Journal of Achievements in Materials and Manufacturing Engineering

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

Development of empirical models for prediction of weld bead geometry in robotic - GMAW

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Received 26.10.2014; published in revised form 01.12.2014

ABSTRACT

Purpose: The objective of this paper is to determine the input-output relationship of robotic gas metal arc welding process using linear as well as second order linear regression analysis.

Design/methodology/approach: Taguchi's L_{27}, 3 level 4 parameter orthogonal array design of experiments and multiple regression techniques has been utilized for the development of empirical model. Arc current, stick-out, arc voltage and travel speed is taken as input parameters and bead geometry has been taken as output responses. The effects and interaction terms on different responses of these selected welding parameters have been analyzed using ANOVA.

Findings: Both techniques results were compared and concluding remarks have been made. The developed empirical model has been found good agreement with the experiment results and predicted error for second order polynomial regression equations lies between 0.58% to 14.86% for bead height, 0.93% to 9.44% for bead width and 0.34% to 2.56% for bead penetration using with actual experimental results.

Research limitations/implications: It was noticed that interaction effects have considerable influence on the formation of weld bead geometry, so it cannot be ignored.

Originality/value: In this present work, an effort has been made to carry out both first as well as second order linear regression analyses on robotic GMAW by L_{27}, Taguchi's design of experiments.

Keywords: Robotic GMAW; Bead geometry; L_{27} orthogonal array design of experiment; Multiple linear regression analysis; Second order regression analysis

Reference to this paper should be given in the following way:

P. Thamilarasi, S. Ragunathan, E. Mohankumar, Development of empirical models for prediction of weld bead geometry in robotic - GMAW, Journal of Achievements in Materials and Manufacturing Engineering 67/2 (2014) 72-85.

ANALYSIS AND MODELLING

1. Introduction

In automobile manufacturing sector, more than 85% of products require welding operations in their production line. But automation of welding is a complex process, difficult to monitor, parameterize, and control effectively [15]. Also it jeopardizes the reliability of welded components. The weldment quality purely depends the selection of input variables. But using traditional technique requires a lot of time to complete the task, and also it will not guarantee the output quality. In other words, still the ideal welding parameters combination requirement arises, which can be found only if scientific selection methodology is utilized [18]. Many Researchers have been contributing for the development of new welding processes and gain greater understanding of weld quality and mechanical properties [19].

To predict the weld-bead geometry and shape relations of FCAW process, the fractional factorial technique has been used by Raveendra and Parmar [16]. These models can also be used in a production system for automatic control of welding conditions. For the SAW of micro alloyed steel, Gupta and Parmar [3] has been also used the 2^{5-1} fractional factorial technique for the development of mathematical models. Using factorial techniques, 316L stainless steel onto structural steel IS 2062 in single wire surfacing using the SAW process was studied and a mathematical model has been developed by Murugan et al [13]. Murugan and Parmar [14] used a four-factors 5-levels factorial technique to predict the weld-bead geometry in the deposition of 316L stainless steel onto structural steel IS2062 using the MIG welding process. Yang et al. [20] have used linear-regression equations for computing the weld features from SAW process variables using both positive and negative electrode polarity. The effect of process parameters on the bead shape in a narrow gap-GTAW process with magnetic arc oscillation using statistical experimental design was studied and modeled using linear-regression were proposed by Starling et al. [17]. To predict the interrelationship between robotic CO_2 arc welding parameters and bead penetration, linear and also non linear equations were employed by Kim et al. [7]. They found that all the investigated parameters affect the bead penetration. Kim et al [8] also extended sensitivity analysis for their experiments to predict the effects measurement errors and its uncertainty in their selected parameters. Also they suggested to extend the empirical formulae to plates of varying thickness and many other parameters which were not included in their research. Kim et al. [9], have been used factorial design and non-linear regression analysis, to correlate the interrelationship of robotic GMAW process parameters. Their results showed that all process parameters influenced the responses and the models developed are able to predict the responses with 0-25% accuracy. He concluded that these mathematical models have best fit and it has been used for reverse prediction as well.

Murugan and Parmar [13] developed mathematical models using response surface methodology (RSM) to study the direct and interaction effects of SAW parameters Gunaraj and Murugan [4] have highlighted the use of RSM to develop mathematical models and plot contour graphs relating input parameters to some responses of the weld bead in SAW of pipes . In 1999, Gunaraj and Murugan [5] applied RSM, to determine the effect of heat input and the area of HAZ for low-carbon steel with two joint types, bead on- plate as well as bead-on-joint for SAW process parameters. Koleva [10] has developed models to investigate the influence of electron beam welding (EBW) parameters. The author has suggested the use of the developed models for online control of the process. Gunaraj and Murugan have divided their study into two parts, in the first part [6] they developed a model to relate the weld-bead volume to SAW parameters previous work [5]. In the second part [6] the total volume of the weld bead was optimized (minimized) by keeping the other bead parameters as constrains to obtain sound welded pipes. Also, sensitivity analysis was carried out to predict the effect of the other bead parameters on the total volume.

Gunaraj and Murugan [5] continued their previous study and successfully investigated the effect of SAW parameters on HAZ characteristics. The effect of the laser welding parameters on the bead geometry of 2.5 mm thick AISI304 stainless steel has been investigated by Manonmani et al. [12]. In this study the relationship between the process parameters and the weld bead parameters has been developed using RSM. In 2005, Gunaraj and Murugan [6] extended their study and managed to establish mathematical expressions to predict the penetration size ratio ‘PSR’ (the ratio of bead width to the height of penetration) and the reinforcement form factor ‘RFF’ (the ratio of bead width to the height of reinforcement). Koleva [10] has carried out another work by applying RSM to establish the relationship between performance characteristics and its influencing factors for EBW of austenitic stainless steel. Benyounis et al. [1] have applied RSM to investigate the effect of laser welding parameters based on responses in CO_2 laser butt-welding. Again Benyounis et al. [2] have used the previous models [1] to optimize the process for 5 mm thick, medium carbon steel plates. Koleva and Vuchkov [11] have established the relationship between EBW parameters and weld-depth and weld-width using RSM in order to improve the quality of the process in mass production.

The estimation of interrelationship between input-output welding process parameters has been taken care by many researchers, and they have been realized the difficulties associated with it. They have been tried to get solution for those responses through statistical analysis viz., mathematical model. These models include multiple regression (both linear and non-linear regression), taguchi techniques, response surface methodology, evolutionary algorithms and others.

Thus, in this present work, an effort has been made to carry out both first as well as second order linear regression analyses on robotic GMAW by L_{27}, Taguchi's design of experiments. The results of the both techniques has been compared and some notified observations are made. The rest of the text is organized as follows: in section 2, identification of input-output variables of GMAW welding process and the selection of feasible range has been made. Section 3 explains the experimental setup, and the collection of experimental data as per Taguchi design of experiments using L_{27} orthogonal array. The brief introduction about the present work and the application of both the simple linear regression as well as second order linear regression analyses has been described in section 4, followed by the stated results and its discussion in section 5. Some concluding remarks and the scope for future work is indicated in section 6.

2. Statement of the problem

The present work deals with modeling of a robotic GMAW welding process. Figure 1 shows a relationship between the inputs and responses of the GMAW process. The objective of the present research work is to find the inter-relationship between the input parameters and output responses for 'bead-on-joint'-type GMAW process carried by robot using the statistical techniques carried out on the data collected as per Taguchi design of experiments (DOE) using L_{27} orthogonal array. Arc current, arc voltage, travel speed and stick out are chosen as process input parameters. Table 1 shows the selected four input process parameter and its levels. In this entire process, the composition of consumable electrode, shielding gas (100% CO_2) and other variables are considered as constant.

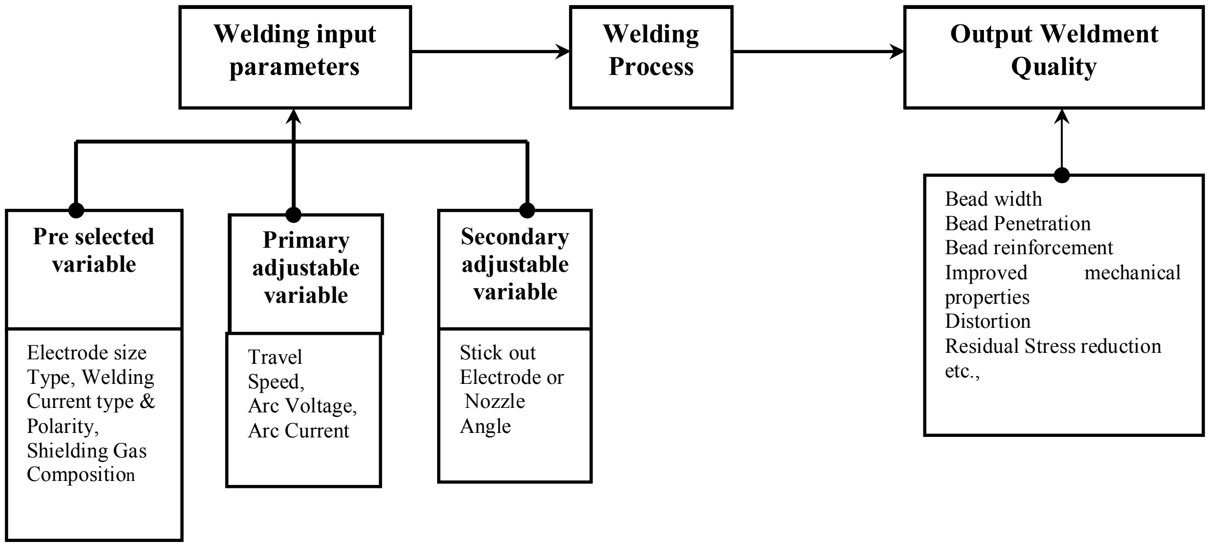

Fig. 1. Welding process

Table 1.
Input factor and their levels of the robotic GMAW process

Sl. No	Parameters	Units	Notation	Levels		
				1	2	3
1	Arc Voltage	Volt	V	16.9	18	20.2
2	Travel Speed	mm/min	S	0.175	0.225	0.3
3	Arc current	Ampere	A	160	190	220
4	Stick out	mm	H	3	5	7

3. Experimental details

This section describes the experimental procedure and bead geometry measurement techniques adopted to carryout the work.

3.1. Experimental setup

Experiments are conducted on the HR5 HW welding robot facility manufactured by KUKA robot as shown in Figure 2.

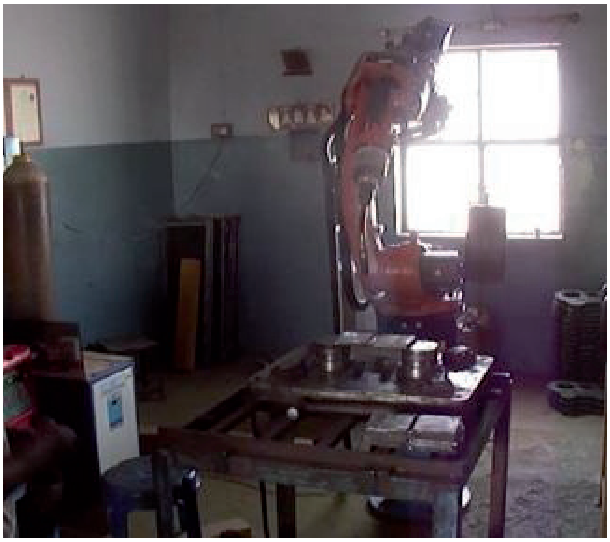

Fig. 2. Experimental setup

Base material

Structural mild steel plates with dimensions of 150× 100 × 10 mm has been chosen as base material and its chemical composition is given in Table 2.

Table 2.
Chemical composition of base metal

Element	C	Mn	Si	S	P	Al
%Max	0.15	0.77	0.188	0.022	0.029	0.027

Electrode wire:

Copper coated mild steel wire (MIG welding wire) with diameter of 0.8 mm manufactured as per ER70S – 6, IS: 6419 – 1971- S4 and DIN: SG2 DIN 8559 by Rasi electrodes Ltd is employed as the welding consumables. The chemical composition of filler wire is as follows in Table 3.

Shielding Gas:

A single pass bead on joint welding technique is performed with 100% CO_2 as shielding gas for complete process. In this work, direct current electrode polarity (DCEP) is used to do entire welding process.

3.2. Measurement of weld bead geometry

Three samples are prepared by eliminating the end effects occurred in the leading and trailing edge of the creator in the sample. 15 mm intervals, with the first and following samples are maintained as shown in Figure 3a and Figure 3b.

Table 3.
Chemical composition of electrode

Element	C	Mn	Si	S	P	Cu
%Max	0.06-0.15	1.4-1.85	0.8-1.15	0.035	0.025	0.5

a)

b)

Fig. 3. a) Sample workpiece before cutting; b) sample workpiece before polished

The transverse faces of the samples are surface ground using a emery cloth j297NB coarse grade 105 × 915 mm universal carborandam belt with the help of a belt grinder polished using standard grades such as grade 1/0 (320 mesh size), grade 2/0 (400 mesh size), grade 3/0 (600 mesh size), grade 4/0 (800 mesh size) and grade 5/0 (1000 mesh size) universal carborandam sand paper.

Then aluminum oxide of size 0.75 microns and velvet cloth in a polishing machine is used to polish the specimen. After that to expose the geometry of the weld bead and heat affected zone (HAZ), the polished specimens are cleaned with alcohol and these prepared specimen are micro-etched by using 2% Nital (the composition of 98% HNO_3 and 2% CH_3OH) solution. Each macro etched sample image is scanned by using a digital camera (as shown in Figure 4) and then it is imported into CAD packages. Using CAD packages, the required critical parameters such as bead height (BH), bead width (BW), bead penetration (BP) have been measured.

3.3. L_{27} orthogonal array design of experiments

There are four input parameters and each of them has been set at 3 levels. Thus, a total of twenty seven combinations of the input parameters are to be considered, according to the Taguchi's L_{27} orthogonal array design of experiments (DOE). The experimental data collected as per above DOE is shown in Table 4.

4. Process modeling using regression analysis

4.1. Regression model

Many researchers were a doted several methods that can be used to model a process such as mathematical model, regression model, and neural network model and so on. In this paper, the regression analysis was adopted for process modeling in order to predict the bead geometry of welded component using robotic GMA welding.

There are different types of regression models depending on the order and nonlinearity of the variables. In this work, three models were proposed to estimate the bead geometry. The first model (Model-1) was defined using the multiple linear regression model, is shown in equation (1). The second Model (Model-2) and the second order polynomial regression model, is shown in equation (2).

$$\hat{Y} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 \quad (1)$$

$$\hat{Y} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_1 X_2 + \beta_6 X_1 X_3 + \beta_7 X_1 X_4 + \beta_8 X_2 X_3 + \beta_9 X_2 X_4 + \beta_{10} X_3 X_4 + \beta_{11} X_1^2 + \beta_{12} X_2^2 + \beta_{13} X_3^2 + \beta_{14} X_4^2 \quad (2)$$

In equations (1) and (2), X_1, X_2, X_3 and X_4 are input variables that represent arc current, stick out, arc voltage and travel speed respectively. The output response y is the value of the estimated bead geometry viz., bead width, bead penetration and bead reinforcement. β_0 is the y-axis intercept, and $\beta_1 \sim \beta_{14}$ correspond to the coefficient of each input variable. Each coefficient value is obtained using the least mean squared method.

Model-1: Multiple linear regression model

The coefficient values of Model-1 (the multiple linear regression models) are shown in Table 5. The coefficient values can be used to determine the influence of the input variables with respect to the output variable which is estimated by the regression model.

Using the coefficients in equation (1) and Table 5, the arc current and stick out appears to have a positive effect on the bead geometry, while the arc voltage and travel speed has negative effects on the bead geometry. But in the calculation of bead penetration, except arc current, other variables have negative correlation with bead penetration. This situation is consistent with the experimental results.

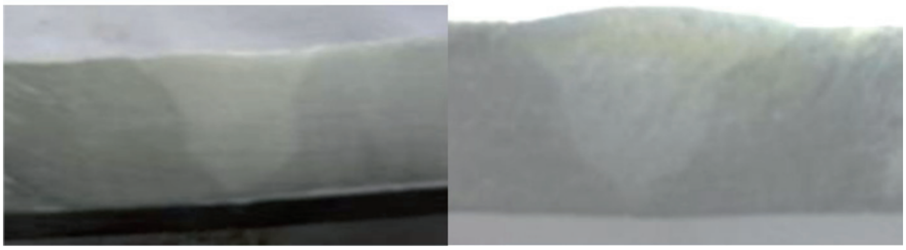

Fig. 4. Sample workpiece after etched

Table 4.
Experimental data collected as per Taguchi L_{27} OA design of experiments

Arc Current	Stick out	Arc Voltage	Travel Speed	Mean value of Bead Width BW	Penetration BP	Reinforcement / Height BH
160	3	16.9	0.225	13.905	12.0175	0
160	3	16.9	0.175	16.46	12.1242	0.7138
160	3	16.9	0.3	11.8075	10.6825	0
190	3	20.2	0.225	17.3875	11.2975	0.9975
190	3	20.2	0.3	12.945	11.0875	0
190	3	20.2	0.175	20.8525	11.9825	1.3175
220	3	18	0.3	14.635	11.389	0
220	3	18	0.225	18.4725	12.084	0
220	3	18	0.175	22.1025	11.9805	1.720375
220	5	20.2	0.175	22.6575	12.0225	1.9125
220	5	20.2	0.225	19.0075	10.9495	1.48375
220	5	20.2	0.3	15.65	10.3825	0.9425
220	7	16.9	0.225	19.67	10.6225	1.6675
220	7	16.9	0.3	17.0425	9.9815	1.1225
220	7	16.9	0.175	21.855	11.425	1.9925
160	5	18	0.225	15.925	11.27	0
160	5	18	0.3	12.0225	10.1425	0
160	5	18	0.175	17.4275	11.525	0.9725
160	7	20.2	0.175	17.96	11.1	1.125
160	7	20.2	0.225	14.9325	10.255	0
160	7	20.2	0.3	12.0525	9.995	0
190	7	18	0.3	15.04	10.267	0.784
190	7	18	0.225	18.3425	10.8525	1.105
190	7	18	0.175	21.0175	10.85	1.83
190	5	16.9	0.175	20.1575	11.3125	1.57
190	5	16.9	0.3	13.9275	10.90475	0
190	5	16.9	0.225	18.01	11.1095	1.0625

Table 5.
Estimated effects and co-efficients for bead geometry using multiple regression

For BW	***Coefficients***	***Standard Error***	***t Stat***	***P-value***
Intercept	13.49543135	2.178873084	6.19376661	3.10851E-06
Arc Current	0.071481481	0.005409502	13.2140594	6.11314E-12
Stick out	0.259583333	0.081142531	3.19910325	0.004140817
Arc Voltage	0.006493506	0.096582283	0.0672329	0.947003587
Travel Speed	-48.90087719	2.579421779	-18.9580772	4.06395E-15
For BH	***Coefficients***	***Standard Error***	***t Stat***	***P-value***
Intercept	-0.608576789	1.172966176	-0.518835753	0.6090553
Arc Current	0.014870972	0.002912131	5.10656093	4.07173E-05
Stick out	0.13548125	0.043681959	3.101537894	0.005206364
Arc Voltage	-0.00024044	0.051993736	-0.004624405	0.996351949
Travel Speed	-8.842511696	1.388596023	-6.367951187	2.08278E-06
For BP	***Coefficients***	***Standard Error***	***t Stat***	***P-value***
Intercept	14.50536908	0.834939846	17.37295106	2.47218E-14
Arc Current	0.003195	0.00207291	1.541311148	0.137503056
Stick out	-0.258241667	0.031093657	-8.305284499	3.15257E-08
Arc Voltage	-0.041272006	0.037010139	-1.115154023	0.276818286
Travel Speed	-8.427532164	0.988429312	-8.526186002	2.01785E-08

Model-2: Multiple linear regression model

In this model, regression analysis is carried out and predictions are attempted with the help of the resulting equations. The coefficient values of Model-2 (second order polynomial regression models) are shown in Table 6. The coefficient values can be used to determine the influence of the input variables with respect to the output variable which is estimated by the regression model.

5. Results and discussion

To find out the input-output relationship in the robotic GMAW process, the three approaches above have been tried the results of which are stated and explained below.

5.1. Results of Model-1

BW = 13.4954 + 0.07148 Arc current + 0.25958 Stick out +0.00649 Arc voltage – 48.9008 Travel speed (3)

BH = – 0.608578 + 0.01487 Arc current + 0.13548 Stick out – 0.00024044 Arc voltage – 8.84251169 Travel speed (4)

BP = 14.06574 + 0.003195 Arc current – 0.25824 Stick out – 0.041272006 Arc voltage – 8. 4275321 Travel speed (5)

For the predicted output – bead width (BW) the arc current stick out and arc voltage appears to have a positive effect on the bead geometry, while the travel speed has negative effects on the bead geometry. For the predicted output – bead height (BH) the arc current and stick out appears to have a positive effect on the bead geometry, while the arc voltage and travel speed has negative effects on the bead geometry. For the predicted output – bead penetration (BP) the arc current appears to have a positive effect on the bead geometry, while the stickout , arc voltage and travel speed has negative effects on the bead geometry. From the above three equations, the arc current has positive correlation with all bead geometry responses. This situation is consistent with the experimental results.

5.2. Results of Model-2

BW = -27.7176 + 0.0757256 arc current + 18.5587 stick out - 0.231962 arc voltage + 91.8508 travel speed - 0.000349846 arc current*arc current - 0.0407682 arc current*stick out + 0.0183061 arc current*arc voltage + 0.0722578 arc current*travel speed + 0.0160764 stick out*stick out - 0.600097 stick out*arc voltage - 62.2335 stick out*travel speed - 1.85698 arc voltage*travel speed + 9.7185 travel speed*travel speed + 0.151546 arc current*stick out*travel speed - 0.0478088 arc current*arc voltage*travel speed + 1.91086 stick out*arc voltage*travel speed (6)

BP = 46.826 - 0.105128 arc current - 7.84697 stick out - 0.79964 arc voltage - 117.706 travel speed + 2.75432e-005 arc current*arc current + 0.0190117 arc current*stick out + 0.000502064 arc current*arc voltage + 0.31439 arc current*travel speed + 0.0250347 stick out*stick out + 0.203923 stick out*arc voltage + 32.4291 stick out*travel speed + 1.61911 arc voltage*travel speed + 2.02133 travel speed*travel speed - 0.0880248 arc current*stick out*travel speed + 0.00539736 arc current*arc voltage*travel speed - 0.855016 stick out*arc voltage*travel speed (7)

BH = -18.982 + 0.134009 arc current + 4.03845 stick out + 0.310802 arc voltage + 54.1999 travel speed - 0.000226154 arc current*arc current - 0.0092899 arc current*stick out + 0.000876991 arc current*arc voltage - 0.379244 arc current*travel speed - 0.00615451 stick out*stick out - 0.118215 stick out*arc voltage - 19.9655 stick out*travel speed - 2.49232 arc voltage*travel speed + 80.4698 travel speed*travel speed + 0.0588644 arc current*stick out*travel speed + 0.00395214 arc current*arc voltage*travel speed + 0.504862 stick out*arc voltage* travel speed (8)

The coefficients of Model-2 (the second order polynomial regression model) are shown in Table 6. Values in Table 6 show that travel speed has a positive effect on the bead geometry, while the stick out and arc current have negative effects. The coefficient values of the second order polynomial regression model are very complicated due to its nonlinear terms.

Table 6.
Estimated effects and coefficients for bead geometry using second order polynomial regression

For BW	***Coefficients***	***Standard Error***	***t Stat***	***P-value***
Intercept	-27.7176	48.090	-0.57637	0.577
Arc Current	0.0757	0.287	0.26415	0.797
Stick out	18.5587	6.413	2.89383	0.016
Arc Voltage	-0.2320	2.831	-0.08192	0.936
Travel Speed	91.8508	192.888	0.47619	0.644
Arc Current * Stick out	-0.0408	0.015	-2.78156	0.019
Arc Current * Arc Voltage	0.0183	0.016	1.16187	0.272
Arc Current * Travel Speed	0.0723	1.051	0.06874	0.947
Stick out * Arc Voltage	-0.6001	0.236	-2.53918	0.029
Stick out * Travel Speed	-62.2335	26.337	-2.36299	0.040
Arc Voltage * Travel Speed	-1.8570	11.635	-0.15960	0.876
Arc Current * Stick out * Travel Speed	0.1515	0.060	2.51441	0.031
Arc Current * Arc Voltage * Travel Speed	-0.0478	0.064	-0.74603	0.473
Stick out * Arc Voltage * Travel Speed	1.9109	0.961	1.98785	0.075
Arc Current * Arc Current	-0.0003	0.000	-1.36595	0.202
Stick out * Stick out	0.0161	0.058	0.27897	0.786
Travel Speed * Travel Speed	79.7185	43.528	1.83145	0.097
For BP	***Coefficients***	***Standard Error***	***t Stat***	***P-value***
Intercept	46.826	37.373	1.25294	0.239
Arc Current	-0.105	0.223	-0.47187	0.647
Stick out	-7.847	4.984	-1.57444	0.146
Arc Voltage	-0.800	2.200	-0.36339	0.724
Travel Speed	-117.706	149.901	-0.78522	0.451
Arc Current * Stick out	0.019	0.011	1.66912	0.126
Arc Current * Arc Voltage	0.001	0.012	0.04100	0.968
Arc Current *X4	0.314	0.817	0.38485	0.708
Stick out * Arc Voltage	0.204	0.184	1.11029	0.293
Stick out * Travel Speed	32.429	20.467	1.58443	0.144
Arc Voltage * Travel Speed	1.619	9.042	0.17906	0.861
Arc Current * Stick out * Travel Speed	-0.088	0.047	-1.87930	0.090
Arc Current * Arc Voltage * Travel Speed	0.005	0.050	0.10837	0.916
Stick out * Arc Voltage * Travel Speed	-0.855	0.747	-1.14454	0.279
Arc Current * Arc Current	0.000	0.000	0.13838	0.893
Stick out * Stick out	0.025	0.045	0.55901	0.588
Travel Speed * Travel Speed	2.021	33.827	0.05975	0.954
For BH	***Coefficients***	***Standard Error***	***t Stat***	***P-value***
Intercept	-18.9820	38.272	-0.49597	0.631
Arc Current	0.1340	0.228	0.58737	0.570
Stick out	4.0384	5.104	0.79124	0.447
Arc Voltage	0.3108	2.253	0.13792	0.893
Travel Speed	54.1999	153.510	0.35307	0.731
Arc Current * Stick out	-0.0093	0.012	-0.79643	0.444
Arc Current * Arc Voltage	0.0009	0.013	0.06994	0.946
Arc Current * Travel Speed	-0.3792	0.837	-0.45332	0.660
Stick out * Arc Voltage	-0.1182	0.188	-0.62851	0.544
Stick out * Travel Speed	-19.9655	20.960	-0.95255	0.363
Arc Voltage * Travel Speed	-2.4923	9.260	-0.26915	0.793
Arc Current * Stick out * Travel Speed	0.0589	0.048	1.22719	0.248
Arc Current * Arc Voltage * Travel Speed	0.0040	0.051	0.07749	0.940
Stick out * Arc Voltage * Travel Speed	0.5049	0.765	0.65993	0.524
Arc Current * Arc Current	-0.0002	0.000	-1.10951	0.293
Stick out * Stick out	-0.0062	0.046	-0.13420	0.896
Travel Speed * Travel Speed	80.4698	34.641	2.32293	0.043

5.3. Estimated results of the regression models

The actual bead geometry data measured from experiments were compared with estimated bead geometry using the three regression models as developed in the previous section (equations 3, 4 and 5) for first order multiple linear regression equations. Similarly, for second order linear multiple regression equations (equations 6, 7 and 8) were also compared with the experimental values. The values used in formulating the regression models were defined as the regression data, are compared with the average value of experimental results and are shown in Fig. 5, Fig. 6 and Fig. 7. These regression data were compared to the estimated values obtained from each model. In addition, in order to verify the estimation performance of each model, evaluation data ware obtained by experiment, its normal probability distribution, residual plots, histogram for standardized residual along with observation order is plotted and shown in Fig. 8, Fig. 9 and Fig. 10.

5.4. Regression statistics and ANOVA for Model-1 and Model-2

Furthermore, a statistical analysis of variance (ANOVA) is performed to see which process parameters are statistically significant. Finally, a confirmation experiment is conducted say fisher's F test or Student 't' test as per the requirements used to verify the statistically significant parameters obtained from the mathematical modeling. Usually, the change of the welding process parameter has a significant effect on the quality characteristic when the F value is large. The results of bead geometry are tabulated in Table 7. As per this technique it was found that calculated F ratios were larger than the tabulated values at 95% confidence level; hence the model is considered to be adequate.

Using statistical software Minitab, ANOVA calculations were computed. One more criterion that is commonly used to illustrate the adequacy of a fitted regression model is the coefficient of determination (R^2) and adjusted R^2. For the models developed the calculated R^2 and adjusted R^2 values are provided in Table 8. These values indicate that the regression model is quite adequate. It indicates that the considered process parameters are highly significant factors, which affects the bead geometry of robotic GMAW joints.

5.5. Testing the coefficients for significance

The analysis of variance (ANOVA) is a statistical techniques used to test the significance of the predicted equation. Degree of freedom (DF), Sum of Squares (SS), Adjusted sum of squares (Adj SS), mean square (MS), Standard Error for the estimated coefficient (SE Coef) are the terminology used to test the significance of the predicted empirical relation. The ratio of adjusted mean square value to the residual error gives F value, which is used to test the hypothesis. The ratio of corresponding value under coefficient and standard error yields the T-values.

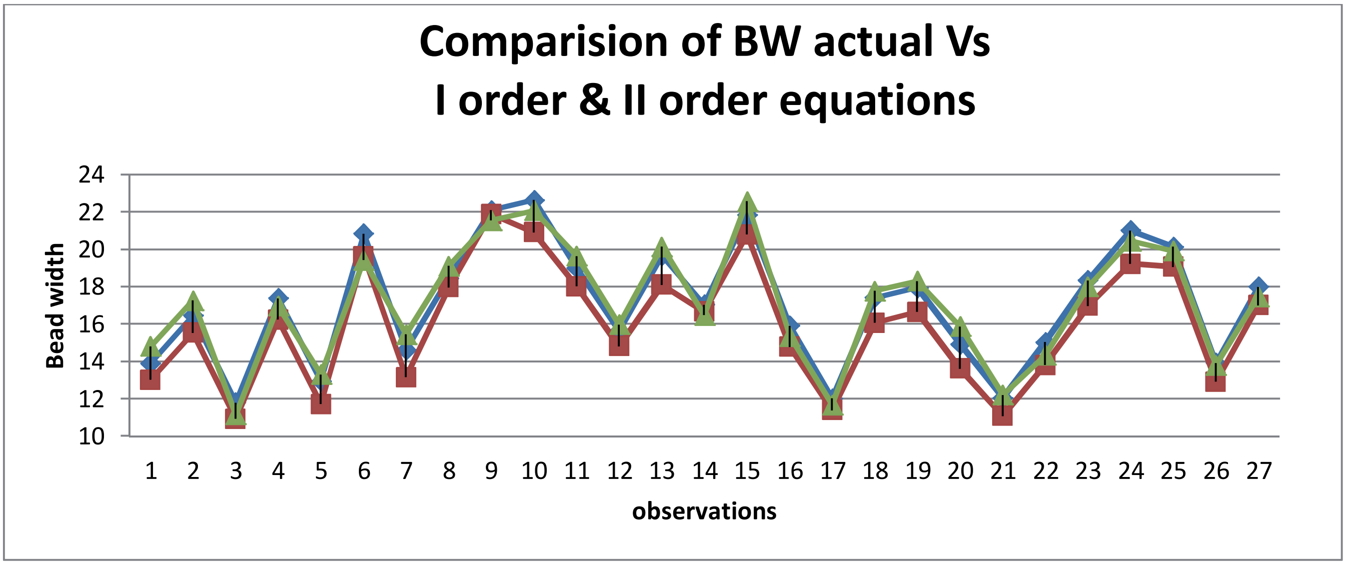

Fig. 5. Comparison chart of bead width with actual, I order and II order regression equations

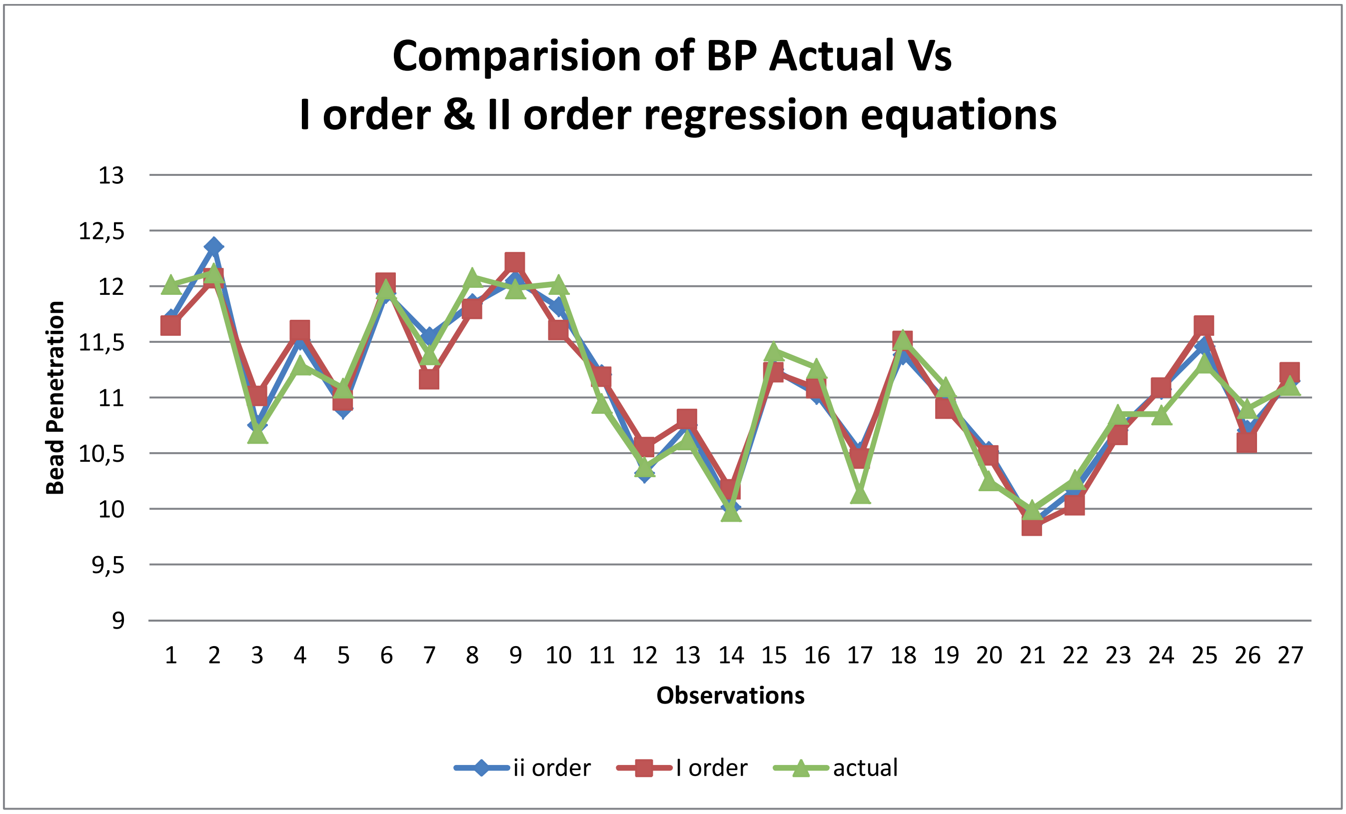

Fig. 6. Comparison chart of bead penetration with actual, I order and II order regression equations

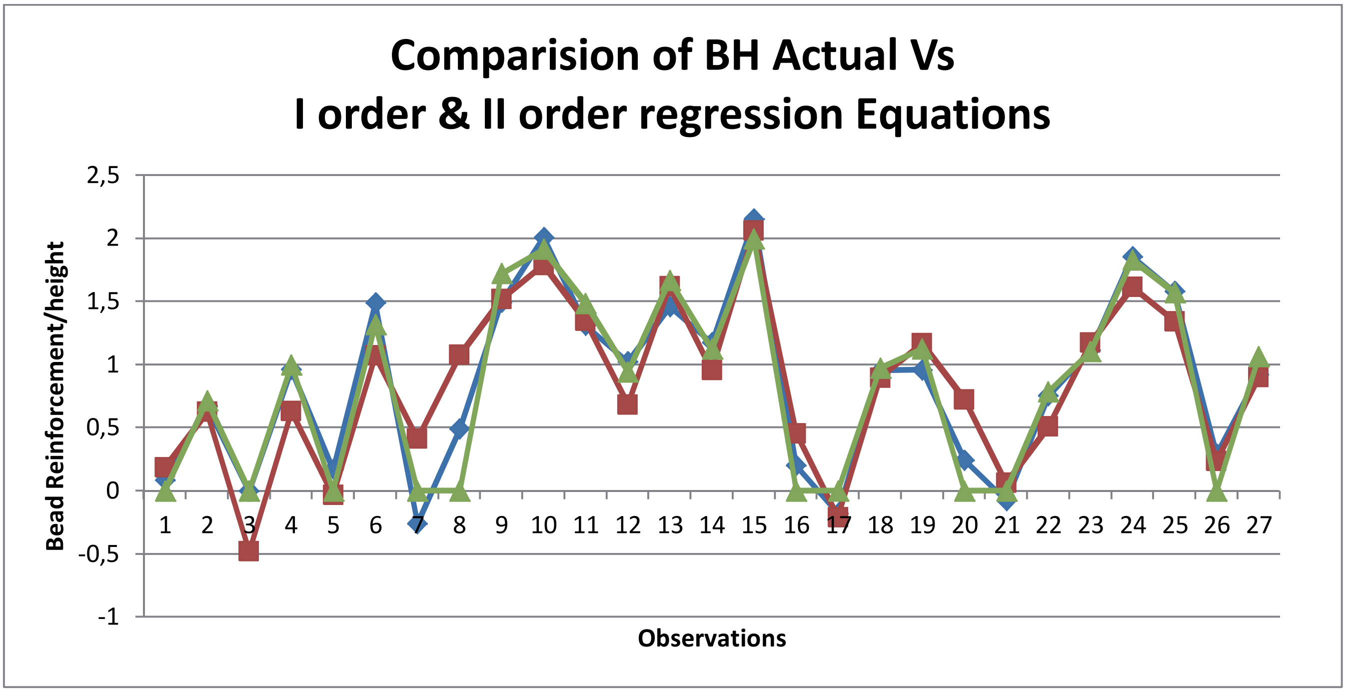

Fig. 7. Comparison chart of bead reinforcement/height with actual, I order and II order regression equations

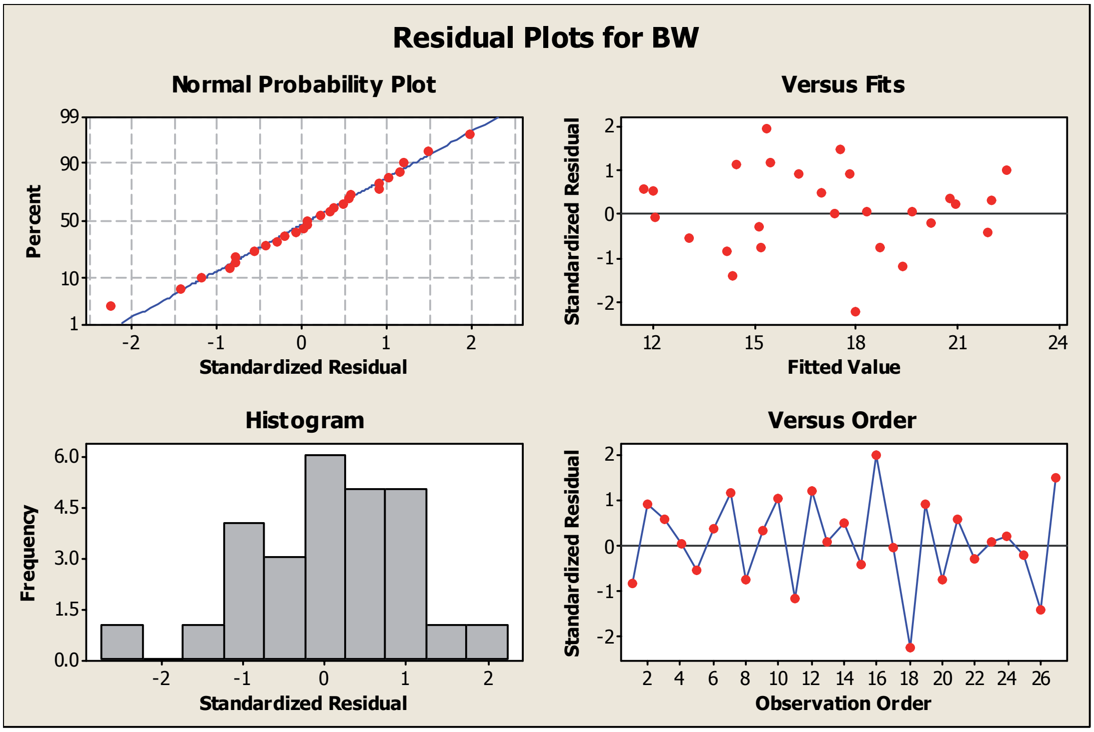

Fig. 8. Residual plots of BW for Model-2

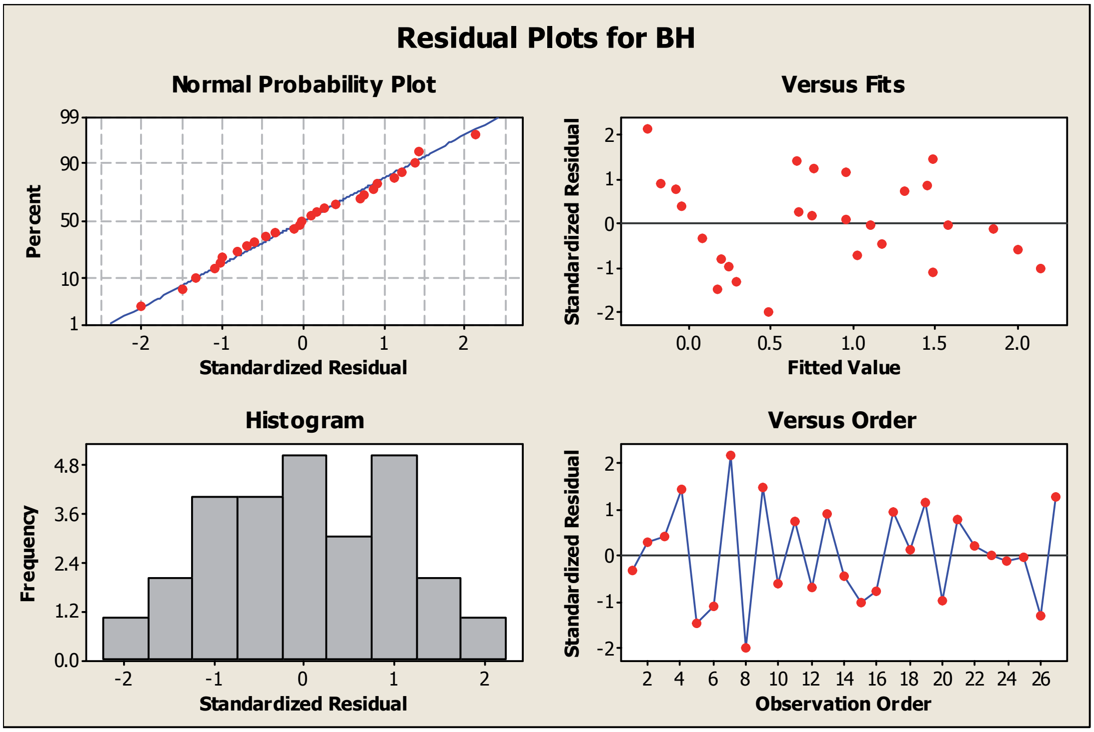

Fig. 9. Residual plots of BH for Model-2

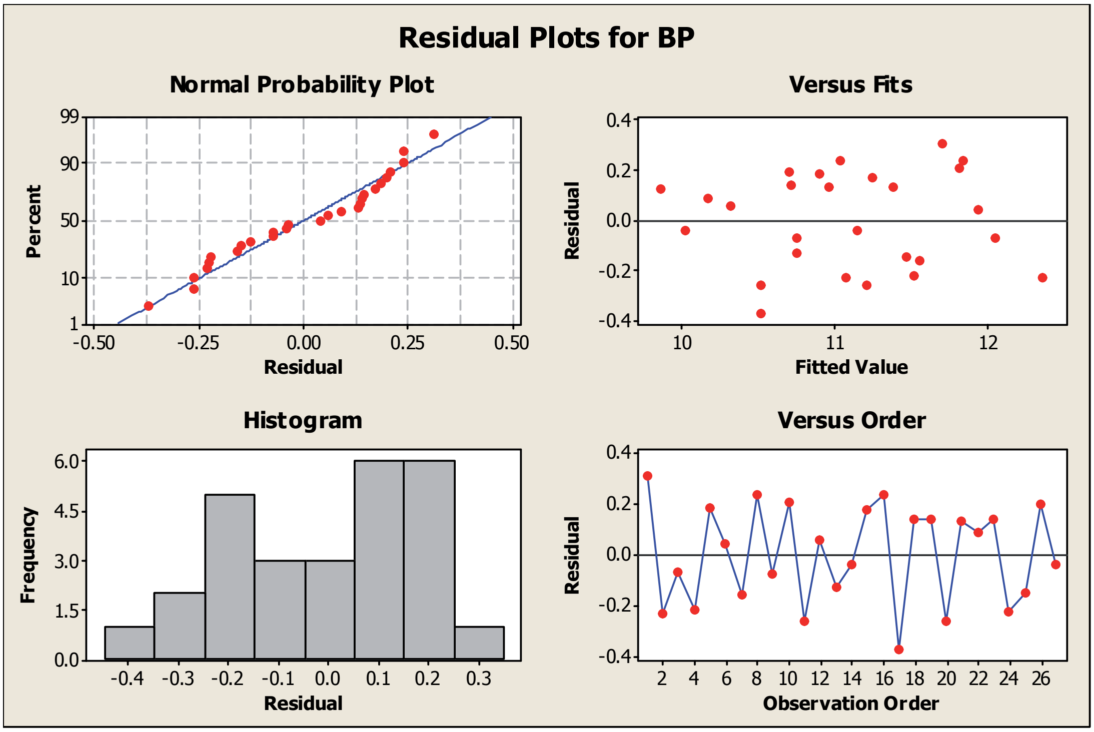

Fig. 10. Residual plots of BP for Model-2

Table 7.
Regression Statistics and ANOVA for Model-1

Regression Statistics

	Bead Width BW	Bead Height BH	Bead Penetration BP
Multiple R	0.980381818	0.882848955	0.93193028
R Square	**0.961148509**	**0.779422278**	**0.868494047**
Adjusted R Square	0.954084602	0.739317237	0.844583874
Standard Error	0.688517204	0.370026574	0.263838428
Observations	27	27	27

ANOVA

		df	*SS*	*MS*	*F*	*Significance F*
Bead Width	Regression	4	258.009136	64.502284	136.0647097	3.52303E-15
	Residual	22	10.4292307	0.47405594		
	Total	26	268.4383667			
Bead Height	Regression	4	10.47517575	2.618793937	19.06183139	6.76901E-07
	Residual	22	3.022451801	0.137384173		
	Total	26	13.49762755			
Bead Penetration	Regression	4	10.11393631	2.528484078	36.32320172	2.14681E-09
	Residual	22	1.531435751	0.069610716		
	Total	26	11.64537206			

Table 8.
Regression Statistics and ANOVA for Model-2

Regression Statistics			
	Bead Width BW	**Bead Height BH**	**Bead Penetration BP**
Multiple R	0.9941	0.9182	0.926
R Square	0.9847	0.7873	0.8075
Adjusted R Square	12.1324	11.4446	11.2925
Standard Error	0.39718	0.308672	0.316102
Observations	27	27	27

ANOVA

		df	*Seq SS*	*Adj SS*	*Adj MS*	*F*	*P*
Bead Width	Regression	16	266.861	266.861	16.6788	105.724	0.000000
	Residual	10	1.578	1.578	0.1578		
	Total	26	268.438				
Bead Height	Regression	16	12.4984	12.4984	0.781152	7.81775	0.001131
	Residual	10	0.9992	0.9992	0.099920		
	Total	26	13.4976				
Bead Penetration	Regression	16	10.6926	10.6926	0.668287	7.01406	0.001777
	Residual	10	0.9528	0.9528	0.095278		
	Total	26	11.6454				

Minimum value of ‘p’ is preferred in which the hypothesis greater values can be rejected. The F-values are determined as shown in Table 7 and Table 8. Most of the terms have significant contributions on bead geometry as their p-values are found to be less than the significance level $\alpha=0.05$.

The regression coefficients (shown in Tables 5 and 6) were the indicators for the factors that affects the output response. To avoid cumbersome mathematical labour, insignificant coefficients may be eliminated without sacrificing much of the accuracy. To attain this the t-test and F tests are used. The test of significance was done automatically by the MINITAB software. The developed model has been found good agreement with the experiment results and predicted model’s error for second order polynomial regression equations lies between 0.58% to 14.86% for bead height, 0.93% to 9.44% for bead width and 0.34% to 2.56% for bead penetration using with actual experimental results.

6. Conclusions

Experiments conducted using DOE concepts were applied to develop regression models using multiple regression techniques both linear as well as non linear were applied to predict the weld bead geometry for IS:2062 structural steel plates. The values of BP, BW and BH increase with the increase in arc current, whereas these values decrease with the increase in travel speed. However, bead penetration increases with the decrease in travel speed (S) and stickout (h) to a higher value but starts decreasing on further increasing travel speed of electrode and stickout. It was noticed that interaction effects have considerable influence on the formation of weld bead geometry, so it cannot be ignored.

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