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Optimization of TIG Welding Input Variables for AISI 1020 Low Carbon Steel Plate Using Response Surface Methodology

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Abstract- Based on the Design of experiment (DOE), an experimental design matrix having thirteen (13) center points, six (6) axial points and eight (8) factorial points resulting in twenty (20) experimental runs was generated which included temperature ranging from 96.13-213.86 A, voltage ranging from 16.95-27.04 V and gas flow rate ranging from 11.29-19.70 L/min. The aforementioned twenty runs were used as input parameters for TIG welding experimental procedure as well as prediction and optimization using Response Surface Methodology (RSM), with the output responses being temperature distribution, Induced Stress Distribution and bead penetration depth. The optimization result revealed that an input current of 120 A, voltage of 23.95 V and gas flow rate of 15.63 L/min will produce a weld material with temperature of 326.53^{0}C, ISD of 231.746 N/m^2 and bead penetration depth of 6.47911 mm. To validate the results, regression plot between the experimental values and RSM predicted values showed proximity in the coefficient of determination (R^2) for the output responses, indicating that RSM can be used as alternative tool to the prediction and optimization of weld parameters.

Keywords Optimization, Weld parameters, Experimentation, Weld quality, Steel plate.

1. Introduction

Welding technologies have a wide range of application in many industries such as manufacturing industries, aerospace industries, automobile industries etc. Among the various welding technologies, Tungsten Inert Gas (TIG) welding plays a significant role in welding of mild steel or thin sections of non-ferrous metals such as copper alloys, aluminium alloys, magnesium and stainless steel. TIG welding also referred to as Gas tungsten arc welding (GTAW) is an electric arc welding process that applies a non-consumable tungsten electrode in the fusion of two or more metals together [1, 2].

According to Benyounis and Olabi [3], optimization of welding parameters is essential to obtaining good weldment with the required bead geometry and weld quality. Kumar and Vijay [4] employed Taguchi approach of orthogonal array using analysis of variance (ANOVA) to determine the influence of process parameter (current, voltage and gas flow rate) on the mechanical properties of TIG welding joint of austenitic stainless steel (AISI 316) and mild steel. The result indicated that these parameters influenced the tensile strength and hardness of the welded joint if they are not optimised to obtain optimum range of values.

Adopting the bead on plate method in robotic Gas Metal Arc Welding (GMAW) of AS 1204 mild steel plate, factorial experimental design was employed by Kim et al. [5] to correlate the welding process parameters which included arc current, welding voltage and welding speed to the output responses which included bead width and bead penetration depth for optimization. Taguchi's L27 orthogonal was used in the optimization of TIG welding process parameters such as current, voltage, root gap and gas flow rate in order to determine their effects on the properties mechanical properties of AISI 304 stainless steel plate. The regression plot between input variables and response values (bending strength and micro-hardness) were designed with the help of Response Surface Methodology (RSM). The result indicated that Hardness property was significantly affected by the Welding voltage, while the strength of the weld joints improved with decreasing welding voltage but was exposed to thermal stress at increasing welding current of 70 A [6].

Katherasan et al. [7] used Particle Swarm Optimization (PSO) algorithm and Artificial Neural Network (ANN) to Simulate and optimize weld bead geometry based on specific input variables such as voltage, torch angle, wire feed rate, welding speed with the output process parameters being the weld reinforcement, bead penetration depth and weld bead width. Stainless steel 316L (N) of 8 mm thickness was used for the welding experimentation and 1.2 mm diameter filler wire of same grade. The experimental results obtained were input in the ANN application to establish a relationship between the input variables and output responses while the ANN generated results were then embedded into the PSO algorithm to optimize the process input variables. Principal Component Analysis (PCA) was combined with Taguchi method to optimize eight (8) selected input variables (current, welding speed, gas flow rate, work piece gap, arc angle, groove angle, and electrode extension length) for optimum weld quality characteristics (hardness and bending strength of 10 mm thickness aluminium foam plate). The experimental results indicated that the optimal process design could be employed in similar welding applications to improve the characteristics of weld quality [8].

Modelling and optimization of bead geometry parameters in tungsten inert gas (TIG) welding of stainless Steel-304 was investigated by [9]. It was observed from the investigation that the input variables had varying effects on the Tensile strength. Taguchi and ANOVA technique was used to obtain an optimal solution of 150 A for welding current, 28 V for the voltage and gas flow rate of 14 l/min.

Abhishek et al. [10] carried out an investigation based on Taguchi approach [L9], using Analysis of variance (ANOVA) in the analysis TIG welding process parameters such as current, voltage and wire speed in order to determine their responses on the mechanical properties (with tensile strength and hardness) of low carbon steel (ASTM A29) and to obtain optimal welding solutions. The result revealed that welding current had the most significant effect on the tensile and hardness property of the ASTM A29 weldment, followed by welding voltage and welding speed. The optimal parametric solution for tensile strength was welding current of 230 A, followed by welding voltage of 18 V and wire speed of 2.2 m/s, while the optimal solution for hardness was welding voltage of 18 V, welding current 215 A, and wire speed of 2.2 m/s.

Taguchi technique was employed for optimization of TIG welding process parameters (Welding pressure, welding speed and welding temperature) for joining of 301 stainless steel plates with the objective of producing weld joint with maximum impact strength and hardness. L27 orthogonal array was selected according to the aforementioned process parameters and experimental tests were performed respectively, using Signal-to-Noise (SN) ratio to evaluate the experimental results which indicated that welding speed had the greatest influence on impact strength, followed by welding pressure and temperature [11].

Activated Tungsten Inert Gas (ATIG) welding parameters (electrode gap, travel speed, current and voltage) were optimized for controlling aspect ratio of ASTM/UNS S32205 DSS welds by using Taguchi Orthogonal Array (TOA) experimental design, Analysis of Variance (ANOVA) and Pooled ANOVA techniques. The optimum process parameters were found to be 1 mm electrode gap, 130 mm/min travel speed, 140 A current and 12 V voltage. The aspect ratio and the ferrite content for the DSS joints fabricated using the optimized ATIG parameters were found to be well within the acceptable range and there was no macroscopically evident solidification cracking [12]. Siva et al. [13] optimized the weld bead parameters of nickel-based over lay deposited by plasma transferred arc surfacing. The results showed that penetration is increased as the welding current increased and decreased when travel speed increased.

This study is focused on the prediction and optimization of TIG Welding Input variables for AISI 1020 low carbon steel plate using RSM.

2. Research Methodology

The specific objective of the optimization model was to maximize the temperature of a given weldment, minimized the Induced Stress Distributions (ISDs) and to maximize the bead penetration depth. The final solution of the optimization process was to determine the optimum values of the input variables (current, voltage and gas flow rate) that will maximize the temperature, minimized the ISDs and maximize the bead penetration (depth). The randomized design matrix comprised of three input variables, namely; (current (Amp), Voltage (V) and gas flow rate (L/min) with three response variables, namely; (temperature, ISDs and bead penetration (depth). To generate the experimental data for the optimization process the following steps were followed;

i. Statistical design of experiment (DOE) using the central composite design method (CCD) was done. Central composite design (CCD) is unarguably the most acceptable design for response surface methodology (RSM). The design and optimization was done using statistical software and for this particular problem, Design Expert 7.01 was used.
ii. Design expert was used to generate DOE for twenty (20) experimental runs as input parameters for experimental TIG welding procedure and RSM prediction and optimization.

For the experimental procedure, mild steel plate of 10 mm thickness was cut into a dimension of 120x30 mm (length x width) each as shown in Fig 1.

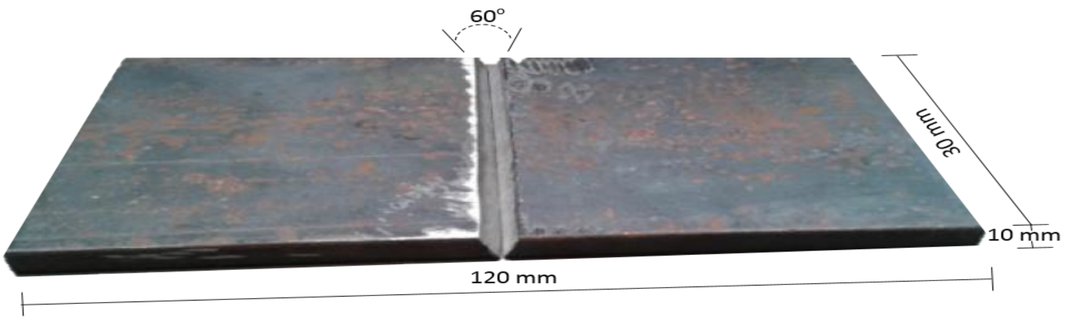


Fig. 1. V-butt specimen of AISI 1020 Low Carbon Steel Plate

Sand paper was used to smoothen each of the two specimen to eliminate all possible coatings, corrosion or rust that may have accumulated on the material. The two steel plates where chamfered at 30 degrees, after which, fusion welding was used to join the two plates together to form an angle of 60 degree with 2mm depth. The milling of the angle was done using a vertical milling machine. The welding was carried out with the plates properly clamped to avoid misalignment during welding process. Before welding, surface of the samples to be welded were cleaned using acetone in order to eliminate surface contamination, and welding was applied to fuse the two flat plates together. The weld bead penetration values were measured using digital planimeter with 1-µm accuracy. K-type thermocouples were attached to the surface of the workpiece and the temperature was recorded at 20 points as the arc passed along the workpiece. Also, a strain gauge was used to measure the residual stresses induced in the steel plate while the welding torch passed over the plate at a height of 2.5mm from the workpiece at constant velocity of 1.72 mm/s^{-1}.

3. Results and Discussion

Following the research methodology, results obtained from the TIG welding experimentation are presented in Table 1.

Table 1. Experimental TIG Welding Input Variable and Output Responses

Run No.	Current (A)	Voltage (V)	Gas Flow Rate (L/min)	Temperature Experimental Values (°C)	ISD Experimental Values (N/m^2)	Bead Penetration Experimental Values (mm)
1	155	22	15.5	298	329.86	6.459
2	155	22	15.5	287	334.56	6.47
3	155	22	15.5	265	303.76	6.475
4	155	22	15.5	264	317.21	6.375
5	155	22	15.5	265	317.02	6.343
6	155	22	15.5	265	316.33	6.304
7	155	27.04	15.5	319	314.37	6.416
8	96.13	22	15.5	393	144.54	6.378
9	155	22	11.29	300	337.45	6.996
10	155	16.95	15.5	308	300.21	5.702
11	213.86	22	15.5	423	290.77	6.605
12	155	22	19.70	253	396.95	5.803
13	120	19	18	251	340.27	6.698
14	190	19	13	365	297.99	6.454
15	190	25	13	354	402.36	6.823
16	120	25	18	308	263.31	6.592
17	190	25	18	323	387.16	6.586
18	120	19	13	325	275.88	6.815
19	120	25	13	375	249.27	6.478
20	190	19	18	380	327.19	6.023

To accept any model, its satisfactoriness must first be checked by an appropriate statistical analysis output. To diagnose the statistical properties of the response surface model, the normal probability plot of residual were employed. The normal probability plot of studentized residuals was employed to assess the normality of the calculated residuals. The normal probability plot of residuals which is the number of standard deviation of actual values based on the predicted values was employed to ascertain if the residuals (observed-predicted) follows a normal distribution. It is the most significant assumption for checking the sufficiency of a statistical model. To determine the presence of a possible outlier, the cook's distance plot was generated for the each response. The cook's distance is a measure of how much the regression would change if the outlier is omitted from the analysis. A point that has a very high distance value relative to the other points may be an outlier and should be investigated. The cook's distance plot has an upper bound of 1.00 and a lower bound of 0.00. Experimental values smaller than the lower bound or greater than the upper bounds are considered as outliers and must be properly investigated. To study the effects of combine input variables on each response variables (temperature, induced stress distribution and bead penetration), 3D surface plots presented in Figs 2-4 were employed.

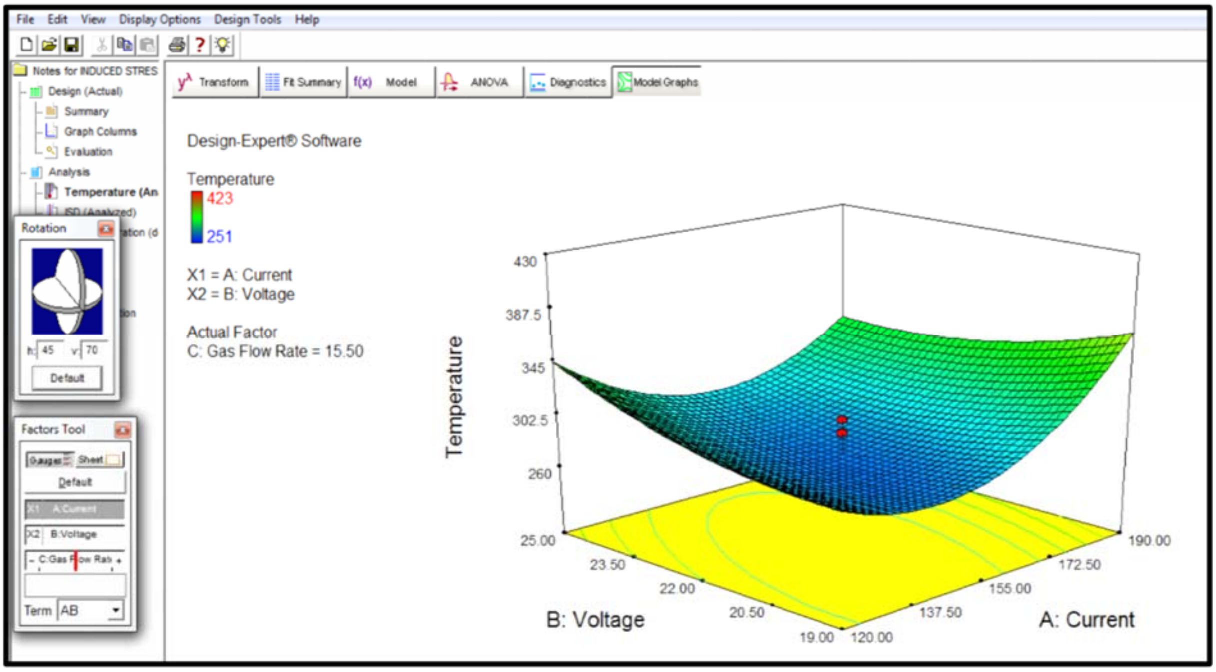


Fig. 2. Effect of current and voltage on temperature

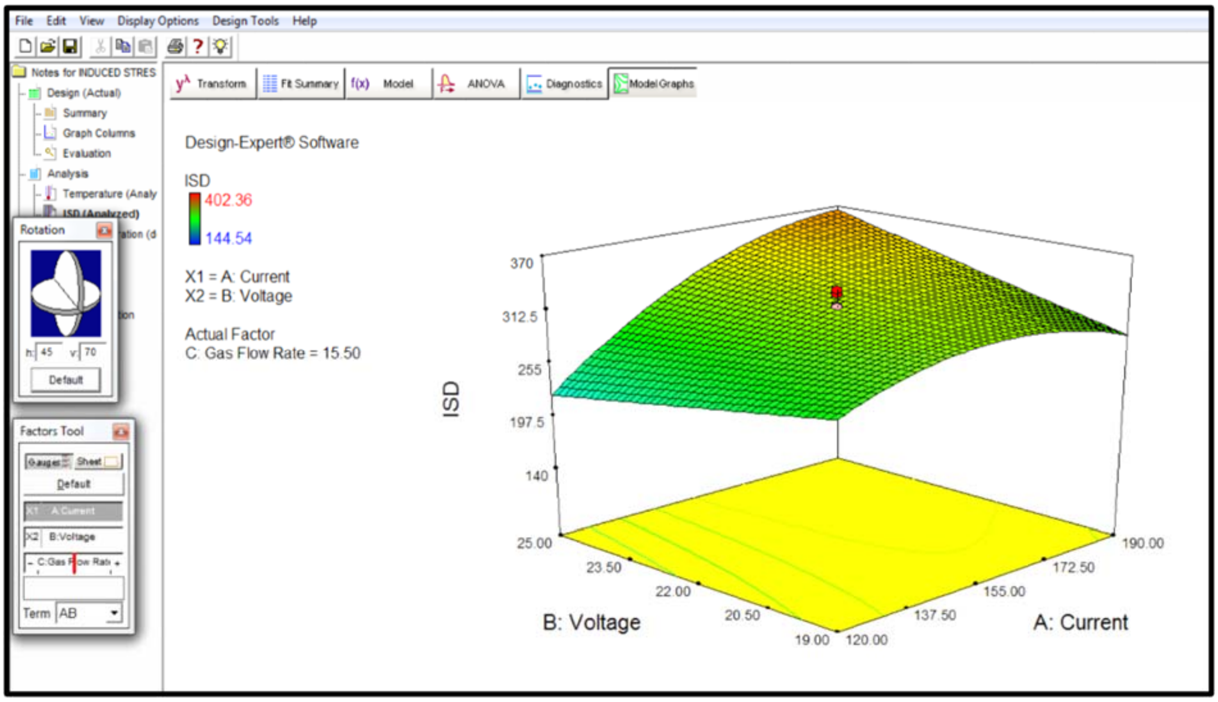
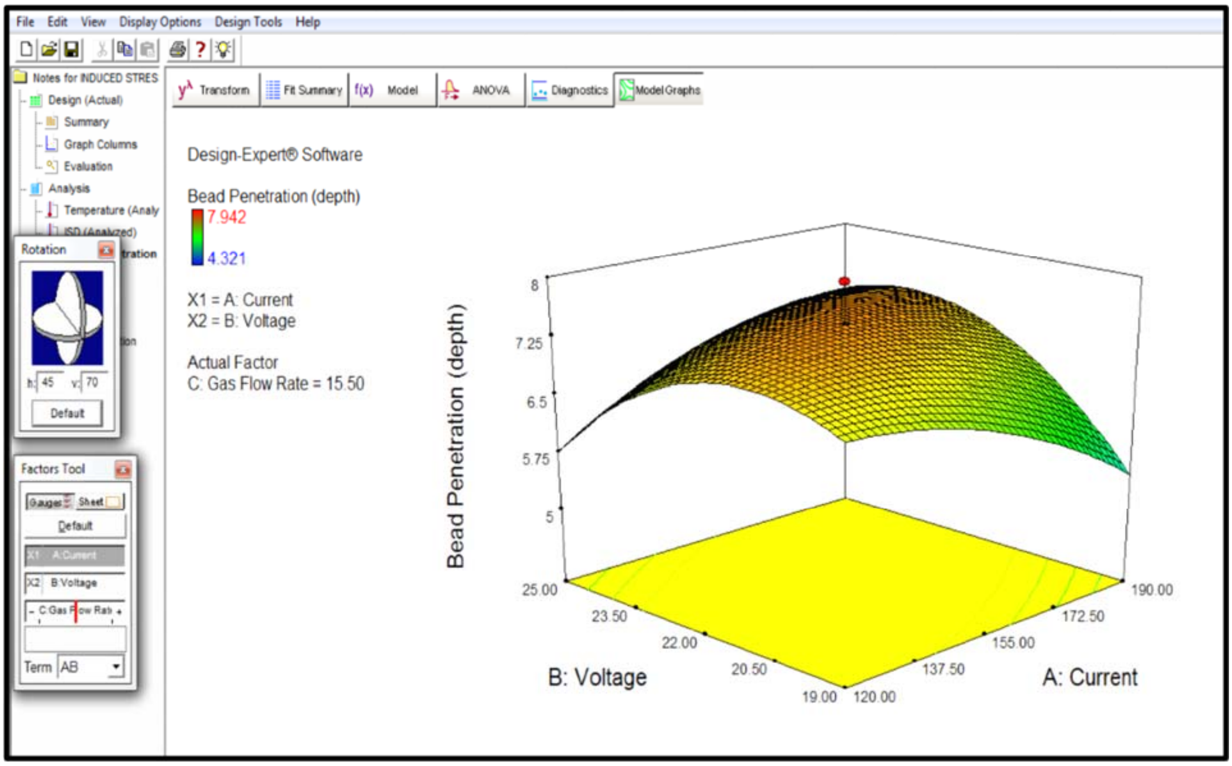


Fig. 3. Effect of current and voltage on induced stress distribution (ISD)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Bead Penetration (depth)
7.942
4.321

X1 = A: Current
X2 = B: Voltage

Actual Factor
C: Gas Flow Rate = 15.50

Fig. 4. Effect of current and voltage on bead penetration

The 3D surface plot as observed in Figs 2-4 shows the relationship between the input variables (current, voltage and gas flow rate) and the response variables (temperature, induced stress distribution and bead penetration). It is a 3 dimensional surface plot which was employed to give a clearer concept of the response surface. Although not as useful as the contour plot for establishing responses values and coordinates, this view may provide a clearer view of the surface. As the color of the curved surface gets darker, the temperature and bead penetration increases proportionately while the induced stress distribution decreases. The presence of a coloured hole at the middle of the upper surface gave a clue that more points lightly shaded for easier identification fell below the surface. Finally, numerical optimization was performed to ascertain the desirability of the overall model. In the numerical optimization phase, design expert was programmed to; determine the optimum current (Amp), voltage (volts) and gas flow rate (L/min) that will maximize temperature, minimize induced stress distribution (ISD) and maximize bead penetration (depth). The constraint set for the numerical optimization algorithm is presented in Table 2. The numerical optimization generated about seventeen (17) optimal solutions which are presented in Table 3.

Table 2. Constraints for numerical optimization of selected responses

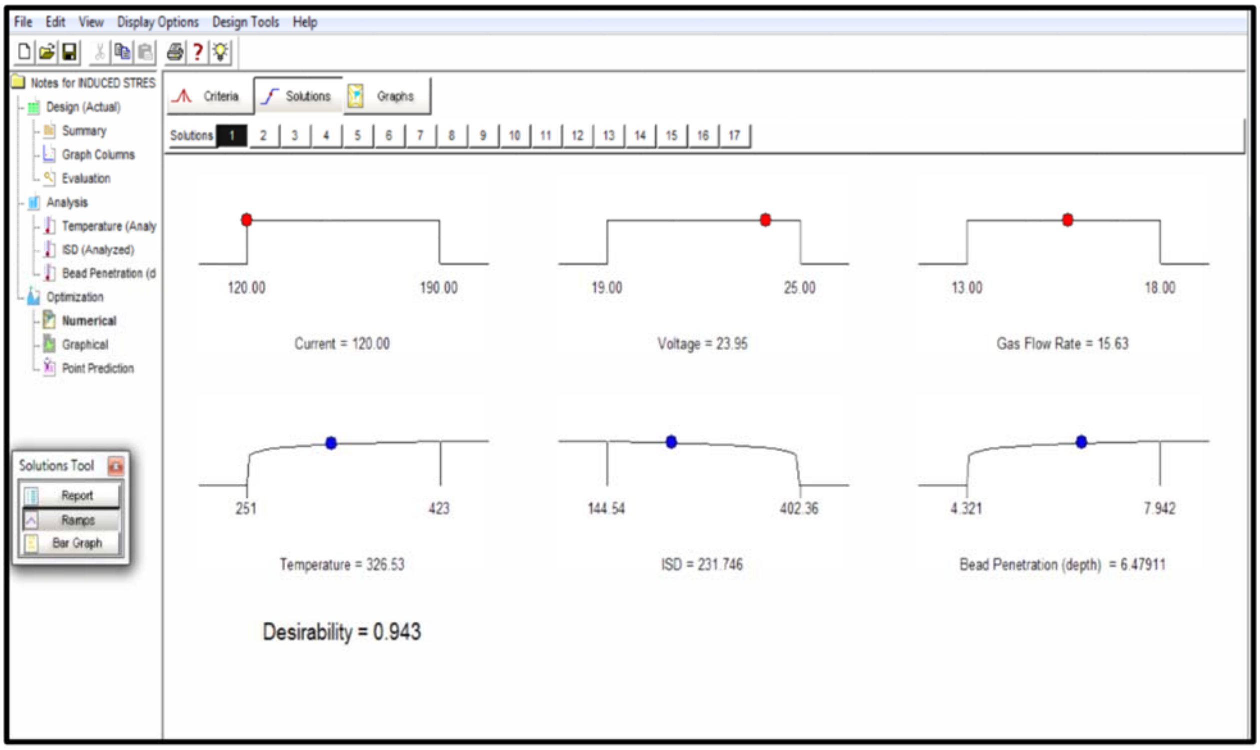
Constraints	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
Current	In range	120	190	1	1	3
Voltage	In range	19	25	1	1	3
Gas flow rate	In range	13	18	1	1	3
Temperature	Maximize	251	423	0.1	1	5
ISD	Minimize	144.54	402.36	1	0.1	5
Bead Penetration	Maximize	4.321	7.942	0.1	1	5

Table 3. Optimal solutions of numerical optimization model

Runs	Current	Voltage	Gas Flow Rate	Temperature	ISDs	Bead Penetration	Desirability	Optimum
1	**120.00**	**23.95**	**15.63**	**326.53**	**231.746**	**6.47911**	**0.943**	**Selected**
2	120.00	23.93	15.62	326.227	231.956	6.4904	0.943	-
3	120.00	23.92	15.60	326.366	231.917	6.48594	0.943	-
4	120.00	23.89	15.60	326.106	231.094	6.49548	0.943	-

5	120.00	23.89	15.55	326.707	231.845	6.47487	0.943	-
6	120.00	23.87	15.55	326.326	232.076	6.48856	0.943	-
7	120.01	23.95	15.65	326.126	231.98	6.49247	0.943	-
8	120.00	24.32	15.93	327.606	230.556	6.42317	0.943	-
9	120.00	23.32	15.02	326.317	234.27	6.48131	0.943	-
10	190.00	20.40	14.62	349.845	303.791	6.45395	0.934	-
11	190.00	20.38	14.60	350.077	303.479	6.44218	0.934	-
12	190.00	20.38	14.68	350.131	303.355	6.43812	0.934	-
13	189.99	20.30	14.48	350.861	302.468	6.40052	0.934	-
14	190.00	20.54	14.54	348.503	305.868	6.52503	0.934	-
15	190.00	20.14	14.18	352.521	300.876	6.31371	0.934	-
16	190.00	20.34	15.12	350.633	303.244	6.39829	0.934	-
17	120.00	19.12	13.54	315.661	261.914	6.05896	0.926	-

From the results of Table 3, it was observed that a current of 120amp, voltage of 23.95volts and gas flow rate of 15.63L/min will produce a weld material with temperature of 326.53°C, Induced Stress Distribution (ISD) of 231.746 N/m^2 and bead penetration (depth) of 6.47911mm. This solution was selected by design expert as the optimal solution with a desirability value of 94.30%. The ramp solution which is the graphical presentation of the optimal solution is presented in Fig 5. The ramp display combines individual graphs for clearer understanding by selecting optimal from most desirable to least. The desirability bar graph shows the accuracy with which the model is able to predict the values of the selected input variables and the corresponding responses presented in Fig 6. The desirability bar graph signifies how well a particular variable satisfies the criteria, making it one of the most frequently used multi-response optimization techniques in practice. However, the desirability lies between 0 and 1 and represent closeness of a response to its ideal value. If a response value is found within the unacceptable range, the desirability is 0, but if found within the ideal range, the desirability is 1, therefore, values closer to one are better.



Current = 120.00

Voltage = 23.95

Gas Flow Rate = 15.63

Temperature = 326.53

ISD = 231.746

Bead Penetration (depth) = 6.47911

Desirability = 0.943

Fig. 5. Ramp solution of numerical optimization

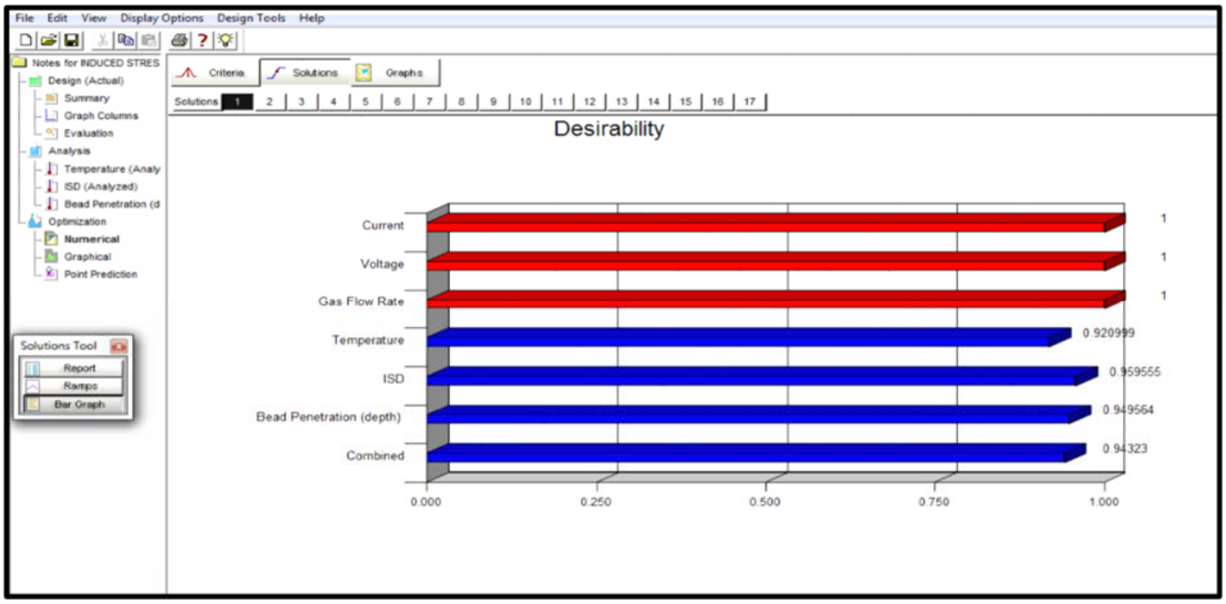


Fig. 6. Prediction accuracy of numerical optimzation

It can be deduce from the result of Fig 6 that the model developed based on response surface methodology and optimized using numerical optimization method, predicted the

i. Temperature with an accuracy level of 92.09%

ii. Induced Stress Distributions (ISDs) with an accuracy level of 95.96% and

iii. Bead Penetration (depth) with an accuracy level of 94.96%

Prediction accuracy of the numerical optimzation for temperature, ISDs and bead penetration (depth) shows that these resposes are close to one which is the ideal value, implying that they are close to actual values needed to achieve optimum welds with little or no defects. Finally, based on the optimal solution, the contour plots showing each response variable against the optimized value of the input variable is presented in Figs 7-10.

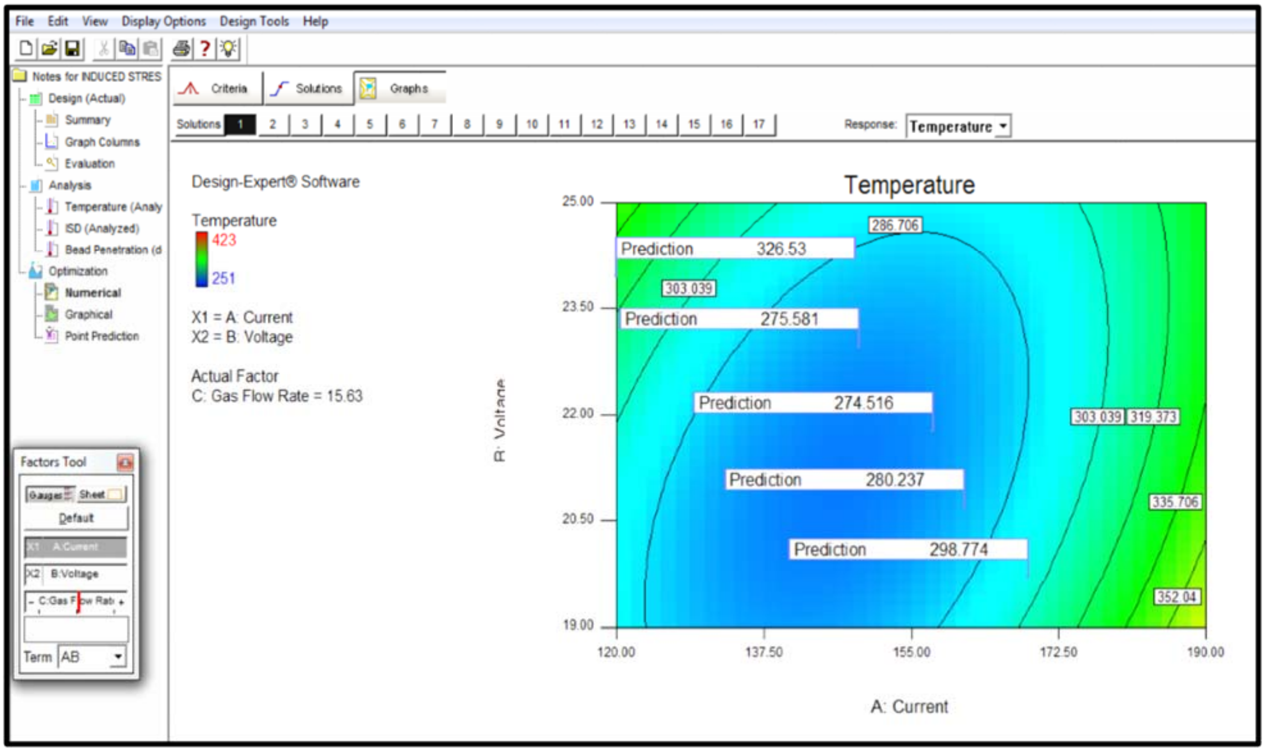
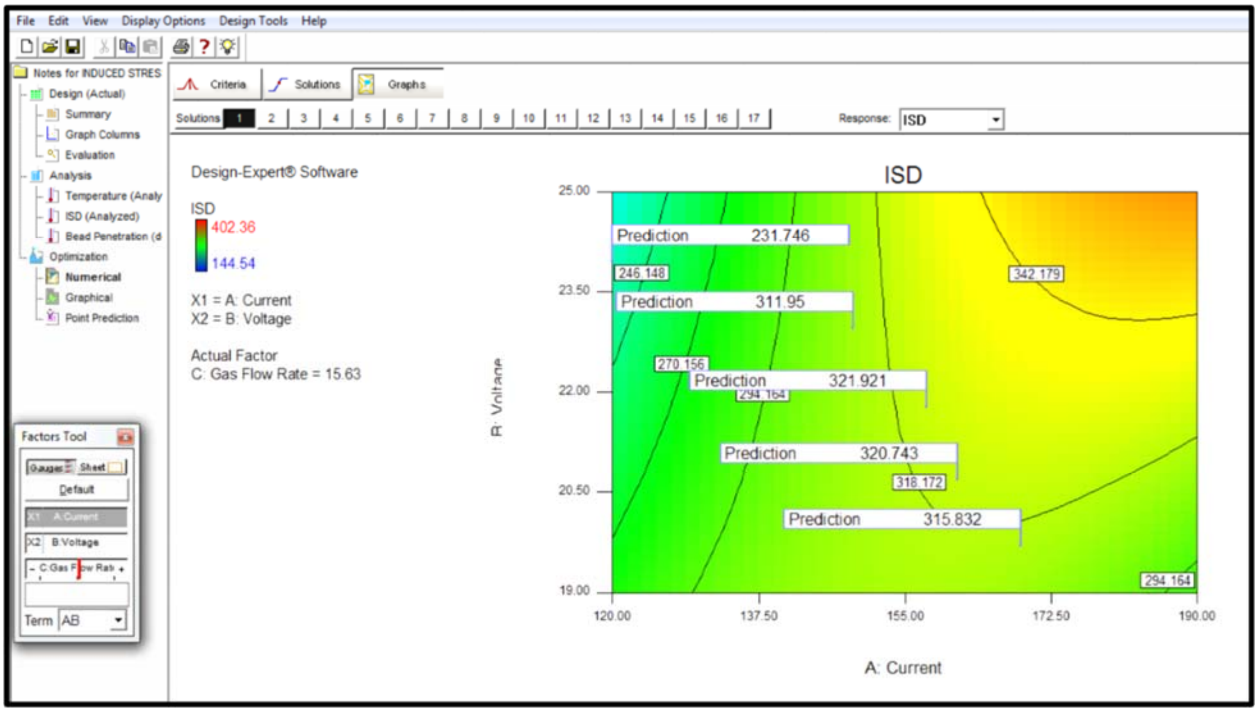


Fig. 7. Predicting temperature using contour plot



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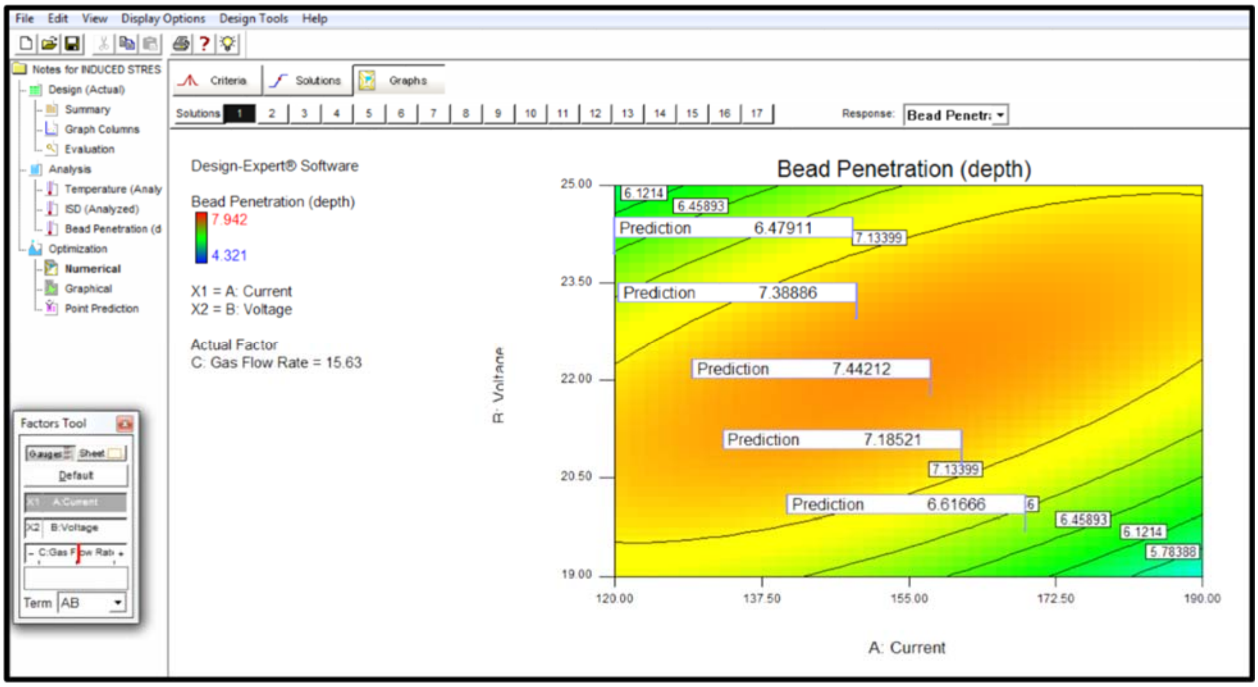
ISD
402.36
144.54

X1 = A: Current
X2 = B: Voltage

Actual Factor
C: Gas Flow Rate = 15.63

Fig. 8. Predicting induced stress distribution using contour plot



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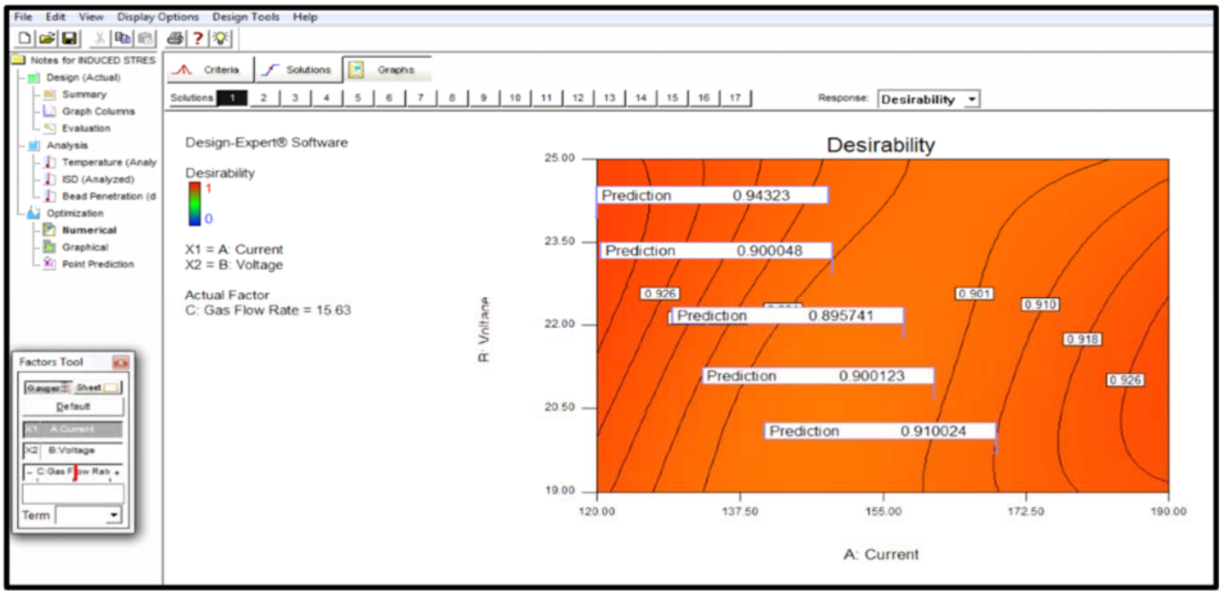
Bead Penetration (depth)
7.942
4.321

X1 = A: Current
X2 = B: Voltage

Actual Factor
C: Gas Flow Rate = 15.63

Fig. 9. Predicting bead penetration using contour plot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Desirability
1
0

X1 = A: Current
X2 = B: Voltage

Actual Factor
C: Gas Flow Rate = 15.63

Prediction 0.94323
Prediction 0.900048
Prediction 0.895741
Prediction 0.900123
Prediction 0.910024

Fig. 10. Predicting desirability using contour plot

Plant flag was employed for annotation of values from the predictors and the responses at any point on the above plots. The contours are showing curved lines because the model contains quadratic equations that are statistically significant. As presented in Figs 7-10, the contour plot can be employed to predict the optimum values of the input variables based on the flagged response variables. To validate the output responses, the experimentally obtained values were plotted with the RSM predicted values and they both maintained the same graphical trend as shown in Fig 11 and 12 respectively.

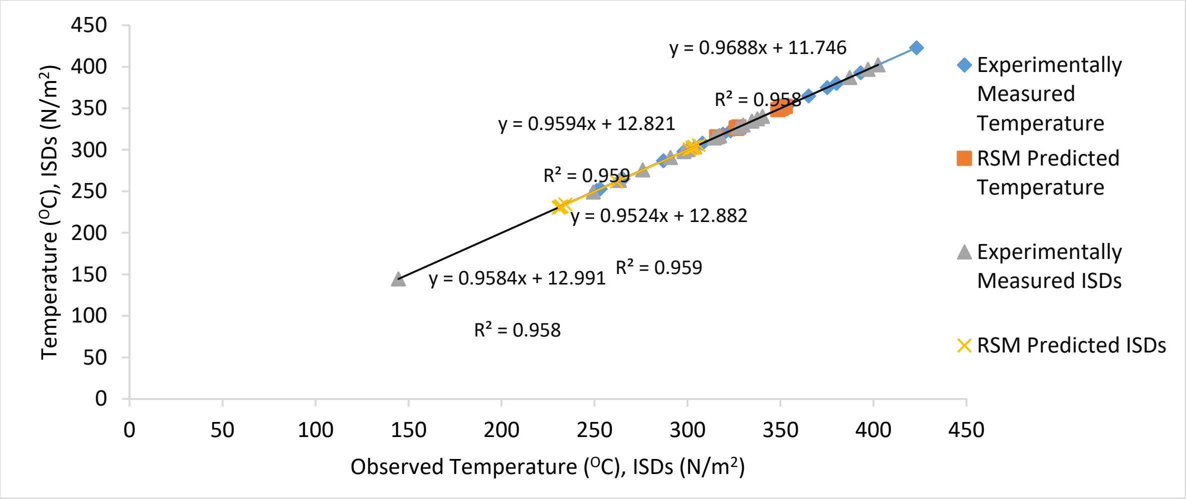

Fig. 11. Regression Plots for Experimental and RSM Predicted Temperature and ISDs

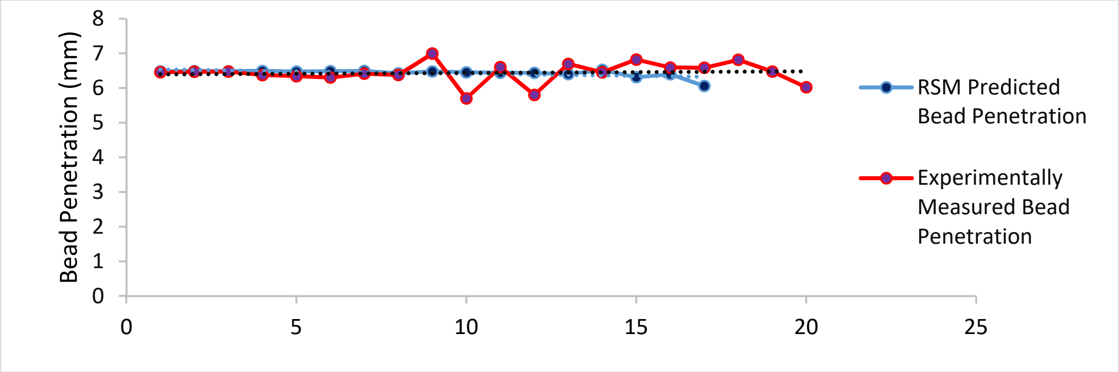

Fig. 12. Graph of Experimental and RSM Predicted Bead Penetration

4. Conclusion

Response surface methodology using numerical optimization was effective in predicting the optimal value of current, voltage and gas flow rate needed to maximize temperature, minimize induced stress distribution (ISD) and maximize bead penetration (depth). It was also useful in determining the exact mathematical relationship between the input variables (current, voltage and gas flow rate) and each individual response variables namely; (temperature, induced stress distribution and bead penetration). One of the fundamental challenges with response surface methodology (RSM) is the inability to accurately predict the response variables without design of experiment. This therefore implies that the performance of RSM is dependent on the experimental design. Using Design expert software, process input parameters (current, voltage, gas flow rate) were generated for twenty runs based on design of experiment, which was also used to conduct the TIG welding experimentation as well as predicting and optimizing the welding process input parameters using Response Surface Methodology. Regression plot for the output responses produced coefficient of determination (R^2) of 0.9582 for the experimental temperature and 0.9595 for the RSM temperature, 0.9599 for the experimental ISDs and 0.9584 the RSM ISDs, which are all closely related. Similarly, the experimental bead penetration depth graphically maintained the same trend with the RSM bead penetration depth. This led to the conclusion that both methods are suitable for predicting weld parameters but RSM would produce optimal solutions that can save cost, time and above all eliminate possible errors that can compromise weld quality.

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