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Numerical Simulation and Optimization of Stefan Dimensionless Number to Control TIG Molten Metal Fluidity

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Abstract

Welding researchers have a responsibility of improving the integrity and strength of welded structures, the fluid flow of the molten metal has a major effect on energy transport from the weld pool to the surrounding material, which in turn affects the geometry. Additionally, the flow motion and its volatilities determine the material properties and quality of the weld. This study was carried out with the aim of optimizing and predicting the dimensionless parameters characterizing molten metal flow patterns of mild steel weld pool ,with a purpose of developing models to explain the relationship between this dimensionless numbers and the flow pattern. A 30-run central composite design matrix was generated which guided in performing the experiments, the stefan dimensionless number was computed and recorded for each specimen. Thereafter the response surface methodology expert system was employed to analyse the data collected from the experiment.In this study the second order polynomial model was adopted having current, voltage, gas flow rate and welding speed as input factors while the stefan dimensionless numbers is the target response. The result obtained possessed adequate strength to predict the targeted response.RSM model produced numerical optimal solutions having a combination of current 189.85A ,voltage 18.00v wire diameter 1.61mmand wire feed rate of 25mm/min to produce a welded joint with with Stefan number of 2.69 x10 ^{6}, at a desirability value of 71.8%.In this study an approach using the response surface methodology for optimizing and predicting weld process parameters in order to enhance the integrity of welded joints has been successfully introduced and its effectiveness and efficiency well demonstrated.

1. Introduction

The integrity and strength of a weld joint is determined by the quality of the molten metal fluidity and surface tension present around the weld pool. The point on the weld pool surface having maximum surface tension starts to migrate towards the core of the weld pool located close to the edge. In this circumstances there exist three dimension of fluid flow: one is an outward fluid flow caused by the Marangoni effect; the second is the inward fluid flow caused by the Marangoni effect and the third is the fluid flow controlled by electromagnetic force. The fluid flow pattern moves towards the centre of the weld pool results in larger penetration depth and a lower width/penetration ratio of the weld .The similar effects of oxygen on fluid flow within the weld pool is in reasonable agreement with the findings of many researchers[1].An unsteady state model was developed to control the electromagnetic force, velocity and temperature in a gas metal arc welding .The model did not only focus on the electromagnetic interaction with the surface tension forces, but also considered the energy exchange by spray transfer from the weld pool to the molten filler metal droplets .The model developed can be employed to liquid metal thermodynamics existing in in both the GMA and gas tungsten arc (GTA) welding processes[2].A numerical study was conducted to examine the coupling between temperature distribution, surface tension and internal flow pattern of gas metal arc welds [3].An experimental study was done to investigate the effects of oxygen on weld penetration. An inward Marangoni flow was suggested to explain the mechanism and was confirmed with a high speed video camera [4]. In welding the fluid flow pattern of the molten metal determines the geometry of the weld metal and the microstructural configuration of the heat-affected zone. Additionally, the flow motion and its volatilities determines the material properties and quality of the weld[5].The concept of modeling fluid motion in weld pools was first proposed by [6].The effect of the viscous dissipation on the surface tension and its role on the shape of weld pool was investigated [7].The influence of surface active elements on the fluidity and weld pool shape was studied [8].Numerical studies have shown different fluid flow patterns of the weld pool for different sulphur contents. For the sulphur free steel, surface tension has a linear relationship with temperature [9]. Fluidity is one of the most important factors that play a role in the welding industry. A comparative study between the theoretical fluid dynamics value and the computational fluid dynamics value for validating the fluidity of the aluminium alloy was done [10].

2. Methodology

2.1. Design of experiment

For an optimal experimentation process a design of experiment is required. The design expert software was employed for this task. A particular experimental design matrix is selected based on its capacity to handle certain number of input process parameters and the central composite has been known as one of the best experimental matrix and was chosen for this study. The process parameters considered in this study are current, voltage, wire diameter, wire feed rate and the Stefan number.

2.2 Method of data collection

The central composite design matrix was developed using the design expert software, producing 30 experimental runs. The input parameters and output parameters make up the experimental matrix and the responses recorded from the weld samples was used as the data.

2.3. Preparation of weld specimen

150 pieces of mild steel coupons measuring 60 mmx 40 mmx10 mm was used for the experiments, the experiment was performed 30 times, using 5 specimens for each run. The mild steel coupons were bevelled and machined, thereafter the tungsten inert gas welding equipment was used to weld the plates using 100% pure Argon gas to protect the weld specimen from atmospheric interaction.

3. Results and discussion

Experimental design is very important for determining the optimum solution for most manufacturing process, the central composite design happens to be the most applied experimental matrix .in this study the central composite design was employed for the welding experiment. Table 1 shows the process parameters and the Stefan dimensionless number response values.

Table 1: central composite design matrix

current	voltage	Wire diameter	Wire Feed	Stefan
190.00	18.00	1.60	25.00	2.69
110.00	22.00	1.60	45.00	2.8
110.00	18.00	4.00	45.00	2.82
190.00	22.00	4.00	45.00	2.81
110.00	18.00	1.60	45.00	2.86
150.00	20.00	2.80	35.00	2.88
150.00	20.00	2.80	35.00	2.87
150.00	20.00	2.80	35.00	2.88
110.00	18.00	4.00	25.00	2.84
110.00	22.00	1.60	25.00	2.8
150.00	20.00	2.80	35.00	2.88
150.00	20.00	2.80	35.00	2.81
150.00	20.00	2.80	35.00	2.82
150.00	20.00	0.40	35.00	2.86
110.00	22.00	4.00	45.00	2.81
110.00	22.00	4.00	25.00	2.84
70.00	20.00	2.80	35.00	2.83
150.00	16.00	2.80	35.00	2.64
150.00	20.00	2.80	55.00	2.91
190.00	18.00	4.00	25.00	2.58
110.00	18.00	1.60	25.00	2.81
150.00	20.00	5.20	35.00	2.84
150.00	24.00	2.80	35.00	2.62
190.00	22.00	4.00	25.00	2.75
190.00	18.00	1.60	45.00	2.9
190.00	22.00	1.60	25.00	2.82
190.00	22.00	1.60	45.00	2.97
190.00	18.00	4.00	45.00	2.87
230.00	20.00	2.80	35.00	2.88
150.00	20.00	2.80	15.00	2.76

The experimental data was subjected to different statistical test to check for suitability, compatibility and significance. The analysis of variance ANOVA is one test statistic use to check for the significance of the quadratic model which is in reasonable agreement with [11]as shown in Table 2.

Table 2: ANOVA Table for Stefan

Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob > F	
Model	0.19	14	0.014	9.10	< 0.0001	Significant
A-current	3.375E-004	1	3.375E-004	0.22	0.6446	
B-voltage	1.504E-003	1	1.504E-003	0.99	0.3360	
C-wire diameter	5.704E-003	1	5.704E-003	3.75	0.0720	
D-wire feed rate	0.043	1	0.043	27.91	< 0.0001	
AB	9.506E-003	1	9.506E-003	6.24	0.0246	
AC	0.011	1	0.011	6.90	0.0191	

AD	0.032	1	0.032	20.69	0.0004	
BC	5.625E-005	1	5.625E-005	0.037	0.8502	
BD	7.656E-003	1	7.656E-003	5.03	0.0405	
CD	7.562E-004	1	7.562E-004	0.50	0.4918	
A^2	1.860E-004	1	1.860E-004	0.12	0.7316	
B^2	0.079	1	0.079	51.84	< 0.0001	
C^2	5.030E-005	1	5.030E-005	0.033	0.8582	
D^2	1.574E-004	1	1.574E-004	0.10	0.7522	
Residual	0.023	15	1.523E-003			
Lack of Fit	0.018	10	1.751E-003	1.64	0.3045	not significant
Pure Error	5.333E-003	5	1.067E-003			
Cor Total	0.22	29				

The ANOVA table has helped us to test for the models significance, but to help us check for the strength of the model, the goodness of fit statistics is required. Table 3 shows the goodness of fit statistics for the Stefan dimensionless number.

Table3: Gof Statistics for Stefan

Std. Dev.	0.039	R-Squared	0.8946
Mean	2.81	Adj R-Squared	0.7963
C.V. %	1.39	Pred R-Squared	0.4993
PRESS	0.11	Adeq Precision	11.642

To accept any model, its satisfactoriness must first be checked by an appropriate statistical analysis output. The normal probability plot of residual which is the difference between the observed and predicted response [12] is required for this task Figure 1 shows the plot of residuals for the Stefan number.

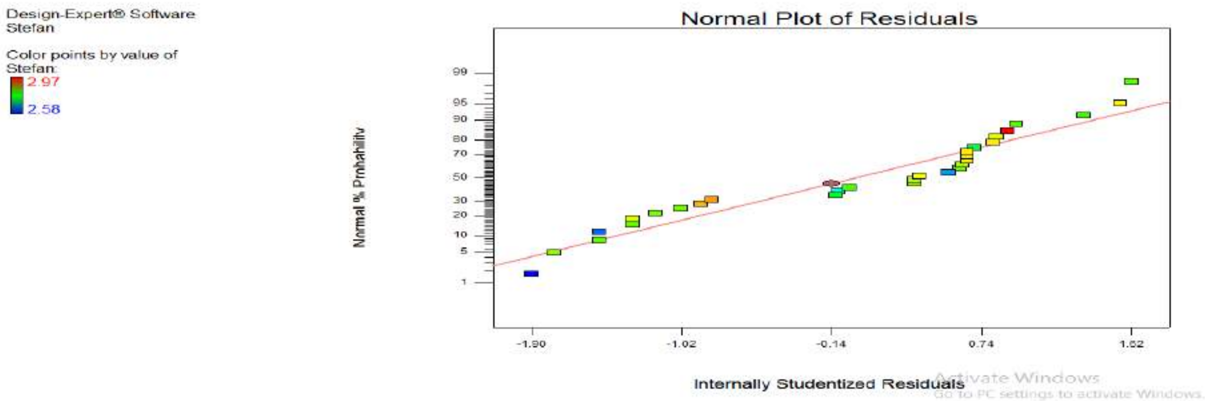

Figure 1: Normal probability plot of studentized residuals for Stefan number

To further test for the suitability and compatibility of the quadratic model for the Stefan dimensionless number a plot of predicted response value versus the actual experimental value is produced as shown in Figure 2.

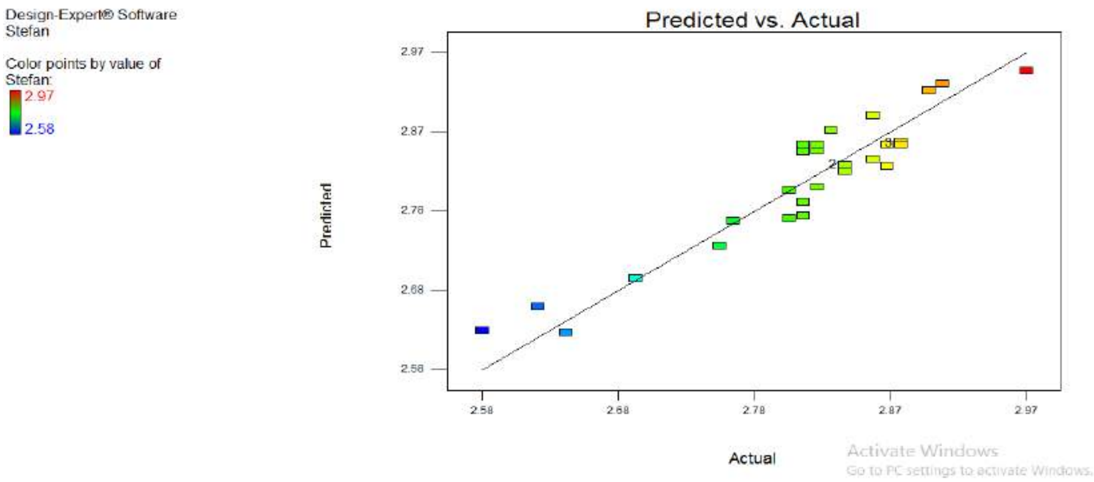

Figure 2: Plot of Predicted Vs Actual for the STEFAN number response

In the collection of data errors can occur, The diagnostic required to check for erroneous data known as outliers is the cook's distance plot which is shown in Figure 3.

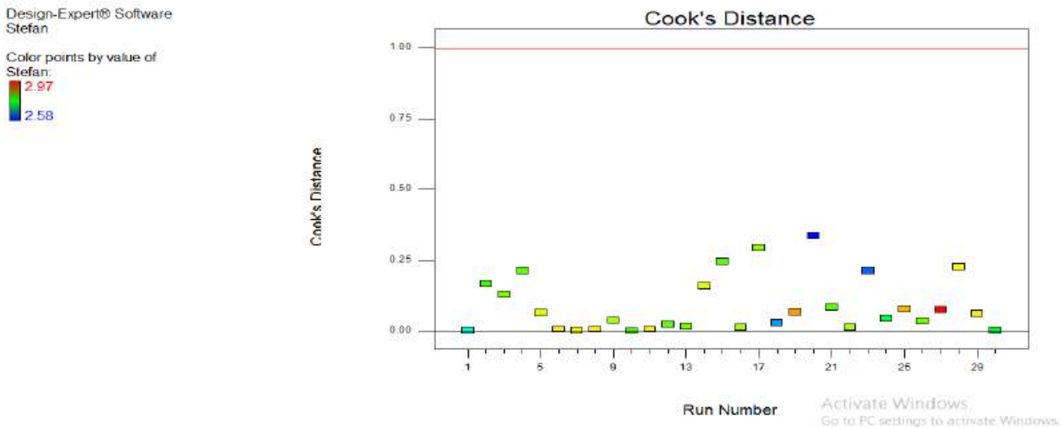

Figure 3: Generated cook's distance for STEFAN number

Interactions occur among process parameters and responses and the surface plot is produced to express the combined interaction between the Stefan response versus current and voltage as shown in Figure 4.

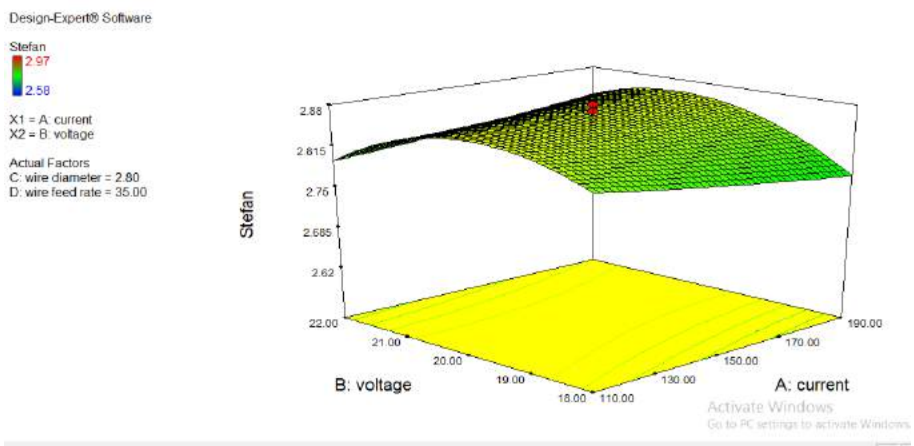

Figure 4: Effect of current and voltage on Stefan number

To study the effects of wire diameter and current on the Stefan, dimensionless number 3D surface plots presented in Figure 5.

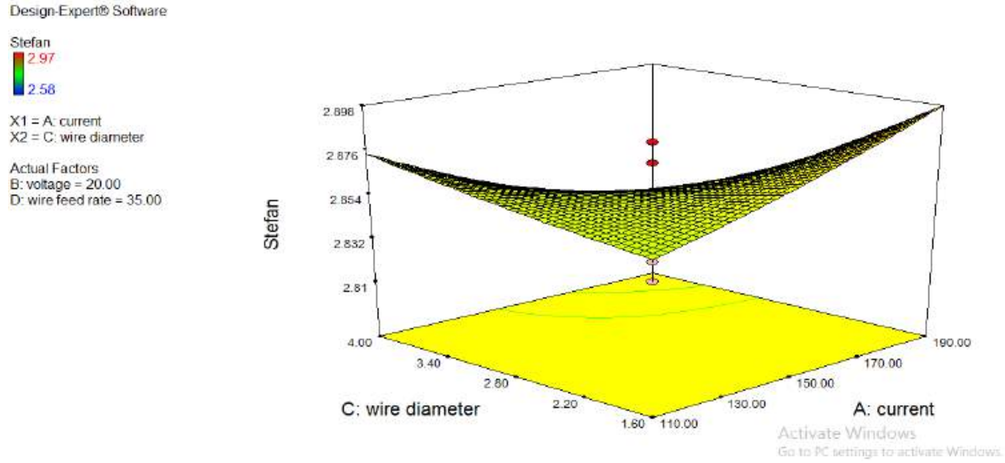

Figure 5: Effect of current and wire diameter on Stefan number

To study the effects of wire feed rate and current on the Stefan number, 3D surface plots presented in Figure 6.

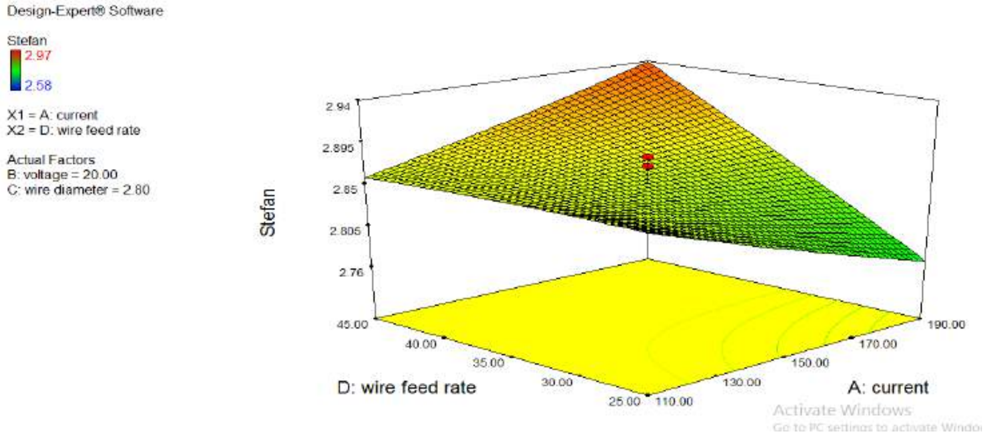

Figure 6: Effect of wire feed rate and current on Stefan number

To study the effects of wire diameter and voltage on the Stefan number, 3D surfaces plots presented in Figure 7.

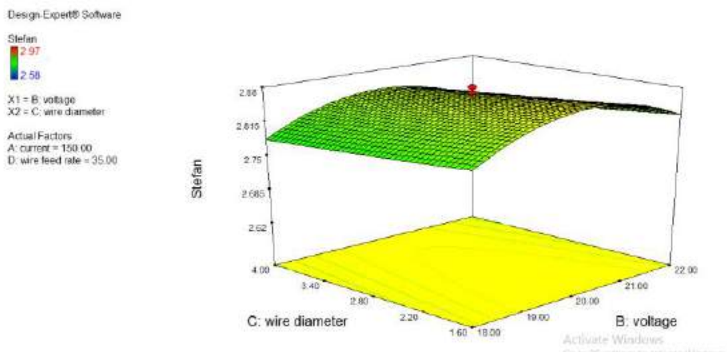

Figure 7: Effect of voltage and wire diameter on Stefan number

To study the effects of wire feed rate and voltage on the Stefan number, 3D surfaces plots presented in Figure 8.

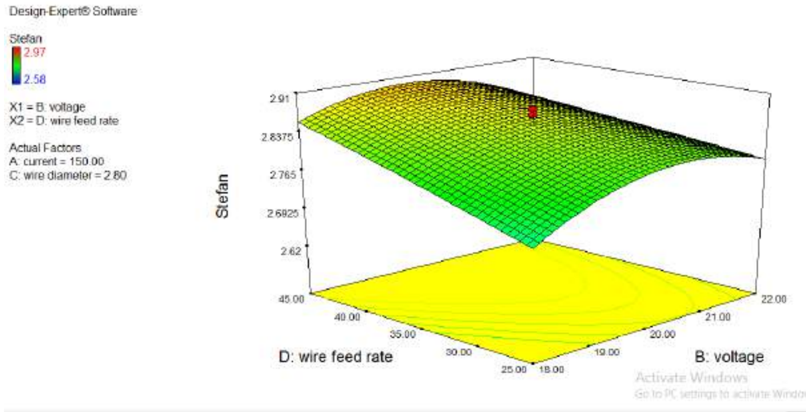

Figure 8: Effect of wire feed rate and voltage on Stefan number

To study the effects of wire feed rate and wire diameter on the Stefan number, 3D surface plots presented in Figure 9.

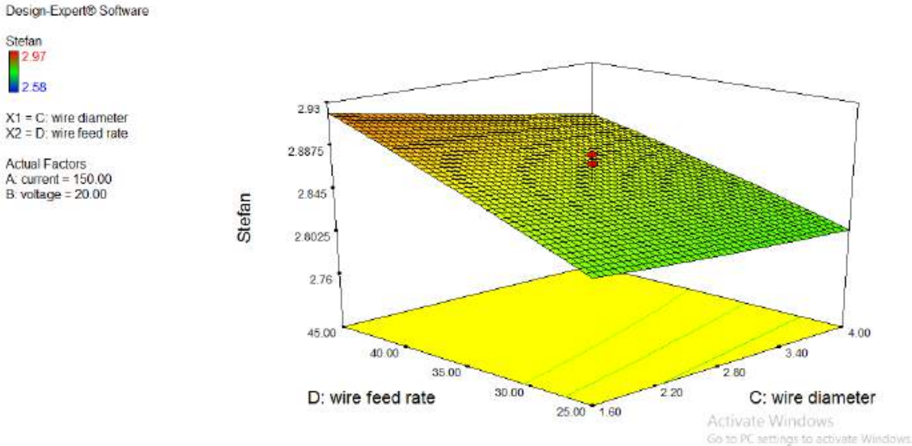

Figure 9: Effect of wire feed rate and wire diameter on Stefan number

A numerical optimisation of the process parameters will produce an optimal solution that can best maximize the Stefan number so as to obtain the molten metal fluidity during the TIG welding,the optimal solution is shown in Table 4.

Table 4: Optimal solution for the Stefan dimensionless number

Current	voltage	wire diameter	wire feed rate	Stefan	Desirability	
189.85	18.00	1.61	25.00	2.69253	0.718	Selected
189.36	18.00	1.60	25.09	2.69421	0.718	
190.00	18.07	1.60	25.00	2.69789	0.716	
189.83	18.00	1.61	25.20	2.69462	0.716	
187.01	18.00	1.60	25.00	2.69556	0.715	
189.99	18.00	1.65	25.00	2.69115	0.714	

4.0 Conclusion

The results obtained in this study shows that the higher the Stefan number the better the flow pattern of the weld metal. Figures 4-9 shows the surface plots of current, wire feed rate, wire diameter and Stefan number, it explains the combined interaction between two input parameters and the Stefan response. Table 3 shows the optimum value for Stefan number, that is a combination of current(189.85amp) voltage (18.00) wire diameter (1.61) and wire feed rate (25.00) will produce a maximum Stefan number of 2.69 x10 ^{6} which translates into an excellent flowability of the molten metal. The model developed shows adequate strength, suitability and significance.

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