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APPLICATION OF RSM IN ANALYZING WELD METAL VISCOSITY IN MILD STEEL WELDS

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ABSTRACT

Weld metal viscosity is an integral part of welding process as it plays a crucial role in the weld quality thereby affecting various parameters such as penetration, bead shape and the potential for possible defects since the viscosity influences how molten metal flows and spreads to fill the welded joints. A number of factors such as temperature, composition can affect the weld viscosity leading to porosity, lack of fusion, incomplete penetration. This study applies response surface methodology (RSM) in analyzing weld metal viscosity in mild steel welds. Twenty (20) experimental runs were carried out using TIG welding process while focusing on four key input parameters – Current (A), Voltage (V), Gas flow rate (L/min) and Material Temperature (^{0}C). The weld viscosity at maximum and minimum level was observed to be 0.00898kg/(m-s) and 0.00635kg/(m-s) respectively where the input parameters (voltage, current and temperatures) were 24V and 21V, 220A, 38^{0}C and 28^{0}C accordingly. This

Introduction:

Viscosity has been described as a rheological property of materials which shows up when the gradient of velocity between close layers of materials is deserved (Hejnak and Migas, 2012). Viscosity of molten welds in mild steel (low-carbon ranging from 0.05 – 0.25% C) (Siqueiros *et al*, 2002) is a key factor during welding processes which affects the flow of fluid, shape of the weld bead, defect formation such as slag inclusion and fusion (Jiang *et al, 2008)*. The process can be described of how the molten metal flows, wets the welded surfaces filling the deep pool and solidifies during the weld pool formation (Mills and Keene, 1992). Tungsten Inert Gas (TIG)

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study explicitly shows that RSM can be applied to analyze and predict optimal value for weld metal viscosity.

Keyword: Mild Steel, Weld Metal Viscosity, Response Surface Methodology (RSM), TIG welding, ANOVA

Welding process produces low viscosity which aid smooth droplets and an even fusion (Kou, 2003). While viscosity decreases with increasing temperature, alloying elements like phosphorus, silicon and sulfur, can increase or decrease the viscosity depending on the actual concentration and interaction with the chosen base metal (Sahoo *et al*, 1988). However, some researchers such as Arunachalam and Gupta (2021) and Joardar *et al* 2014 has applied RSM in both machining processes and determination of cutting forces model.

PROBLEM STATEMENT

During welding processes, residual stresses are inherent and can affect the weld quality. Without precise control over residual stress and weldments, there usually arises a complicated stress and optimization (Zhu and Xie, 2021). The traditional experiment and analytical methods often fall short due to inherent limitations when predicting and controlling residual stress (Ogbeide and Etin-osa 2023). To address these challenges associated with residual stress, computational techniques such as Response Surface Method (RSM) is widely used for optimizing welding parameters, providing insights into the relationship between input variables and response outcome (Otimeyin *et al*, 2025).

RESEARCH OBJECTIVES

1. investigate the influence of welding parameters (current, voltage, gas flow rate, material temperature) on residual stress and weld metal viscosity
2. optimize welding parameters for weld metal viscosity using RSM

RESEARCH QUESTIONS

1. How do welding parameters affect residual stress and weld metal viscosity
2. What is the optimal parameter combination for minimizing residual stress using RSM

RESEARCH METHOD

This study applied Response Surface Method (RSM) to analyze and obtain the optimality for the weld metal viscosity. Mild steel plates were used as the base material due to their widespread industrial application and susceptibility to residual stress during welding. A Tungsten Inert Gas welding machine was employed to conduct the welding operations with the capacity to adjust process parameters such as current, voltage, and gas flow rate. Shielding gas was supplied through a calibrated gas flow regulator to ensure consistent delivery during welding.

Data Collection

Data collection focused on four key input parameters: Current (A), Voltage (V), Gas Flow Rate (L/min), and Material Temperature (°C), which were varied systematically to investigate their effects on weld metal viscosity responses

TABLE 1 WELDING PARAMETERS

Parameters	Value	
	Low	High
Current (A)	190	220
Voltage (V)	21	24
Gas flow rate (L/min)	13	16
Material Temperature (^{0}C)	28	38

Model Building

Using the data obtained from the central composite design (CCD), a second –order polynomial regression model for the weld metal viscosity was developed. The regression equations were fitted by including linear, interaction and quadratic terms.

TABLE 2 EXPERIMENTAL RESULTS WITH 20 RUNS

		Factor 1	Factor 2	Factor 3	Factor 4	Response
Std	Run	A:Current	B:Voltage	C:Gas Flow Rate	D:Material Temp	Weld Metal Viscosity
		A	V	L/min	0C	μ, Kg/(m.s)
5	1	200	22	14	30	0.0072
11	2	200	22	14	30	0.0071
8	3	200	22	14	32	0.0071
18	4	200	22	14	31	0.0072
2	5	200	22	14	32	0.0071
6	6	210	23	15	33	0.00798386
9	7	210	21	15	34	0.00740317
12	8	210	24	15	36	0.00779224
3	9	190	23	15	28	0.00668199
4	10	220	23	15	34	0.00811341
20	11	210	23	13	35	0.00824065
10	12	210	23	16	37	0.00885476

16	13	190	21	13	29	0.00634994
15	14	190	24	13	35	0.00848058
14	15	220	21	13	28	0.00650686
13	16	220	24	13	38	0.00889388
1	17	190	21	16	34	0.00675974
19	18	190	24	16	30	0.00739965
7	19	220	21	16	37	0.00845221
17	20	220	24	16	38	0.00898277

The experimental trials were conducted based on the CCD matrix, and the results for each run are presented. Each row in the table corresponds to a unique combination of the input process parameters (Current, Voltage, Gas Flow Rate, and Ambient Temperature), and the measured output responses (Weld Metal Viscosity). A careful observation of the data reveals how variations in welding parameters significantly affect the viscosity of the mild steel weldments.

Model Analysis

The model analysis used is RSM and ANOVA. The RSM analysis in this study comprehensively assessed the relationship between the welding input parameters and the weld metal viscosity response variables using various statistical and graphical tools. The fit summary will help identify the most suitable model—linear, interaction, or quadratic—based on statistical metrics such as R^2, adjusted R^2, and predicted R^2. The lack-of-fit test will determine the adequacy of the model by comparing the variation due to the model with that due to experimental error. Analysis of variance (ANOVA) will evaluate the significance of each input factor and their interactions, while the fit statistics will provide insights into model precision and reliability.

TABLE 3: Fit Summary for **Weld Metal Viscosity**

Source	Model p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2	
Design Model	< 0.0001	0.0568	0.9495	0.7967	
Linear	< 0.0001	0.0225	0.8604	0.7782	
2FI	0.4866	0.0202	0.8596	0.3472	
Quadratic	**< 0.0001**	**0.8732**	**0.9980**	**0.9528**	**Suggested**
Cubic	0.8732		0.9963		**Aliased**

The Fit Summary for Weld Metal Viscosity and evaluates various models used to predict the viscosity based on their statistical significance and predictive accuracy. The Design Model has a highly significant p-value (< 0.0001) and a strong Adjusted R^2 value of 0.9495, indicating it fits the data well, although its Lack of Fit p-value (0.0568) suggests a minor issue with model fit in certain regions. The Linear model is also statistically significant, with a p-value of < 0.0001, but its Adjusted R^2 of 0.8604 is lower, indicating a weaker fit compared to the Design Model.

TABLE 4: Lack of Fit Tests for **Weld Metal Viscosity**

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Linear	1.424E-06	13	1.095E-07	43.80	0.0225	
2FI	8.566E-07	7	1.224E-07	48.95	0.0202	
Quadratic	**1.688E-09**	**3**	**5.628E-10**	**0.2251**	**0.8732**	**Suggested**
Cubic	0.0000	0				Aliased
Pure Error	5.000E-09	2	2.500E-09			

The Lack of Fit Tests for Weld Metal Viscosity, which assess how well the fitted models represent the data by comparing the variation explained by the model with the unexplained variation (pure error). The Linear model has a Sum of Squares of 1.424E-06, with a high F-value of 43.80 and a p-value of 0.0225, indicating a significant lack of fit. In contrast, the Quadratic model, with a Sum of Squares of 1.688E-09, has a much lower F-value of 0.2251 and a p-value of 0.8732, suggesting it does not exhibit a significant lack of fit, making it the best model for the data.

TABLE 5: ANOVA for **Weld Metal Viscosity**

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0000	14	9.251E-07	691.58	< 0.0001	significant
A-Current	3.191E-07	1	3.191E-07	238.54	< 0.0001	
B-Voltage	8.393E-09	1	8.393E-09	6.27	0.0542	
C-Gas Flow Rate	3.620E-07	1	3.620E-07	270.64	< 0.0001	
D-M. Temp	1.516E-08	1	1.516E-08	11.33	0.0200	
AB	8.056E-08	1	8.056E-08	60.22	0.0006	
AC	3.381E-08	1	3.381E-08	25.27	0.0040	
AD	3.948E-08	1	3.948E-08	29.51	0.0029	
BC	1.077E-07	1	1.077E-07	80.49	0.0003	
BD	1.488E-07	1	1.488E-07	111.24	0.0001	
CD	3.095E-08	1	3.095E-08	23.14	0.0048	
A^2	7.338E-08	1	7.338E-08	54.85	0.0007	
B^2	2.170E-07	1	2.170E-07	162.21	< 0.0001	
C^2	5.566E-07	1	5.566E-07	416.06	< 0.0001	
D^2	4.506E-08	1	4.506E-08	33.69	0.0021	
Residual	6.688E-09	5	1.338E-09			
Lack of Fit	1.688E-09	3	5.628E-10	0.2251	0.8732	not significant
Pure Error	5.000E-09	2	2.500E-09			
Cor Total	0.0000	19				

The ANOVA for Weld Metal Viscosity shows how various factors and their interactions contribute to the variability in the response variable. The Model term has a p-value of < 0.0001, indicating that the model is highly significant in explaining the variation in weld metal viscosity. Among the factors, Current (A), Gas Flow Rate (C), and their quadratic terms (A^2, C^2) show significant effects, with p-values less than 0.0001. Voltage (B) has a p-value of 0.0542, suggesting it is near significance but not quite impactful. Interaction terms such as AB, AC, AD, BC, BD, and CD all have p-values below 0.05, indicating that these interactions significantly affect viscosity. The significant interactions and quadratic terms suggest a complex relationship between factors that influences the weld metal viscosity.

Accuracy of Prediction

With the quadratic model, a reliability plot of the observed and predicted values of the weld viscosity is shown in the figures below

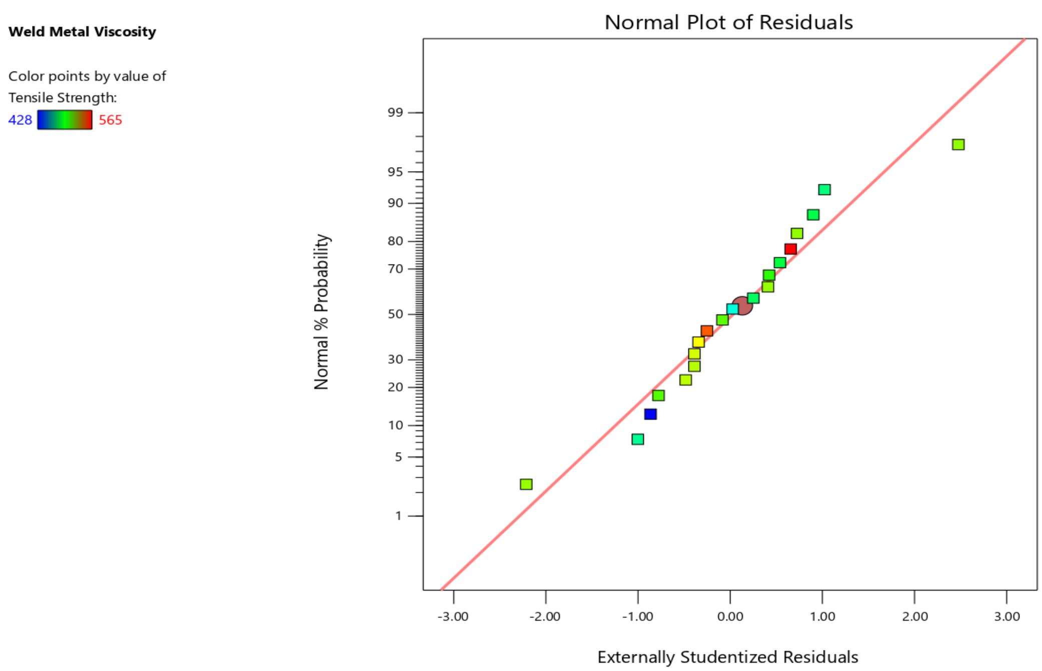

Figure 4: Normal Plot of Residuals for **Weld Metal Viscosity**

The Normal Plot of Residuals for Weld Metal Viscosity (Figure 4) provides an assessment of the normality of the residuals in the regression model with most points closely aligning with the red diagonal line, indicating that the residuals are approximately normally distributed, which supports the validity of the model's assumptions. However, there are some mild deviations, particularly at the extremes, suggesting slight non-normality

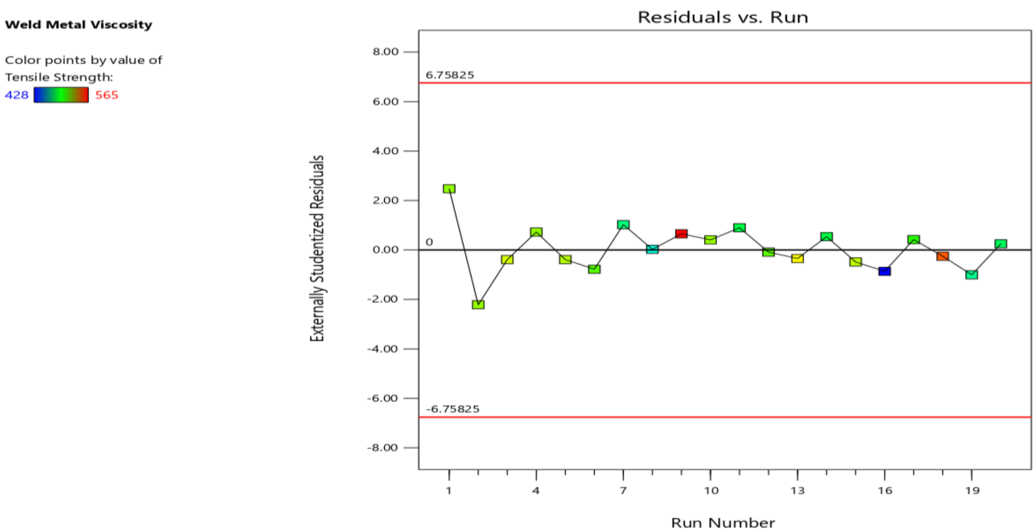

Figure 5: Plot of Residual Vs Run for **Weld Metal Viscosity**

The Residuals vs. Run Plot for Weld Metal Viscosity (Figure 5) reveals that the residuals are generally randomly distributed over the course of the experimental runs, with no discernible pattern or trend, which is a positive indication that the model is well-specified. The absence of trends suggests there are no significant autocorrelations or temporal dependencies in the data, and the model appropriately captures the underlying relationships

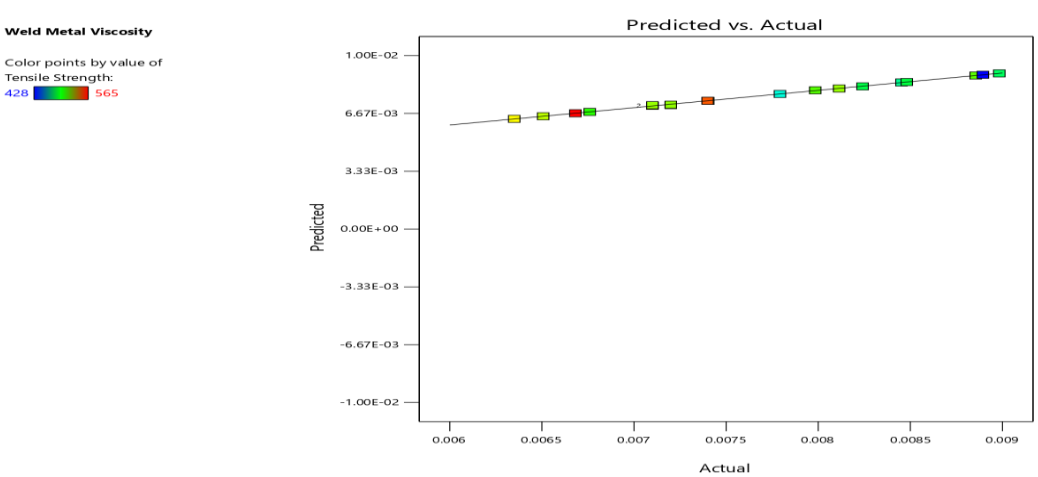

Figure 6: Predicted Vs Actual for **Weld Metal Viscosity**

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The Predicted vs. Actual Plot for Weld Metal Viscosity, presented in Table 4.9, demonstrates that the regression model provides an accurate fit to the data. Most of the points are closely aligned with the diagonal reference line, indicating that the predicted values of weld metal viscosity are very close to the actual observed values. While some scatter exists around the line, it is minimal, implying small prediction errors that are within an acceptable range. Overall, this analysis confirms that the model is effective and robust in predicting weld metal viscosity.

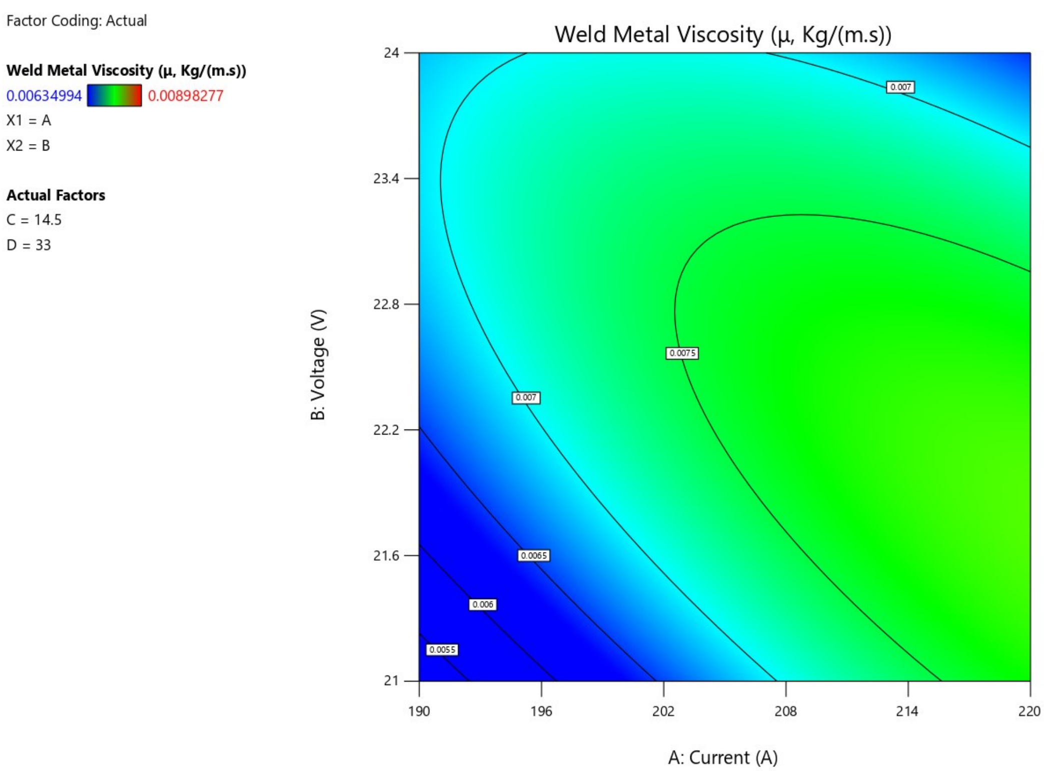

Figure 7: Contour Plot for **Weld Metal Viscosity**

The Contour Plot for Weld Metal Viscosity visually demonstrates how the interaction between Current (A) and Voltage (B) influences weld metal viscosity, with other factors held constant. The plot reveals a clear gradient from lower viscosity values in the bottom-left corner (low A and B) to higher viscosity values in the top-right corner (high A and B), indicating that increasing both current and voltage simultaneously leads to higher weld metal viscosity. The relatively broad green zone suggests some flexibility in factor selection, offering robustness to slight parameter variations. Overall, the contour plot provides crucial insights for optimizing the welding process to achieve desirable viscosity levels through strategic adjustment of current and voltage.

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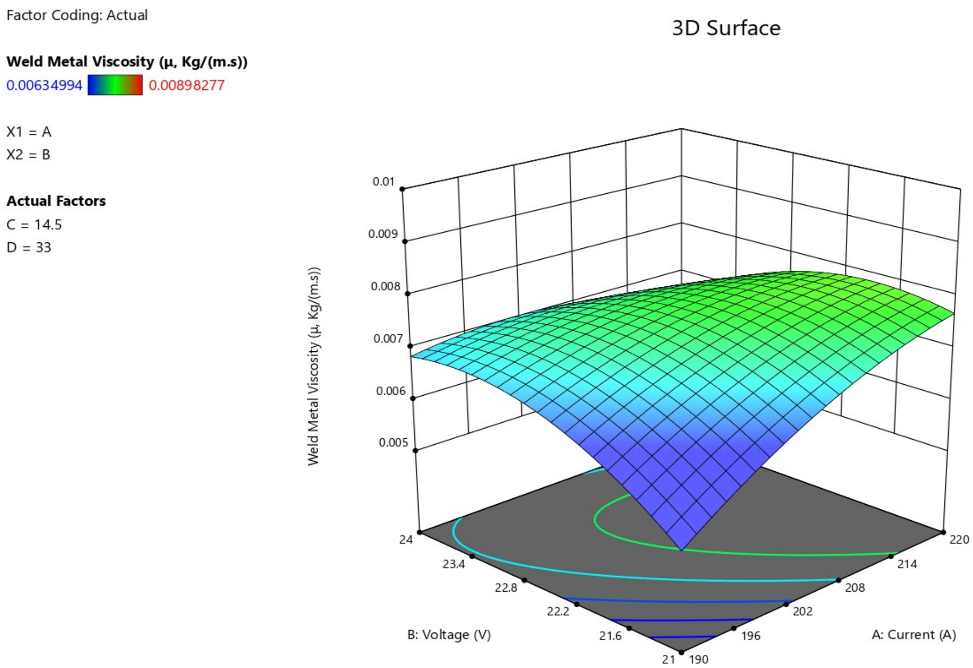

Figure 8: Surface Plot for **Weld Metal Viscosity**

The 3D Surface Plot for Weld Metal Viscosity, offers a detailed three-dimensional visualization of how Current (A) and Voltage (B) interact to affect the weld metal viscosity, while keeping other factors constant (C=14.5 and D=33). The plot reveals an upward-sloping surface from the bottom-left (low A and B) to the top-right (high A and B), indicating that increasing both current and voltage leads to higher weld metal viscosity. The highest viscosity values (around 0.00898 kg/(m·s)) are observed at the peak in the green region, suggesting that optimal process conditions lie in this top-right zone

CONCLUSION

The study successfully shows that Response Surface Method can be effectively applied to mild steel metal for the prediction and optimizing of a weld metal viscosity. Through a systematic experimentation and data modeling technique, the research established significant relationships between input welding parameters (Voltage, Current, Gas Flow and Temperature) and the key response variable (Weld Metal Viscosity)

Key findings from the optimization process shows that Voltage and Current were the most influential parameters affecting the response variable. The optimal welding settings produced by RSM are; Voltage = 24V, Current = 215.935A, Gas Flow Rate = 14.68L/min and Temperature = 28^{0}C which effectively minimized the residual stress while enhancing mechanical properties with a high desirability.

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