat transfer coefficient, it was determined that the quadratic model was a suitable fit for analyzing the experimental data. Table 3 displays the data. In assessing the strength of the quadratic model towards maximizing the convective heat transfer coefficient one way analysis of variance (ANOVA) was done and result is presented in Table 4. The Analysis of Variance in Table 4 above demonstrates that the process parameters have a major impact on the Convective Heat Transfer Coefficient. Because the model's value is less than 0.5, at 0.0002, it is noteworthy. In order to confirm the quadratic model's suitability by optimizing the Convective Heat Transfer Coefficient, goodness of fit statistics were produced and are shown in Table 5. The goodness of fit for the convective heat transfer coefficient is displayed in Table 5. It assesses the quadratic model's suitability and strength. The acquired results indicate that, in the event that any of the input parameters change, the model has a 98% capacity to optimize the Convective Heat Transfer Coefficient. Using RSM, the ideal convective heat transfer coefficient equation for this experiment was also produced. Based on the coded variables in equation 1 below, the ideal equations are supplied show the individual effects and combined interactions of the chosen input variables (welding speed, current, and voltage) versus the computed convective heat transfer coefficient.

Any model's acceptability must first be verified by the results of a suitable statistical study. Figure 1 displays the normal probability plot of residual for Convective Heat Transfer Coefficient in order to diagnose the statistical features of the response surface model.

Table 5: Goodness of for Convective Heat Transfer Coefficient

Std. Dev.	0.026	R-Squared	0.9848
Mean	2.39	Adj R-Squared	0.9712
C.V. %	1.10	Pred R-Squared	0.9327
PRESS	0.031	Adeq Precision	31.446

$$Convective\ Heat\ Transfer\ Coefficient = -120.06435 + 0.27620X_1 + 31.84963X_3 + 5.21946X_2 + 0.012450X_1X_3 - 0.016640X_1X_2 - 0.66600X_3X_2 + 9.11903E - 005{X_1}^2 - 3.62576{X_3}^2 - 0.010759{X_2}^2 \quad (1)$$

Where X_1 = Current; X_2 = Voltage; X_3 = Welding Speed

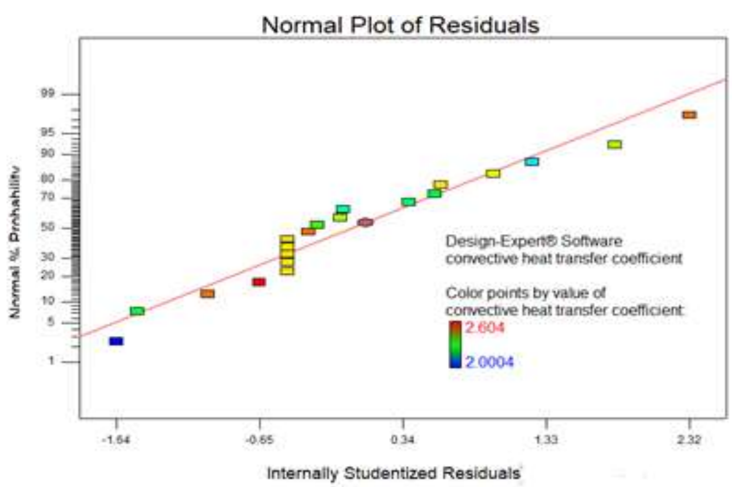

Fig 1: Normal Plot of Residual for Convective Heat Transfer Coefficient

The points exhibit a minor scattering, but they nonetheless appear to follow a straight line. There isn't any pattern that stands out, like a "s-shaped" curve, except from the linear trend. That means that additional analysis can be carried out without changing the response data, and that the residuals are likely to be normally distributed. Figure 2 shows the creation of a 3D surface that was used to investigate the impact of combining welding speed and current on the convective heat transfer coefficient. The surface plots in Figure 2 demonstrate how the combined interaction of welding speed and current has a major impact on the convective transfer coefficient. Thus, raising the welding current and speed will raise the convective transfer coefficient. To further explore the effects of voltage and current on the convective heat transfer coefficient, a three-dimensional surface plot was developed, as shown in Figure 3. The surface plots in Figure 3 show how the convective heat transfer coefficient is impacted by the interaction between voltage and current. The convective transfer coefficient is largely influenced by current, and an increase in current will cause the convective transfer coefficient to grow proportionately, as the 3D diagram indicates. Voltage's impact on the convective heat transfer coefficient is negligible. The 3D surface plot that was made to look into the effects of welding voltage and speed on convective heat transfer is shown in Figure 4.

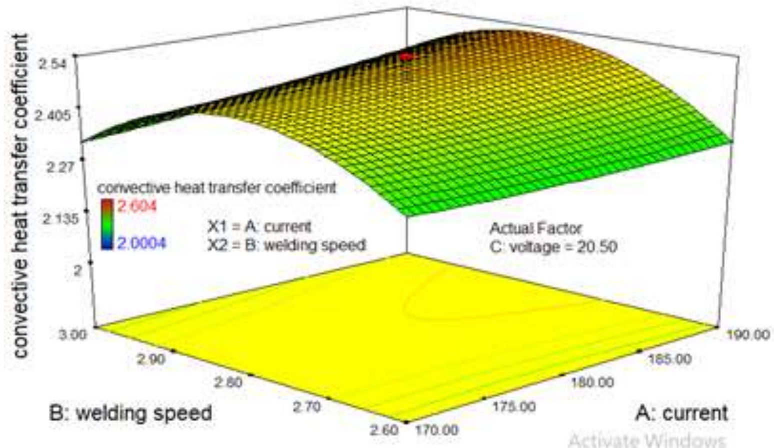

Fig 2: Effect of Welding Speed and Current on Convective Transfer coefficient

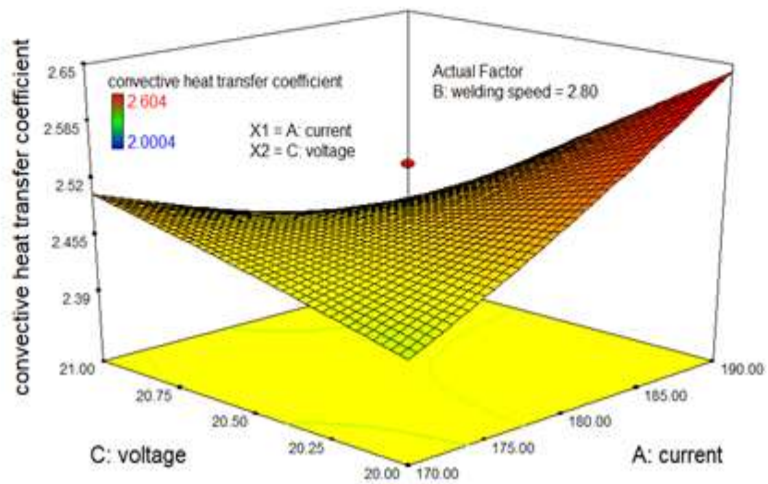

Fig 3: Effect of Voltage and Current Convective Heat Transfer Coefficient

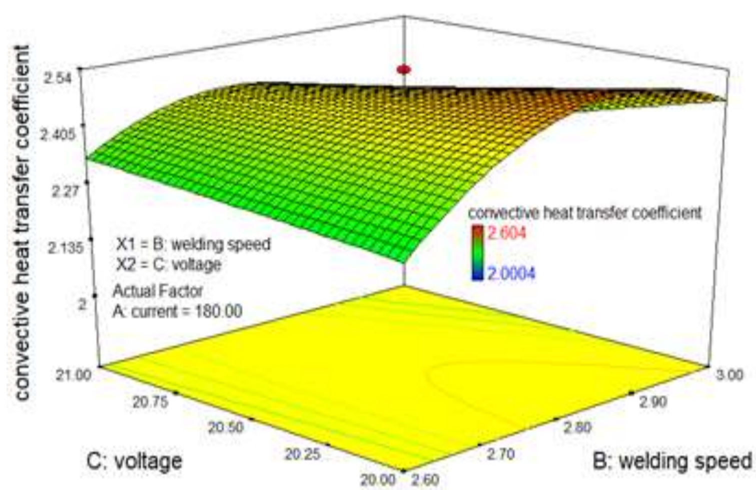

Fig 4: Effect of Voltage and Welding Speed on Convective Heat transfer coefficient

Figure 4's 3D surface plot illustrates the link between welding speed and voltage and how it impacts the convective heat transfer coefficient. The 3D graphic shows that both voltage and current have a major impact on the Convective Transfer coefficient. The Convective Transfer coefficient will rise when the voltage and welding speed are increased simultaneously.

Conclusion: This study used RSM to predict the heat transfer coefficient of the mild steel that was welded during the TIG welding process under steady state conditions. The convective heat transfer coefficient of the welded mild steel samples was predicted in this study using the response surface methodology. The convective heat transfer coefficient of the weld steel was predicted using RSM, according to the results, and it was found that this tool is useful for predicting the convective heat transfer coefficient during the TIG welding procedure. In this research, we have successfully employed RSM to determine that the quadratic model was the most appropriate model for the heat transfer coefficient.

Declaration of Conflict of Interest: **T**here is no conflict of interest.

Data Availability Statement: Data are provided by the first author upon request.

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