PRINT ISSN 1119-8362
Electronic ISSN 2659-1499

Full-text Available Online at
https://www.ajol.info/index.php/jasem
https://www.bioline.org.br/ja

J. Appl. Sci. Environ. Manage.
Vol. 29 (4) 1123-1128 April 2025

Solidus Temperature in Optimization and Prediction of Alloy Mild Steel in Tungsten Inert Gas Weldment

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ABSTRACT: Solidus temperature indicates the temperature at which an alloy is completely solid it is considered as an important parameters of alloy in Tungsten Inert Gas (TIG) welding. Therefore, the objective of this paper was to investigate the solidus temperature in the optimization and prediction of alloy mild steel in Tungsten Inert Gas (TIG) weldment using response surface methodology and other appropriate standard procedures. Data obtained show that The result from the response surface methodology shows that a combination of current of 180A, voltage 19V, gas flow rate 13L/min, l produce optimal solidus temperature of 1278.00oC and a desirability of 91.5%. The developed model would minimize solidus temperature.

DOI: https://dx.doi.org/10.4314/jasem.v29i4.14

Cite this Article as: IGBINAKE, A. O: ALIYEGBENOMA, C. O. (2025). Solidus Temperature in Optimization and Prediction of Alloy Mild Steel in Tungsten Inert Gas Weldment. *J. Appl. Sci. Environ. Manage.* 29 (4) 1123-1128

Dates: Received: 14 February 2025; Revised: 26 March 2025; Accepted: 09 April 2025; Published: 30 April 2025

Keywords: Solidus; temperature; weldment; tungsten inert gas; mild steel; desirability

The solidus temperature specifies the temperature below which a material is completely solid, and the minimum temperature at which a melt can co-exist with crystals in thermodynamic equilibrium (Tunde *et al.*,2024) Solidus and Liquidus temperatures are important parameters in processes such as welding and heat treatment as the temperature ranges at which the liquid weld metal begins to solidify and the base metal or filler material achieves its melting point by changes from a solid to a liquid state are crucial metrics in welding. The quest for optimality and stability of the process is a major concern to the professionals in the industry. They presented a study devoted to comparison of solidus and liquidus temperatures determined by two methods of thermal analysis for one real steel grade 100CrMo7 (Gryc *et al.*, 2017). Two modern devices for high-temperature analysis were used. The direct thermal analysis method was used during an experiments realised on large samples (22 g) at NETZSCH JUPITER device. Small bearing steel samples (up to 210 mg) were studied by differential thermal analysis method at Setaram SETSYS 18TM.The robustness of both used thermo-analytical methods was documented. Measured results were compared with liquidus and solidus temperatures used in industry and calculated by specialized IDS and ThermoCalc software. Measured temperatures differ from the theoretically calculated by tens for liquidus to more than 100 °C for solidus. An analytical microsegregation model quantifies the effects of solid-state diffusion between the cases of Scheil and Lever rule, and it has been widely applied to predict microsegregation characteristics Lu *et al.*, 2022). For multicomponent steels, the liquidus correlation can be introduced in the analytical microsegregation model to determine

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the effects of all the individual components, followed by an investigation of the relationship between temperature and solid fraction. However, investigations on the analytical microsegregation model show that there is an inconsistency in the solidus temperature, and therefore, a certain solidus temperature value is required as input for calculating the solidus temperature value using the model. In their previous work, they investigated this inconsistency, and the results suggested that the input solidus has only a slight influence on the predicted results. In their present study, they investigate the influence of input solidus on the output throughout the solution procedure of single-phase solidification. Herein, based on low (0.04C, d-solidification) and high carbon (0.55C, g-solidification) steel, the inconsistency in the solidus temperature is clearly analyzed, and the results confirm that the deviations in the solidus temperature can be ignored. They believed that providing a reasonable solidus temperature value as an input while solving the analytical microsegregation model is feasible and reliable. Their work centered their discussion of the results obtained by the simultaneous use of three methods of thermal analysis in three different specialized devices with the aim to precise solidus and liquidus temperatures (Karel *et al*., 2014). The low carbon as-cast steel (130 mm round format) from Continuous Casting Machine No. 3 in ArcelorMittal Ostrava a.s. (CCM No. 3) were studied. The series of experiments with large samples (approx.23 g) based on direct thermal analysis was carried out on Netzsch STA 449 F3 Jupiter device. The differential scanning calorimetry (DSC) method with special 3D sensor for other samples (approx. 1 g) was applied on Setaram MHTC 96 device. The third device (Setaram SETSYS 18TM) was used for solidus and liquidus temperatures determination by differential thermal analysis method on small steel samples (approx. 150 mg). Thermo analytically determined solidus and liquidus temperatures were then compared with values obtained by calculations (specialized Thermocalc, IDS and CompuTherm software) and with liquidus temperature currently defined in CCM No. 3 practice for continuous casting of discussed steel grade. The melting efficiency is one among the vital factors regarded in Tungsten Inert Gas (TIG) welding while appraising the quality of welds. In the welding field, proper melting efficiency brings about the development of a weld pool that is dense (GODFREY, S and TONBRA, E: 2022). Their study was done to optimize and predict melting efficiency of mild steel weldment, utilizing Response Surface Method (RSM).Central composite design (CCD) matrix was used to gather data from the sets of experiments, the specimen was produced from mild steel plates and welded with the TIG process, thereafter the RSM was employed for the optimization and the prediction of the responses from the process parameters. Response Surface Methodology was used to predict melting efficiency of TIG welds. The model had p-values less than 0.05 which shows the significance of the model and “predict R-Squared” value of 0.790025 is in moderately good agreement with the “Adj R-Squared” value of 0.9985. One way analysis of variance (ANOVA) was done and the result showed that it is a significant model and possess a very good fit. To validate the significance and adequacy of the model, a coefficient of determination (R-Squared) of 0.904201 indicating the appreciable strength of the model. The computed signal to noise ratio of 19.41136. A study by Huang *et al*. (2018) showed that the solidus temperature had a significant effect on the microstructure and mechanical properties of the weld joint. The study found that welding at temperatures below the solidus temperature resulted in a more refined microstructure and higher strength, while welding at temperatures above the solidus temperature resulted in a coarse-grained microstructure and decreased strength

Solidus temperature which indicates the temperature at which an alloy is completely solid is one of the important parameters considered in the welding of alloy in Tungsten Inert Gas (TIG) welding when assessing the performance and integrity of an alloy. In the field of welding, and metallurgy, a good solidus temperature results in the formation of high quality alloy (GODFREY, S and TONBRA, E: 2022), In order to achieve a good solidus temperature, the optimization and prediction of solidus temperature of mild steel weldment, using response surface methodology is necessary; hence, the objective of this paper is to investigate the solidus temperature in the optimization and prediction of alloy mild steel in Tungsten Inert Gas (TIG) weldment

MATERIAL AND METHOD

The study involving the amelioration of mild steel heat treated welded joint was carried out under the following sub headings:

i. Data Collection
iii. Design of Experiment (DOE)
iv. Data Analysis

Data Collection: The total number of experimental runs that can be generated using the CCD is defined in equation 1.

$$N = 2n + no + 2n \quad (1)$$

Where; N = the number of experimental runs based on CCD design; 2n = the number of factorial points ; n0 = the number of center points; 2n = the number of axial points; n = the number of variables

The key input parameters considered in this work were welding current, welding voltage and gas flow rate, while the response or measured parameters was solidus temperature. The range and level (Weman 2011; Lincoln Electric 2017) of the experimental variables were obtained and are presented in Table 1.

Design of Experiment (DOE): Using the range and levels of the independent variables presented in Table 1, statistical design of experiment (DoE) using central composite design (CCD) method was done. Experimental design was done with the aid of design expert version 13. The total number of experimental runs that can be generated using the CCD, as defined by (Box and Behnken 1960);

Table 1: Range and levels of Independent Variables

Independent Variables	**Range and Levels of Input Variables**	
	Lower Range (-1)	**Upper Range (+1)**
Welding Current (Amp) X_1	150	180
Welding Voltage (Volt) X_2	16	19
Gas flow rate (lit/min) X_3	13	16

Using Equation 1, twenty (20) experimental runs were generated based on the central composite design method and presented in Table 2

Table 2: Design of Experiment matrix

Std	Run	Current (A)	Voltage (V)	Gas flow rate (lit/min)
15	1	165.000	17.500	14.500
16	2	180.000	16.000	16.000
17	3	150.000	19.000	16.000
18	4	165.000	17.500	14.500
19	5	165.000	17.500	14.500
20	6	165.000	20.023	14.500
9	7	180.000	19.000	16.000
10	8	165.000	17.500	14.500
11	9	150.000	19.000	13.000
12	10	165.000	17.500	14.500
13	11	180.000	16.000	13.000
14	12	139.773	17.500	14.500
1	13	180.000	19.000	13.000
2	14	165.000	14.977	14.500
3	15	190.227	17.500	14.500
4	16	165.000	17.500	11.977
5	17	165.000	17.500	17.023
6	18	150.000	16.000	13.000
7	19	150.000	16.000	16.000
8	20	165.000	17.500	14.500

Response surface methodology (RSM): For analysis of design data, Design Expert Statistical Software, Version 13.0 was employed in order to obtain the effects, coefficients, standard deviations of coefficients, and other statistical parameters of the fitted models. The behaviour of the system which was used to evaluate the relationship between the response variables (Y_s) and the independent variables (X_1, X_2, and X_3) was explained using the empirical second-order polynomial equation (Nuran, 2007).

$$Y = \beta_0 + \sum_{i=1}^{q} \beta_i x_i + \sum_{j=1}^{q} \beta_{ii} x_i^2 + \sum_{i=1<j}^{q-1} \sum_{j=2}^{q} \beta_{ij} x_i x_j + \varepsilon \quad (2)$$

Where, X_1, X_2, X_3… X_k = input variables; Y, β_0, β_i, β_{ii}, and β_{ij} = the known parameters, and ε = the random error.

The Response Surface Model *is* a variation of the simple linear regression, with the incorporation of the second order effects of non-linear relationships. It is a popular optimization technique to determine the best possible combinations of variables to determine a specific response to a phenomenon. RSM is particularly useful to understand the relationship between multiple predictor variables with multiple predicted responses. The optimal equation which shows the individual effects and combine interactions of the selected input variables (current, voltage and gas flow rate) against the mesured solidus temperature is presented based on the coded variables in equation 3.

$$Y_s = 1080.45 + 72.78A + 53.50B + 43.40C + 60.75AB + 12.50AC - 11.75BC + +20.46A^2 + 19.22B^2 + 26.29C^2 \quad (20)$$

Where, Y_s = Solidus temperature

To validate the suitability of the quadratic model in analyzing the experimental data, the sequential model sum of squares was calculated for solidus temperature response as presented in Table 4. The Quadratic vs 2FI source was selected as the highest order polynomial source where the additional terms are significant and the model is not aliased

RESULTS AND DISCUSSION

After grinding and polishing of the sample edges, welding work was carried out, and the responses were measured and recorded. The measured response corresponding to the input variable is presented in Table 3

Table 3: Measured responses corresponding to input variables

Exp	I, Amp	E, Volts	GFR, (L/Min)	Solidus Temp ^{0}C
1	165.000	17.500	14.500	1076.000
2	180.000	16.000	16.000	1178.000
3	150.000	19.000	16.000	1091.000
4	165.000	17.500	14.500	1084.000
5	165.000	17.500	14.500	1087.000
6	165.000	20.023	14.500	1221.000
7	180.000	19.000	16.000	1380.000
8	165.000	17.500	14.500	1080.000
9	150.000	19.000	13.000	1043.000
10	165.000	17.500	14.500	1078.000
11	180.000	16.000	13.000	1033.000
12	139.773	17.500	14.500	1018.000
13	180.000	19.000	13.000	1293.000
14	165.000	14.977	14.500	1047.000
15	190.227	17.500	14.500	1257.000
16	165.000	17.500	11.977	1086.000
17	165.000	17.500	17.023	1222.000
18	150.000	16.000	13.000	1037.000
19	150.000	16.000	16.000	1121.000
20	165.000	17.500	14.500	1078.000

Table 4: Sequential model sum of square for Solidus Temperature

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Mean vs Total	2.534E+07	1	2.534E+07			
Linear vs Mean	1.372E+05	3	45717.66	14.61	< 0.0001	
2FI vs Linear	31879.00	3	10626.33	7.59	0.0035	
Quadratic vs 2FI	**17898.32**	**3**	**5966.11**	**199.73**	**< 0.0001**	**Suggested**
Cubic vs Quadratic	204.53	4	51.13	3.26	0.0957	Aliased
Residual	94.18	6	15.70			
Total	2.552E+07	20	1.276E+06			

Table 5: Lack of fit test for Solidus Temperature

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Linear	49988.53	11	4544.41	259.68	< 0.0001	
2FI	18109.53	8	2263.69	129.35	< 0.0001	
Quadratic	**211.21**	**5**	**42.24**	**2.41**	**0.1778**	**Suggested**
Cubic	6.68	1	6.68	0.3817	0.5638	Aliased
Pure Error	87.50	5	17.50			

To test how well the quadratic model can explain the underlying variation associated with the experimental data, the lack of fit test was estimated for each of the responses. Model with significant lack of fit cannot be employed for prediction. Results of the computed lack of fit for the solidus temperaturet is presented in Table 5. The selected model should have a p-value higher than 0.05, showing insignificant lack-of-fit.

The model statistics computed for solidus temperature response based on the model sources is presented. The suggested model have an R^2 of 0.9984 Adjusted R^2 of 0.9970 and the Predicted R^2 of 0.9306 showing a significant model.

In assessing the strength of the quadratic model towards minimizing solidus temperature one-way analysis of variance (ANOVA) . The Model F-value of 695.34 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate model terms are significant. In this case A, B, C, AB, AC, BC, A^2, B^2, C^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve the model. The Lack of Fit F-value of 2.41 implies the Lack of

Fit is not significant relative to the pure error. There is a 17.78% chance that a Lack of Fit F-value this large could occur due to noise. Non-significant lack of fit is good. To diagnose the statistical properties of the response surface model, the normal probability plot of residual for solidus temperature is presented in Figure 1. To study the effects of combined input variables on the solidus temperature, 3D surface plots presented in Figure 2 was generated as follows:

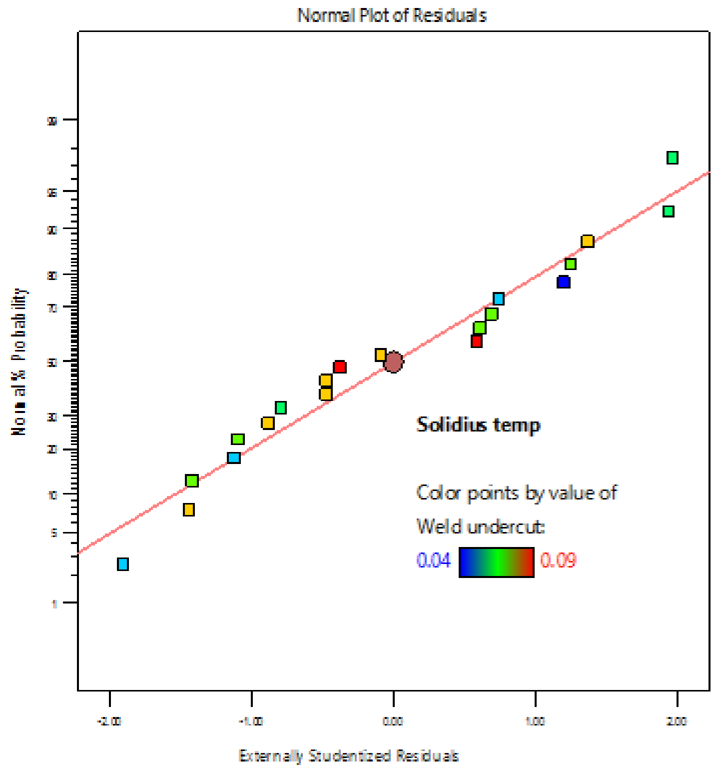

Fig 1: Probability plot of residuals for Solidus Temperature

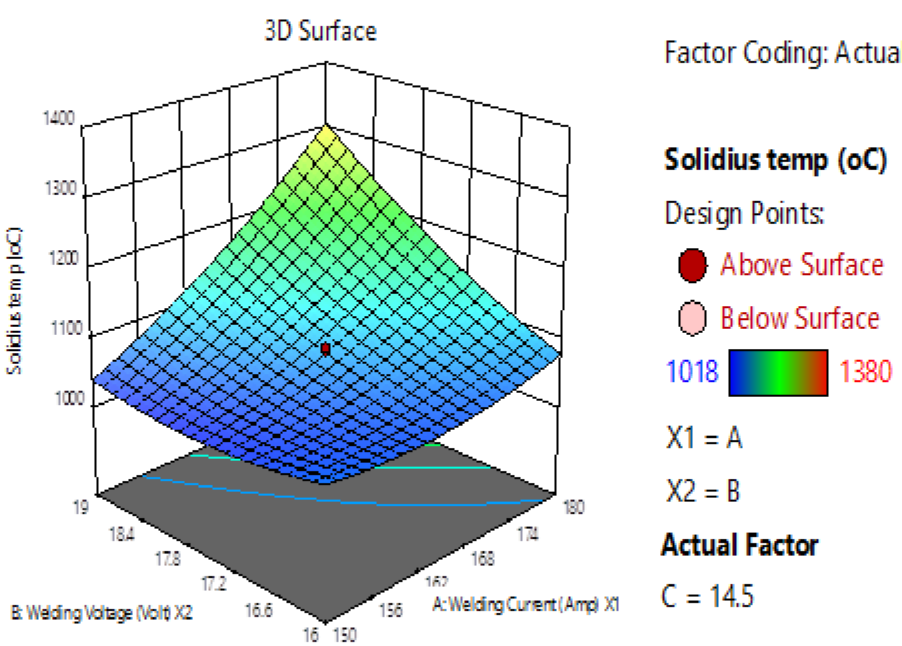

Fig 2: Effect of current and voltage on Solidus Temperature

Conclusion: The study has developed and applied predictive expert models to optimize solidus temperature of TIG mild steel weld using the response surface methodology. Result of the study have shown that the current, voltage and gas flow rate have significant effect on the output responses. The RSM model possesses satisfactory statistical indices making it a highly effective tool to optimize and predict the target responses. The development of a second order quadratic model of the response surface methodology (RSM) to predict and optimize the solidus temperature of TIG mild steel welds has been successfully established.

Declaration of Conflict of Interest: The authors declare no conflict of interest.

Data Availability Statement: Data are available upon request from any of the other authors

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