__Original Research Article__

PREDICTION AND OPTIMIZATION OF TIG WELDING PROCESS PARAMETERS OF AISI 317L STAINLESS STEEL PLATES USING RESPONSE SURFACE METHODOLOGY

Abstract

The quality of welds is greatly influenced by the weld bead geometry and mechanical-metallurgical properties of the welded joint which have a direct relationship with the type of welding process being used and its input process parameters such as welding current, gas flow rate, arc voltage, travel speed etc. In this study, prediction and optimization of tungsten inert gas (TIG) welding input parameters for achieving maximum tensile strength of 317L austenitic stainless steel is investigated. Central composite design of response surface methodology has been employed to develop the experimental plan to identify the effect of process parameters on tensile strength. Square butt joint configuration has been made using three factors - two levels of welding input parameters. The results indicate that gas flow rate has greater influence on tensile strength followed by welding current. The model F-value of 18.19 at a P value of 0.0026 for the tensile strength showed the significance of the model employed. The optimal tensile strength of 618.627 MPa was observed at a current of 150 A, travel speed at 15.69 cm/min and gas flow rate at 8.96 l/min.

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Keywords: Tungsten Inert Gas welding, Tensile strength, Central Composite Design, Analysis of variance, Response Surface Methodology.

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1. Introduction

The grade 317L austenitic stainless steel is an important material that is frequently used in industries like automobile, thermal power plant, nuclear power plant, chemical and pharmaceutical industries as a result of its high strength, weldability, superior corrosion resistance, high ductility and formability. Tungsten inert gas welding is one of the most versatile welding processes that join almost all metals and metal alloys in use today. This welding process is very much preferred for its natural qualities like high-quality and superior welds, low distortion, narrow heat affected zone and it leaves no slag or splatter. TIG welding process is extensively used in the modern industries such as automobile industry, aircraft, nuclear industry, food processing industry, precision manufacturing industry, maintenance and repair work etc. Amongst the various types of welding methods, the Tungsten Inert Gas (TIG) welding is the most frequently used for welding austenitic stainless steel [1]. Welding input parameters play a major role in determining the mechanical properties such as tensile strength, hardness etc of the welded joint. As a result, the careful selection of the welding input process parameters and their levels is crucial for obtaining optimal mechanical properties [2, 3, 4]. Welding current, arc voltage, electrode size, arc travel speed, electrode stick out are the important welding process parameters. There are several optimization methods that can be used to determine the desired output responses through the development of mathematical equations to postulate the relationships between the input parameters and output variables. One of the most widely used statistical methods of optimization is the response surface methodology (RSM) [5 6, 7].

Koleva [8] applied the response surface method to establish the relationship between performance characteristics of weld width, weld depth and thermal efficiency and its influencing factors (beam power, welding velocity, focus position, focusing current of the beam and the distance to the sample surface) for austenitic stainless steel. Kiaee et al., [9] used response surface methodology for the optimization of TIG welding process parameters for joining of A516-Gr70 carbon steels. The optimization of CO_2 welding process parameters for Weld Bead Penetration of Mild Steel using RSM was reported by [10]. Mathematical models were developed correlating the welding process parameters such as voltage, travel speed and welding current with weld bead penetration. The optimized values of the various input parameters obtained, were recorded as follows: arc voltage – 20V, travel speed – 40cm/min, welding current – 230A, maximum bead penetration corresponding data is 0.88mm. Optimal welding regimes were found through the thermal efficiency optimization.

In this study, an attempt has been made to optimize the tensile strength properties of AISI 317L stainless steel plates using the response surface methodology.

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2. METHODOLOGY

AISI 317L stainless steel plates of size 100 mm by 45mm by 5mm and ER 317L austenitic steel have been chosen as our base material and filler metal respectively for this study. The chemical composition of the base material is given in Table 1. The mechanical properties of the base material are as follows: tensile strength 595MPa, yield strength 260MPa, Modulus of elasticity 200GPa and hardness, Rockwell B 85. The most significant parameters that affect the mechanical properties of TIG welded joints are identified through extensive study of previous work done. The identified important input parameters are welding current, travel speed and gas flow rate. A number of trials were carried out on 5mm thick AISI 317L stainless steel plates to find out the efficient and practicable working limits of TIG welding parameters and this has been achieved by varying one of the chosen parameters while others remains constant. Non-destructive tests and visual inspection were used to identify the working limits of the welding process parameters.

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The selected input parameters and their levels are shown in Table 2. The central composite design (CCD) of experiments which is the most frequently used method amongst the other types of Response Surface Methodology (RSM) methods, has been chosen for this study because of its flexibility, high efficiency and ability to be run in sequence. Using the Design expert software version 8.0.6, a central composite design matrix of fifteen (15) experimental runs was developed as shown in Table 3. The experiment was performed in three stages. In the first stage, the metal plate edges were prepared and taken for forming the welded joint as shown in the specimen sample shown in Figure 1. The second stage was the welding process and the joint formation using the design matrix. The third stage was the testing and recording of the response (tensile strength). With the fifteen (15) experimental runs generated in Table 3, fifteen coupons were welded using the tungsten inert gas welding method and thereafter allowed to cool naturally in open air, with all necessary precautions observed. The welded plates were sliced in transverse section as shown in Figure 2 to obtain samples for the tensile test.

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Table 1: Chemical composition of grade 317L stainless steel

Element	Content (%)
Iron	Balance
Chromium	18-20
Nickel	11-15
Molybdenum	3-4
Manganese	2
Silicon	1
Phosphorus	0.045
Carbon	0.03
Sulphur	0.03

Table 2: TIG welding parameters and their levels

Parameter	Units	Symbol	Coded Value Low (-1)	Coded Value High (+1)
Welding Current	Amp	A	100	150
Travel speed	cm	B	12	18
Gas flow rate	l/min	C	6	12

Table 3: Central composite design matrix of welding parameters

		Factor 1	Factor 2	Factor 3
Std	Run	A:Welding current	B:Travel speed	C:Gas flow rate
		Amp	cm	l/min
1	10	100	12	9
2	12	150	12	9
3	15	100	18	9
4	7	150	18	9
5	14	100	15	6

6	16	150	15	6
7	3	100	15	12
8	8	150	15	12
9	4	125	12	6
10	13	125	18	6
11	5	125	12	12
12	1	125	18	12
13	2	125	15	9
14	17	125	15	9
15	9	125	15	9

2.1 Tensile Strength Test

The tensile samples were prepared by milling of the top and bottom surfaces to remove flashing and other surface irregularities in accordance with ASTM specification E8/E8M-11. The tensile test was performed on all the thirty welded specimens using the universal testing machine.

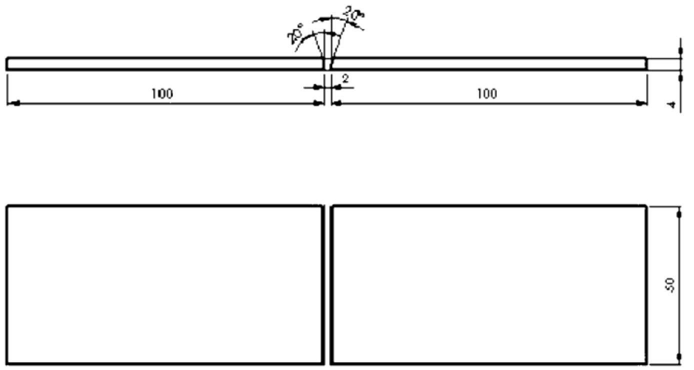

Fig. 1: Sample of specimen

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Fig. 2: Welded specimen

Response Surface Methodology (RSM): The basic concept of RSM include experimental design, regression analysis and optimization algorithms which are used to investigate the empirical relationship. RSM allows you to specify and fit a model up to the second order; usually a second order model is utilized in response surface methodology [11] and is given by Equation (1).

$$Y = b_0 + \sum_{i=1}^{K}(b_i\, x_i) + \sum_{i=1}^{k}(b_{ii}\, x_i^2) + \sum_{i=1}^{K}(b_{ij}\, x_i x_j) + \varepsilon \tag{1}$$

where $Y = response\ variables\ or\ dependent\ variables$
$x_i = predicted\ variables\ or\ independent\ variables$
$b_0 = model\ constant$
$\varepsilon = random\ error$

parameters b_i, b_{ii}, b_{ij} are known as regression coefficient where $i = 1, 2, 3 \ldots k\ and\ j = 1, 2, 3, \ldots k$.

3. Result and Discussion

Response surface methodology from statistical software Design expert 8.0.6 has been applied on the experimental data. The randomized design matrix of the welding parameters (welding current, travel speed and gas flow rate) with the experimental results of the response factor (tensile strength) is presented in Table 4. It is found that sample number 14 shows maximum tensile strength (625.45 MPa) while sample number 7 depicts lowest tensile strength (584.61 MPa).

Table 4: Central composite design of experiment

		Factor 1	**Factor 2**	**Factor 3**	**Response 1**
Std	Run	A:Welding current (A)	B:Travel speed (cm)	C:Gas flow rate (l/min)	Tensile strength (MPa)
1	10	100	12	9	601.11
2	12	150	12	9	606.42
3	15	100	18	9	597.48

4	7	150	18	9	617.37
5	14	100	15	6	608.26
6	16	150	15	6	601.91
7	3	100	15	12	584.61
8	8	150	15	12	599.69
9	4	125	12	6	610.15
10	13	125	18	6	602.24
11	5	125	12	12	592.42
12	1	125	18	12	594.88
13	2	125	15	9	622.42
14	17	125	15	9	625.45
15	9	125	15	9	622.85

Analysis of Variance: ANOVA test was done to ascertain if the model is significant or not and to also evaluate the significant contribution of each of the welding process parameters on the response (tensile strength). When the F-value is large and the p-value is less than 0.05%, it signifies the absence of external influence on the variance and also confirms that the model is significant [11]. Table 5 shows the analysis of variance results for validating the model significance in optimizing tensile strength. The Model F-value of 18.19 implies the model is significant. There is only a 0.26% chance that a “Model F-Value” this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. From observation of Table 5, A, C, AC, A^2, B^2, and C^2 are significant model terms. The lack of fit value of 6.74 implies the lack of fit is not significant which is desirable as we want the model to fit. The ANOVA result shows that gas flow rate is the most significant parameter that affects the tensile strength followed by welding current. Travel speed has the least effect on tensile strength.

Table 5: ANOVA result for validating the model significance

Analysis of variance table [Partial sum of squares - Type III]						
	Sum of		Mean	F	p-value	
Source	Squares	df	Square	Value	Prob > F	Remarks
Model	1956.168	9	217.3521	18.19057	0.0026	significant
A-Current	143.9056	1	143.9056	12.04371	0.0178	significant
B-travel speed	0.437112	1	0.437112	0.036583	0.8558	Not significant
C-gas flow rate	324.6152	1	324.6152	27.16762	0.0034	Significant
AB	53.1441	1	53.1441	4.447723	0.0887	Not significant
AC	114.8112	1	114.8112	9.608753	0.0269	Significant
BC	26.88423	1	26.88423	2.249988	0.1939	Not significant
A^2	343.2433	1	343.2433	28.72664	0.0030	Significant
B^2	256.6154	1	256.6154	21.4766	0.0057	Significant
C^2	865.9337	1	865.9337	72.47151	0.0004	Significant
Residual	59.74304	5	11.94861			
Lack of Fit	54.36777	3	18.12259	6.742955	0.1319	Not significant

Pure Error	5.375267	2	2.687633			
Cor Total	2015.911	14				

Table 6: Goodness of fit statistics

Std. Dev.	3.456676		R-Squared	0.970364
Mean	605.8173		Adj R-Squared	0.91702
C.V. %	0.570581		Pred R-Squared	0.562491
PRESS	881.9787		Adeq Precision	14.50011

Coefficient of determination (R-Squared) of 0.9703 as observed in Table 6 shows the strength of response surface methodology and its ability to predict the optimal values of the selected variables that will maximize the tensile strength. The Coefficient of determination (R-Squared) of 0.9703 indicates that 97% of the total variations as in the case of the response (tensile strength) can be explained by the model. The value of the adjusted coefficient of determination Adj. R-Squared value of 0.917 indicates a model with 91.7% reliability. Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Adequate precision value of 14.5 as observed indicates an adequate signal, indicating that the model can be used to maximize the tensile strength.

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OPTIMALEQUATIONS BASED ON CODED VARIABLES

The optimal equation which shows the individual effects and combined interactions of the selected variables against the measured response (tensile strength) in terms of coded factors is presented in equation (2)

$$Tensile\ strength = 623.5733 + 4.2413A + 0.2338B - 6.37C + 3.645AB + 5.3575AC + 2.5925BC - 9.6417A^2 - 8.3367B^2 - 15.3142C^2 \quad (2)$$

where $A, B\ and\ C$ represents welding current, travel speed and gas flow rate respectively.

The diagnostics case statistics which shows the observed values of tensile strength against their predicted values is presented in Tables 7.

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Table 7 Experimental and predicted tensile strength values

Standard Order	Actual Value	Predicted Value	Residual	Leverage	Internally Studentized Residual	Externally Studentized Residual	Fitted Value DFFITS	Cook's Distance
1	601.11	604.765	-3.655	0.75	-2.11475	** -5.82	* -10.08	* 1.34
2	606.42	605.9575	0.4625	0.75	0.267598	0.24108	0.417562	0.021483
3	597.48	597.9425	-0.4625	0.75	-0.2676	-0.24108	-0.41756	0.021483
4	617.37	613.715	3.655	0.75	2.114748	** 5.82	* 10.08	* 1.34
5	608.26	606.1038	2.15625	0.75	1.247586	1.344617	* 2.33	0.466941
6	601.91	603.8713	-1.96125	0.75	-1.13476	-1.17791	* -2.04	0.386305
7	584.61	582.6488	1.96125	0.75	1.134761	1.177909	* 2.04	0.386305
8	599.69	601.8463	-2.15625	0.75	-1.24759	-1.34462	* -2.33	0.466941
9	610.15	608.6513	1.49875	0.75	0.867163	0.841466	1.457463	0.225591
10	602.24	603.9338	-1.69375	0.75	-0.97999	-0.97517	-1.68904	0.288113
11	592.42	590.7263	1.69375	0.75	0.979988	0.97517	1.689043	0.288113
12	594.88	596.3788	-1.49875	0.75	-0.86716	-0.84147	-1.45746	0.225591
13	622.42	623.5733	-1.15333	0.333333	-0.40864	-0.37176	-0.26287	0.008349
14	625.45	623.5733	1.876667	0.333333	0.664927	0.622907	0.440462	0.022106

15	622.85	623.5733	-0.72333	0.333333	-0.25629	-0.23075	-0.16316	0.003284

Model validation

The adequacy of the model has also been checked by the normal probability plot of the residuals as shown in Fig. 3. From the figure, it is observed that the residuals fall on the straight line, which means the errors are normally distributed and the mathematical relationship is correctly developed. Fig. 4 shows the comparison between the predicted and the actual values of response variables (tensile strength). The graph indicates that the developed model is adequate. It also suggests that the predicted results are in good agreement with measured data.

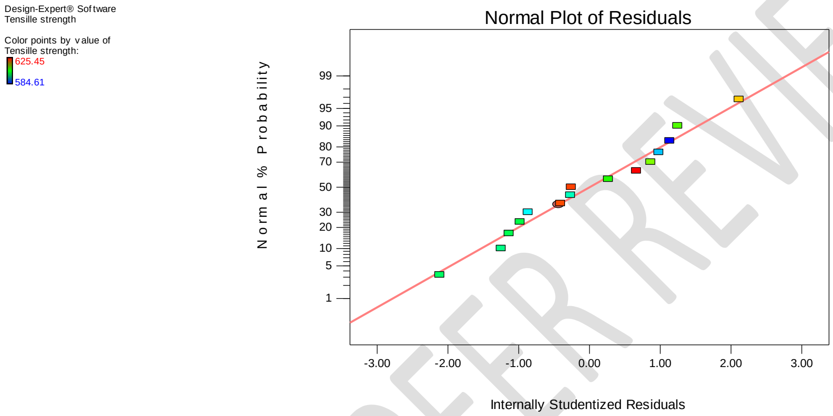

Fig. 3: Residual plot of tensile strength

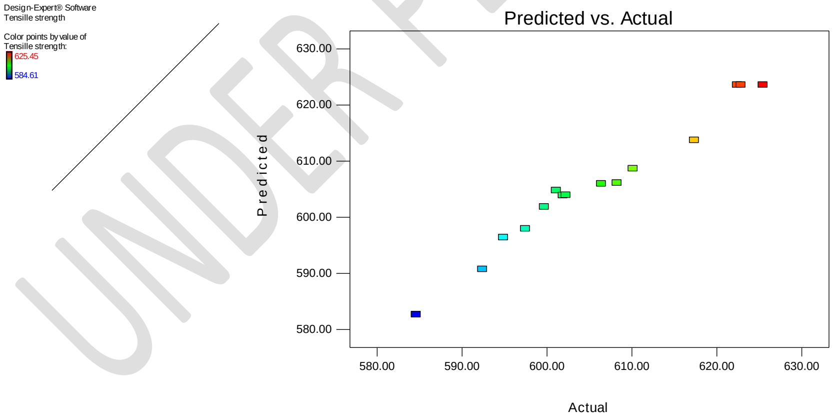

Fig. 4 Predicted vs. actual plot of tensile strength

Effect of the process parameters on tensile strength

The model graphs which show the interaction effects of the process parameters on the measured response (tensile strength) were evaluated using the 3D surface plot as shown in Figs. 5, 6 and 7. Fig. 5 shows the combined effect of travel speed and welding current on tensile strength. It is noticed that tensile strength first increases steadily then decreases with further increase in the levels of the welding current. The tensile strength is found to be optimum at the medium levels of welding current and travel speed. Fig. 6 shows the joint effect of welding current and gas flow rate on tensile strength. It is observed that tensile strength increases with gas flow rate up to a threshold value and thereafter begins to decrease to its minimum value. Tensile strength is optimum at medium values of welding current and gas flow rate. This is because at low gas flow rate, there may be contamination leading to weak joint formation. With further increase in the level of gas flow rate and welding current towards the centre value, the tensile strength is found to be improved and attained its maximum value at center point. Fig. 7 shows the interaction plot between the gas flow rate and travel speed on the tensile strength. It is observed that the tensile strength is optimum at the center value of gas flow rate and travel speed. When the travel speed is low, the heat input is high and it leads to overheating of the base metal and causes formation of low strength joint. The study suggests that it is not recommended to employ very upper or lower level of TIG welding process parameters for obtaining optimal value of tensile strength. Gas flow rate is the most significant parameter on tensile strength and it is followed by welding current and travel speed. The dark colour area on the surface plot as observed in Figs. 5-7 depicts areas of high tensile strength. This agrees with the findings of [12], who investigated tungsten inert gas welding input parameters to attain maximum tensile strength of 316L austenitic stainless steel.

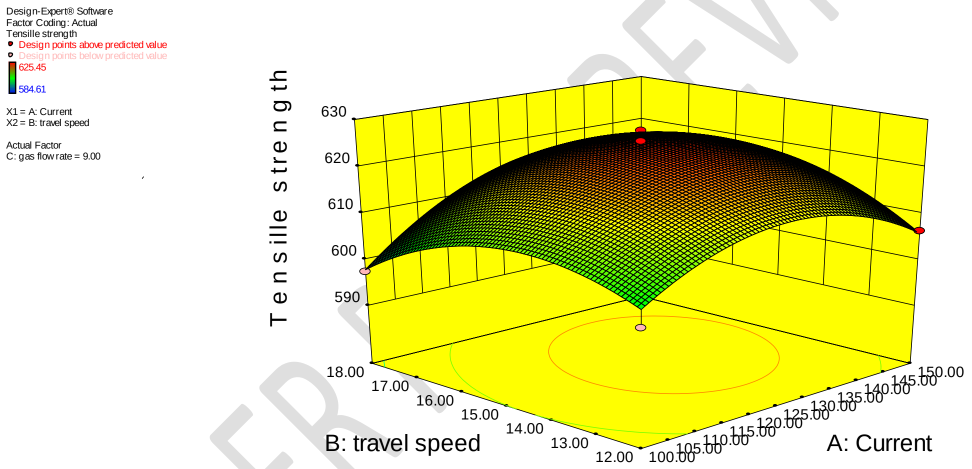

Fig. 5: Effect of travel speed and current on tensile strength

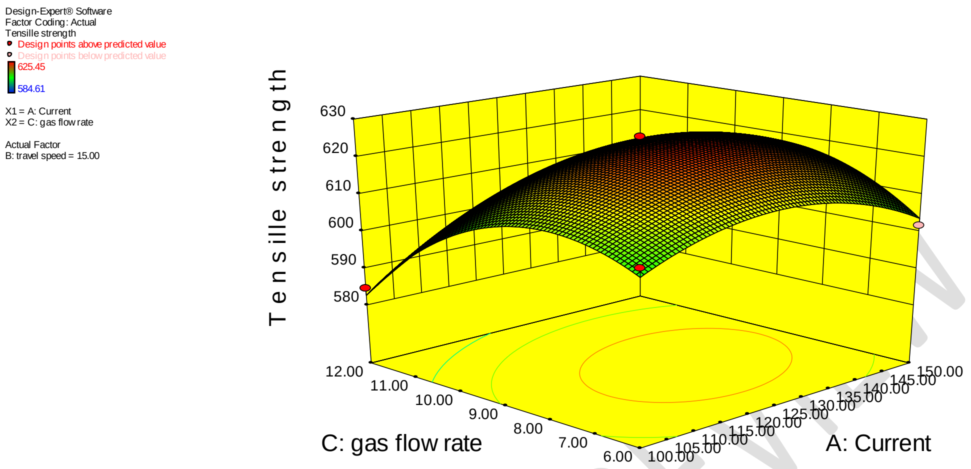

Fig. 6: Effect of gas flow rate and current on tensile strength

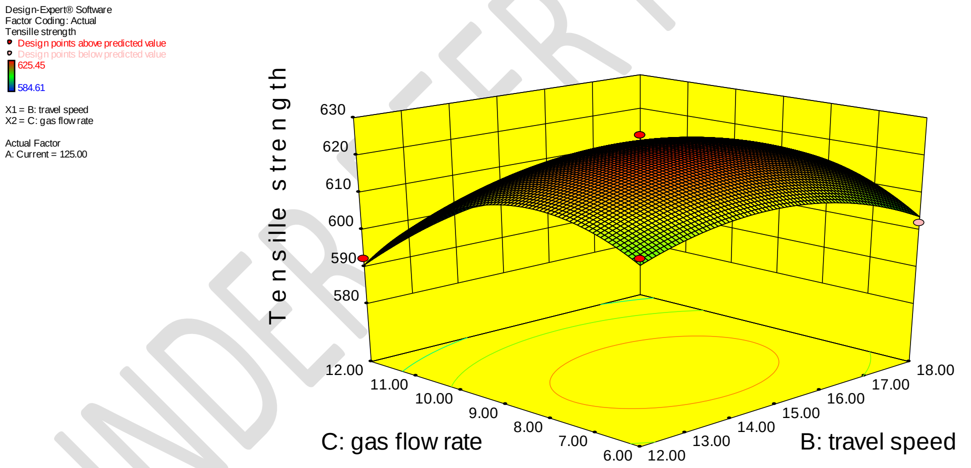

Fig.7: Effect of gas flow rate and travel speed on tensile strength

4 Numerical optimization

In order to ascertain the desirability of the overall model, numerical optimization was performed using the design expert software. The desirability function analysis is applied to get optimum parameters settings to attain maximum tensile strength of welded specimens. The results of multi objective optimization for tensile strength and desirability are shown in Figs. 8-9. The optimum tensile strength: 618.627MPa has been obtained at welding current of 150A, travel speed at 16.69 cm/min and gas flow rate of 8.96 l/min. The value of composite desirability is 0.913.

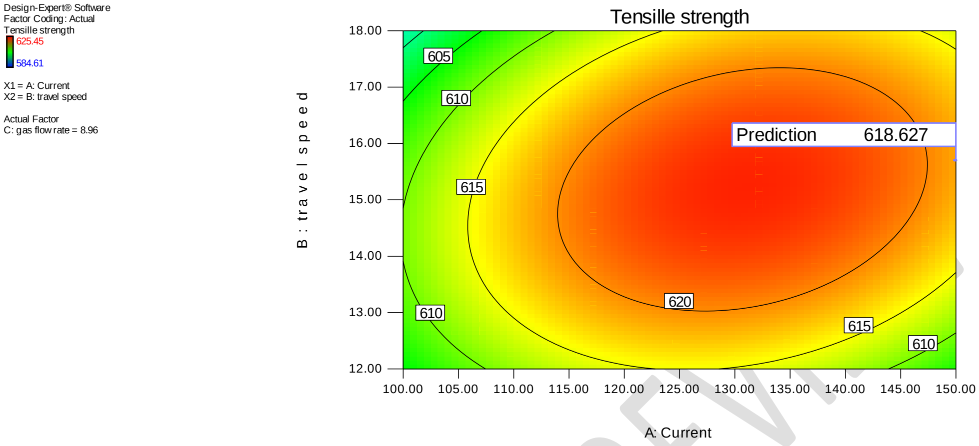

Fig. 8 Optimization results for tensile strength

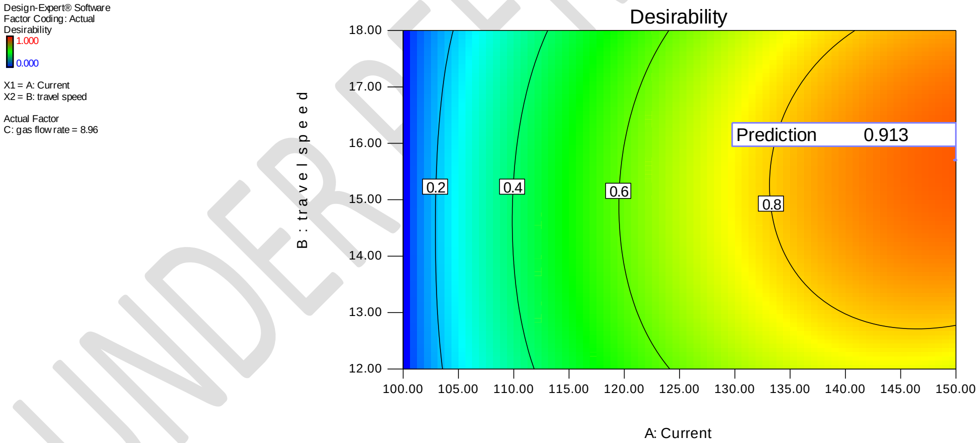

Fig. 9 Optimization results for desirability

4.1 Confirmation test

The results of optimization obtained have been validated by performing confirmatory experiments. The result of confirmatory tests that was conducted at optimum conditions is shown in Table 8. It is observed from Table 8 that the error in terms of percentage between the predicted and experimental results is very small and less than 1%. This shows that the optimized TIG welding process parameters can be considered to obtain higher tensile strength of 317L stainless steel.

Table 8 Multi-objective optimization results

Welding current (A)	Travel speed (cm/min)	Gas flow rate (l/min)	Tensile strength (MPa)	
150	15.69	8.96	Average Actual	622.73
			Predicted	618.627
			Error %	0.658

5. CONCLUSION

The response surface methodology (RSM) was successfully used to predict optimum process parameters settings for maximum tensile strength of TIG welded plates of AISI 317L stainless steel. The following conclusions are drawn based on the experimental results and analysis:

- ❖ Sample no. 14 shows the highest tensile strength while sample no. 7 shows the lowest tensile strength.
- ❖ The ANOVA results showed that the most significant factor affecting tensile strength is gas flow rate followed by welding current.
- ❖ The experimentally obtained data were compared with the predicted values for the response (tensile strength) and the errors were found to be within the acceptable level.
- ❖ An optimum tensile strength of 618.627 MPa is obtained under the welding conditions of current at 150 A, travel speed at 15.69 cm/min and gas flow rate at 8.96 l/min with a desirability value of 0.913.
- ❖ The percentage error between the predicted results and the results of confirmatory test is found to be less than 1% which validates the applied optimization method.

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