DETERMINATION OF GAS METAL ARC WELDING PARAMETERS USING RESPONSE SURFACE METHODOLOGY

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***ABSTRACT*-**This paper presents an experimental design approach to process parameter optimization for gas metal arc welding of austenitic stainless steels. Face-centered central composite design of experiments, based on response surface methodology (RSM) has been adopted. The selected input parameters are welding current, gas flow rate and travel speed. The observed output responses of the ultimate tensile strength and percentage elongation under varied conditions have been discussed and interpreted with use of statistical analysis of variance technique. To determine the optimal welding parameters, a set of mathematical models have been developed relating welding process parameters to each of the responses separately by RSM. Response contour plots have been made from developed mathematical models to illustrate the interaction effects of the welding parameters on response variables. Process optimization has been done by desirability approach. Finally, some useful conclusions have been drawn from the study.

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Keywords-Gas metal arc welding, Austenitic stainless steels, Response surface methodology, Desirability approach, Process optimization

INTRODUCTION

Gas metal arc welding (GMAW) is a semi-automatic or automatic arc welding process that produces coalescence of metals by heating with a welding arc between continuous consumable filler metal electrode and work material. GMAW is being done in the protective shield of a gas or a gas mixture. In recent years different new welding processes have come into use, but still GMA welding is one of the significant welding processes for stainless steel whenever quality and productivity is main concern.

Selection of optimal welding parametric combination to produce desired quality characteristics in weldment is time consuming and costly process [1]. Statistical design of experiments methods can provide optimum results with minimum number of experiments and with significant accuracy. Response surface methodology is one of the important methods of DOE, can be used to analyse, model and optimize the manufacturing processes / systems by developing empirical relation between the control variables i.e. input parameters and output responses. With use of the RSM, quality / efficiency of the process / system can be improved without increasing the cost. Because parametric optimization can improve performance measures and it also ensures lower cost of welding operation. Desirability function approach is an simple and flexible optimization technique used to solve multi-response problems.

Kiaee et al., [1] used RSM for the optimization of TIG welding process parameters for joining of A516-Gr70 carbon steels. Gunaraj et al., [2] also utilized RSM application to predict desired weld quality characteristics in submerged arc welding of pipes. Elatharasan et al., [3] conducted experimental analysis in friction stir welding of AA 6061-T6 aluminum alloy by using RSM. They conducted experiments as per face-centered central composite design and mathematical relationships relating input and output variables had also been developed by RSM. Benyounis et al., [4] had done research investigation for butt joining of medium carbon steels in laser welding process by RSM. Islam et al., [5] proposed integrated finite element method - RSM combined with genetic algorithm to determine optimal arc welding parameters. Ankita et al., [6] optimized the bead geometry of submerged arc weld using fuzzy based desirability function approach. Satheesh et al., [7] made an analysis to study the variations of welding parameters and consumables on weld bead hardness and material deposition rate of welded steels. Researchers found optimum welding conditions for optimizing both the responses simultaneously by using desirability function approach.Periasamy et al., [8] found optimum welding factors for multi-responses for joining of Al/Sicp metal matrix composites in friction stir welding process based on desirability function approach. In this paper, experimental investigation has been carried out to study the significance of welding process variables on weld quality characteristics in gas metal arc welding of austenitic stainless steels. The applications of RSM are then used for planning the experiments and analysing the results by developing the second order mathematical models. Optimal responses have been predicted by desirability approach.

RESPONSE SURFACE METHODOLOGY AND DESIRABILITY FUNCTION APPROACH

Response surface methodology (RSM) is used to examine the relationship between response variable and a set of quantitative experimental variables [9]. RSM may be applied, where one wants to find the operating conditions that produce the best response and identify new operating conditions that produce improved product quality over the quality achieved**.** In the present study, RSM's face-centered experimental design with three factors, three levels, and fifteen runs (Table 1) are selected. The experimental design consists of a set of points lying at the midpoint of each edge and replicated center point of a multidimensional cube. The mathematical model is then developed that illustrates the relationship between the process variable and response. In the RSM, the quantitative form of relationship between the desired response and independent input variables can be presented as follows

$$Y = f(I, F, T) \quad (1)$$

where, I, F, T are input parameters and Y is the response variable, which is required to be optimized. Here, it is assumed that the independent variables (input parameters) are continuous and controllable by experiments with negligible errors. The complete description of the process behavior can be obtained through quadratic / higher order polynomial model. Hence, these quadratic models are established by using the least squares method, which includes interaction terms of input variables to minimize / maximize the response variable. The full quadratic model of the three factors is shown in Eq.2.

$$Y = \beta_0 + \beta_1 (I) + \beta_2 (F) + \beta_3 (T) + \beta_{11} (I^2) + \beta_{22} (F^2) + \beta_{33}(T^2) + \beta_{12}(I*F) + \beta_{13}(I*T) + \beta_{23}(F*T) \quad (2)$$

The betas are coefficients of linear, quadratic and interaction of input parameters I, F and T. The term β0is the intercept term, β_1, β_2 and β_3 are the liner terms,β_{11}, β_{22} and β_{33} are the squared terms, and β_{12},β_{13} and β_{23} are the interactions between the independent / input variables. This empirical model is useful to determine the optimum parametric condition to obtain desired response variable.

Desirability function approach was introduced by Harrington [10]; is an efficient tool for solving the multi-objective optimization problems. Desirability between 0 and 1 denotes the closeness of a response to its ideal value. If a response falls within the undesirable intervals, the desirability is 0, and if a response falls within the ideal intervals or the response reaches its ideal value, the desirability is equal to 1. Individual desirability values related to each of the quality characteristics are calculated using the formula proposed by Derringer and Suich in1980's. There are three types of desirability function: Lower-the-Better (LB), Higher-the-Better (HB) and Nominal-the-Best (NB). The mathematical formula of desirability function of the lower-the-better (LB) criteria is given Eqs. 1-3. d_i varies within the range 0 to 1, ˆy is expected to be the lower the better. Mathematical equation for Higher-the-better (HB) criterion is shown in Eqs. 4-6. d_i varies within the range 0 to 1 and ˆy is expected to be the higher the better.

$$\text{If } \hat{y} \le y_{\min},\ d_i = 1 \quad (1)$$

$$\text{If } y_{\min} \le \hat{y} \le y_{\max},\ d_i = \left(\frac{\hat{y} - y_{\max}}{y_{\min} - y_{\max}}\right)^r \quad (2)$$

$$\text{If } \hat{y} \ge y_{\max},\ d_i = 0 \quad (3)$$

$$\text{If } \hat{y} \le y_{\min},\ d_i = 0 \quad (4)$$

$$\text{If } y_{\min} \le \hat{y} \le y_{\max},\ d_i = \left(\frac{\hat{y} - y_{\min}}{y_{\max} - y_{\min}}\right)^r \quad (5)$$

$$\text{If } \hat{y} \ge y_{\max},\ d_i = 1 \quad (6)$$

The individual response desirability values are added to calculate the overall desirability values by using Eq. 7. Here, D is the overall desirability value, di is the individual desirability value of i^{th} quality characteristic and n is the total number of response characteristics,w_i is the weightage of individual response.

$$D = \left(d_1^{w_1} d_2^{w_2} \ldots\ldots\ldots\ldots d_n^{w_n}\right)^{\frac{1}{\sum w}} \quad (7)$$

Table 1. Input parameters and their levels

Process Parameters	Level I	Level 2	Level 3
Current (I)	100	115	130
Gas flow rate (F)	10	12	14
Travel speed (T)	4.5	5	5.5

EXPERIMENTATION

Welding set-up has been prepared, checked and made ready for doing welding. The photographic view of the set-up is shown in Fig.1. Butt joints are made by welding two pieces of austenitic stainless steel, grade AISI 304. Each pieces has the dimensions 100 mm x 70 mm x 3 mm. Twenty welded samples are thus made, by carrying out welding at different levels of current, gas flow rate and travel speed, as per RSM face – centered central composite design of experiments, given in Table 2. Photographic view of a welded specimen (sample no. 6) is shown in Fig. 2.

Fig 1: The welding set-up

Fig 2: Photographic view of a sample just after welding

ANALYSIS AND DISCUSSION OF EXPERIMENTAL RESULTS

EMPIRICAL MODELING USING RSM

Statistical tool, response surface methodology (RSM) from MINITAB 16.1 software has been applied on experimental data as shown in Table 2, to build up mathematical relationships between the welding process parameters and output responses: ultimate tensile strength (UTS) and percentage elongation (PE). RSM is one of the empirical modeling techniques, used to carry out the analysis of experiments with the reduced experimental runs [9]. General model of second order mathematical model is shown in Eq. 2. The values of all constants such as β_0,β_1, β_2, β_3, β_{11}, β_{22}, β_{33}, β_{12}, β_{13} and β_{23} in the Eq. 2 are determined through least square method by using experimental data and application of RSM. The developed models are shown in Eq. 8 and Eq. 9 for UTS and PE respectively.

$$Y_{UTS} = 1491.99 + 3.669(I) + 4.40(F) - 470.48(T) - 0.08(I*I) - 1.55(F*F) + 19.35(T*T) - 0.02(I*F) + 1.60(I*T) + 7.21(F*T) \quad (8)$$

$$Y_{PE} = 519.32 + 0.82(I) - 49.37(F) - 88.25(T) - 0.014(I*I) + 0.56(F*F) - 0.79(T*T) + 0.09(I*F) + 0.26(I*T) + 5.22(F*T) \quad (9)$$

Table 2.Box-Behnken design and output responses

S. No	Input Parameters			Output responses	
	Current (I)	Gas flow rate (F)	Travel speed (T)	UTS	PE
1	115	12	5.0	560.28	44.88
2	115	10	5.0	573.16	55.88
3	100	14	4.5	568.06	45.44
4	115	12	5.0	560.36	52.25
5	100	10	4.5	561.39	57.40
6	100	12	5.0	558.53	45.80
7	115	12	5.0	571.03	50.68
8	115	12	5.0	554.67	52.23

9	130	10	4.5	565.25	50.45
10	100	10	5.5	529.84	39.99
11	130	14	5.5	589.06	61.80
12	130	10	5.5	555.60	42.07
13	115	14	5.0	568.12	48.94
14	115	12	5.0	571.40	51.13
15	115	12	5.0	577.92	54.17
16	100	14	5.5	539.34	50.02
17	130	14	4.5	543.83	50.41
18	130	12	5.0	573.71	48.42
19	115	12	4.5	586.09	52.91
20	115	12	5.5	577.31	47.03

VALIDATION OF THE DEVELOPED RELATIONSHIP

The adequacy of the developed mathematical model has been checked by analysis of variance (ANOVA). Table 3 and 4 shows the analysis variance tables of UTS and PE respectively. In ANOVA table, P- value is determines which parameters is significance on the response of interest. ANOVA test is performed at 95% confidence levels i.e. 5% significance levels. If P-value of a particular factor becomes less than 0.05; then it is concluded that influence of the respective factor on output response is significant. From Table 3, it is found that individual and squared combination effects of all the input parameters are insignificant on UTS. In so far as interaction effects concerned, interaction effects of current and travel speed has considerable effect on UTS, and other two interactions do not have significant effect as their P values are less than 0.05 and greater than 0.05 respectively. ANOVA table for UTS depicts that welding process parameters are not influencing much for UTS.

ANOVA results for PE (Table 3) shows that individual effect of gas flow rate has significant effect, as its p value is 0.006. Individual effects of current and travels speed, and its squared combination effects are insignificant, because their significance variable (P) value is more than 0.05. Interaction effects of current and gas flow rate, gas flow rate and travel speed have significant effect on PE, as its P values are 0.044 and 0.001 respectively. And interaction effect of current and travel seed have lesser influence on PE, as its P value is greater than 0.05.

Table 3.Analysis of Variance for ultimate tensile strength (UTS)

Source	DF	Seq SS	Adj MS	F	P
Regressio n	9	3022.83	335.87	2.84	0.060
Linear	3	659.78	121.32	1.03	0.422
I	1	494.07	29.52	0.25	0.628
F	1	53.68	1.07	0.01	0.926
T	1	112.02	351.57	2.97	0.116
Square	3	796.21	265.40	2.24	0.146
I*I	1	669.67	317.34	2.68	0.133
F*F	1	62.18	106.47	0.90	0.365
T*T	1	64.36	64.36	0.54	0.478
Interactio	3	1566.84	522.28	4.41	0.032
I*F	1	2.13	2.13	0.02	0.896
I*T	1	1148.40	1148.40	9.70	**0.011**
F*T	1	416.31	416.31	3.52	0.090
Residual Error	10	1183.51	1183.51		
Lack-of-	5	794.08	158.82	2.04	0.226
Pure	5	389.42	77.88		
Total	19	4206.34			

CONTOUR PLOTS

The contour plots are drawn from the developed mathematical models of the output responses separately by using RSM application. The relationship between UTS and PE with the welding parameters has been illustrated graphically by these plots. The contour plots are 2-dimensional graphs that show contours of constant response, with two varying input parameters, while the other parameter is held at constant value. Contour plots are useful for identifying the combined effects of any two parameters on the response. Each line in the plots is a constant - response line. The contour lines, with little or no curvature indicate lesser or no interaction effect; whereas bent or circular contours suggest interaction effect to be significant on the response. The contour plots for UTS are shown in Figs. 3-5 and for PE are given in Figs. 6-8.

From contour plots of UTS and PE, it is found that all the welding variables are significantly influencing the output responses significantly. Investigation is continued to determine the single optimum parametric condition to optimize both the responses: UTS and PE, simultaneously by using desirability function approach.

Table 4. Analysis of Variance for percentage elongation (PE)

Source	DF	SeqSS	AdjMS	F	P
Regression	9	397.06	44.118	4.03	0.020
Linear	3	57.381	63.408	5.79	0.015
I	1	21.025	1.478	0.13	0.721
F	1	11.707	134.856	12.31	0.006
T	1	24.649	12.369	1.13	0.313
Square	3	31.903	10.634	0.97	0.444
I*I	1	16.744	25.704	2.35	0.157
F*F	1	15.051	13.832	1.26	0.287
T*T	1	0.107	0.107	0.01	0.923
Interaction	3	307.778	102.593	9.37	0.003
I*F	1	58.428	58.428	5.34	0.044
I*T	1	31.363	31.363	2.86	0.121
F*T	1	217.987	217.987	19.91	0.001
Residual Error	10	109.508	10.951		
Lack-of-Fit	5	58.883	11.777	1.16	0.436
Pure Error	5	50.625	10.125		
Total	19	506.570			

MULTI-OBJECTIVE OPTIMIZATION BY DESIRABILITY FUNCTION APPROACH

Response optimizer tool from the RSM is applied on experimental data as shown in Table 2 to optimize the both the responses combinedly. Response optimizer uses desirability function approach to find out the desired solution. Desirability approach describes how desired a given solution is. The general approach is to first convert the response into an individual desirability function d_i that may vary over the range $0 \le d_i \le 1$. If response y_i meets the target value then $d_i = 1$ and if response falls beyond the acceptable limit then $d_i = 0$. In case of several responses, an overall desirability function (D on the response optimizer graph) is used. Optimization plot is drawn based on the desirability function approach and shown in Fig.9. This optimization plot is directly obtained by RSM application. The predicted optimal parametric setting is: current (I): 127.8788 A, gas flow rate (F) = 13.6364 l/min and travel speed (T) = 5.50 mm/s and optimized output responses are: UTS = 583.4746 MPa and PE = 58.0808 %.

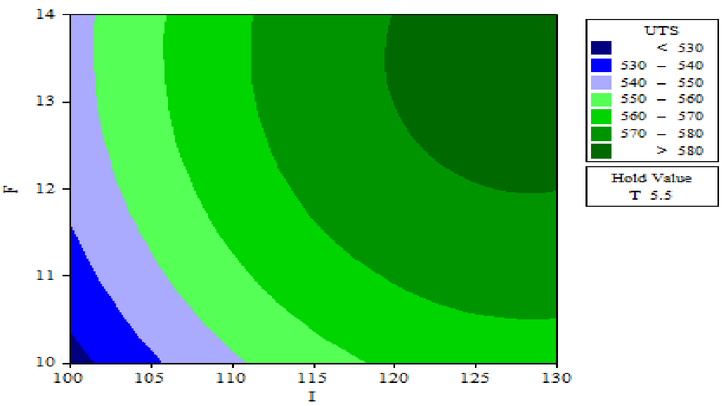

Fig. 3: Contour plot showing combined effect of current (I) and gas flow rate (F) on UTS at travel speed = 5.5 mm/s

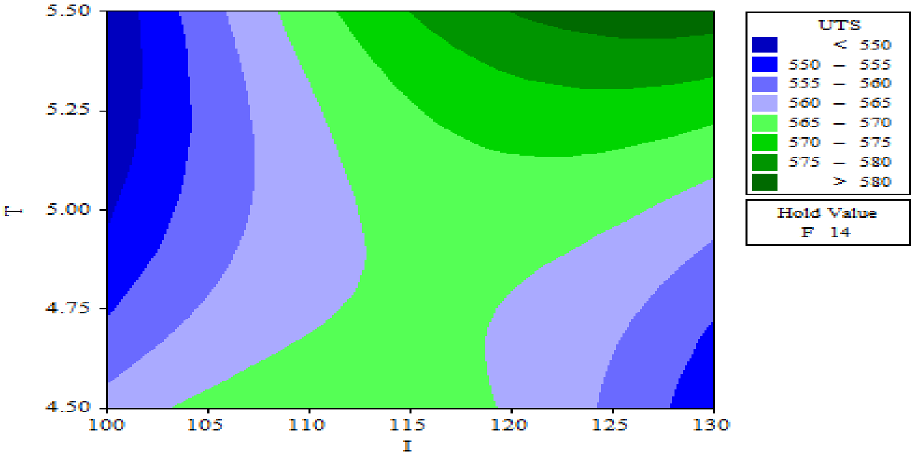

Fig. 4:Contour plot showing combined effect of current (I) and travel speed (T) on UTS at gas flow rate (F) = 14 l/min

CONFIRMATORY TEST

A confirmation experiment is needed to determine the optimum conditions and to compare the results with the expected conditions [11]. Two confirmatory tests have been conducted at the optimized parametric combination. Results of tensile test of the sample show that measured UTS of the sample is 582.46 MPa and measured percentage elongation of the sample is 57.88 %; both are very close to the optimized UTS and percentage elongation as determined by desirability function approach.

CONCLUSIONS

The following main conclusions are drawn from the results of the present study:

- Mathematical models have been developed to correlate input parameters with i) UTS and ii) PE. Adequacy of the models has been tested using ANOVA.
- In so far as the response UTS is considered only, interaction between the current and travel speed is found to be significant, and other parameters are insignificant at 95 % confidence level.
- In case of the response PE is considered, individual effects of gas flow rate and interaction effects of current and gas flow arte, and gas flow rate and travel speed have significant effect. All other factors are insignificant.
- Based on the mathematical models contour surface plots have been generated. These plots may be useful for prediction of the response (UTS/PE) at some given combination of any two parameters while the third parameter is held constant at one of its levels. Interaction effects are also predictable from contour plots, developed in the present study.
- In order to maximize UTS and PE simultaneously in GMA welding of austenitic stainless steel, the optimal parametric combination is obtained by desirability function approach, which is current (I): 127.8788 A, gas flow rate (F) = 13.6364 l/min and travel speed (T) = 5.50 mm/s.
- The confirmatory test result indicates the validity of the optimized parametric condition for maximization of both the welding responses UTS and PE combinedly.
- RSM combined with desirability function approach is useful for analysis, modeling and optimization of GMA welding of austenitic stainless steels

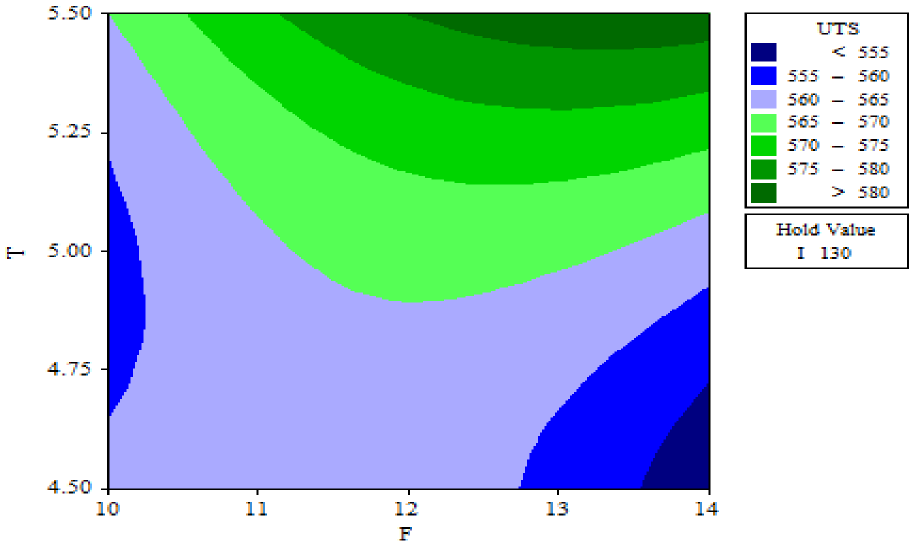

Fig. 5: Contour plot showing combined effect of gas flow rate (F) and travel speed (T) on UTS at current (I) = 130

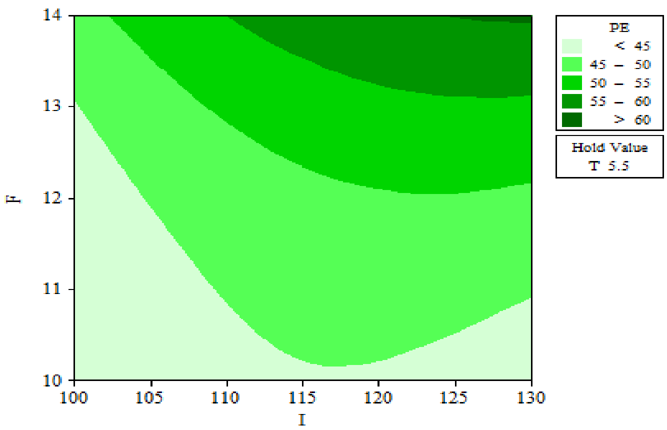

Fig. 6:Contour plot showing combined effect of current (I) and gas flow rate (F) on PE at travel speed (T) = 5.5 mm/s

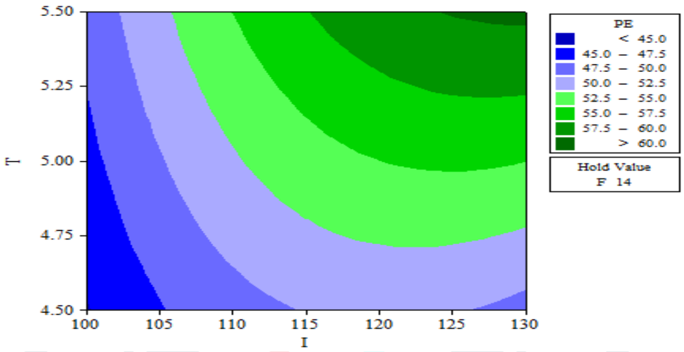

Fig. 7:Contour plot showing combined effect of current (I) and travel speed (T) on PE at gas flow rate (F) = 14 l/min

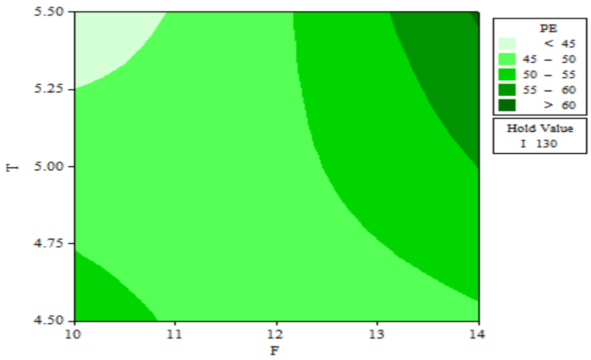

Fig. 8:Contour plot showing combined effect of gas flow rate (F) and travel speed (T) on PE at current (I) = 130 A

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