A Comparative Study between Linear and Nonlinear Regression Analysis for Prediction of Weld Penetration Profile in AC Waveform Submerged Arc Welding of Heat Resistant Steel

Uttam Kumar Mohanty[1], Abhay Sharma[2], Mitsuyoshi Nakatani[3], Akikazu Kitagawa[4], Manabu Tanaka[5] and Tetsuo Suga[6]
[1,2]Department of Mechanical & Aerospace Engineering, IIT Hyderabad, Sangareddy, India
[3,4]Technical Research Institute, Hitachi Zosen Corporation, Osaka, Japan
[5,6]Joining & Welding Research Institute, Osaka University, Japan
[2]Corresponding author email: abhay@iith.ac.in

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ABSTRACT

Alternating current with square waveform provides better control of weld quality and reduces the effect of the arc-blow in the submerged arc welding process. This paper presents a comparative study in between conventionally used linear regression and newly proposed nonlinear regression analysis for prediction of weld penetration profile, i.e. weld width, penetration and penetration shape factor in the AC waveform welding of heat resistant steel. The comparison is based on second order linear regression and nonlinear regression analysis using Levenberg-Marquardt method. The frequency, electrode negative ratio, welding current, and welding speed are used as input parameters to obtain the models for penetration and width. The models are developed following a design of experiment and extra experiments are conducted to check the adequacy of the models. The results show that the Levenberg-Marquardt method associated with exponential function without considering constant term is more effective as compared to second order linear regression in terms of predictability and accuracy. The significant effect of process variables on the outcomes is analyzed. The investigation shows a new approach to weld penetration profile prediction that can be horizontally deployed to other welding process where predication is difficult because of the complex shape of the weld bead.

Keywords: Weld bead geometry; linear regression; process variable; nonlinear regression; model adequacy.

1.0 INTRODUCTION

Heat resistant steels are widely used in pressure vessel, gas turbine, steam generator, and offshore applications. Welding of heat resistant steel is a major concern due to its physical and thermal properties. The gas tungsten arc welding (GTAW), submerged arc welding (SAW), and gas metal arc welding (GMAW) are three common welding techniques used in joining heat resistant steel. Among these welding techniques, the SAW is most desirable, wherein the arc is submerged under the flux thereby reducing spatter and thermal losses. In GTAW and GMAW, the arc is open to the atmosphere, thereby, increasing arc disturbances and spatters. Since SAW has the upper hand, it is utilized with different power sources (i.e., direct and alternating current - DC and AC). The DC source provides more deposition and more penetration, when electrode used as negative and positive polarity, respectively. The advantage of alternating current (AC) power source with square waveform is customized bead geometry (i.e., penetration and deposition) and reduction in arc blow. The customized bead geometry can be achieved by investigating the effect of welding parameter. Monteiro and Scotti [1] studied the behavior of weld quality by considering the effect of electrode negative (EN) duration in case of AC GMAW. The major influence of current, voltage, and frequency on the geometry of bead in both single and tandem wire SAW was obtained by Pepin [2]. Chaudhry et al. [3] reported an analytical model for the penetration profile using square AC SAW.

The bead quality in SAW process is mainly influenced by different welding parameters. Therefore, it is essential to control these input variables to find a better quality of the weld. Yang et al. [4] developed a linear regression model for SAW process considering positive and negative polarity in DC power source. Sen et al. [5] reported prediction of weld bead geometry by using multiple regression analysis for double pulse GMAW. Singh et al. [6] applied second order polynomial to establish relationships among the input variables like wire feed and travel speed and outputs like penetration, width, reinforcement height, penetration size, and reinforcement form factors. Datta et al. [7] analyzed the bead geometry in SAW using a quadratic response technique. Shah and Das [8] noticed the effect of variation of activating flux on bead morphology in austenitic stainless steel. Mahapatra et al. [9] modelled and discussed the importance of electrode diameter, current, arc travel speed, electrode feed rate, arc length, and arc speed on weld bead characteristics. Roy et al. [10] identified the significance of heat input on the shape factor and heat affected zone in case of SAW.

More often, the welding processes are very complex and the linear regression models do not give accurate predictions. Nonlinear regression has been successful in predicting complex weld bead shape. Sharma et al. [11] developed a curvilinear regression model of penetration, width and bead shape. The model of weld seam width in case of laser welding was proposed by Petkovic [12] using support vector regression, which is a kind of nonlinear regression. Many researchers applied artificial neural network (ANN) as a nonlinear regression tool to determine the bead dimension of GMAW [13] and SAW [14] welds. Sarkar et al. [15] and Xiong et al. [16] comparatively investigated linear regression and ANN based nonlinear regression to describe the behavior of weld bead. Xiong et al. [16] observed that ANN based nonlinear regression gives better results than linear regression in GMAW process.

Prediction of weld bead penetration and width for heat resistance steel is not revealed from the literature survey. The article focuses on prediction of weld penetration and weld width which are significant because of the complexity in weld bead shape (e.g. bi-elliptic shape of carbon steel [3]). A second order linear regression and nonlinear regression analysis techniques are evaluated for their effectiveness in prediction of penetration profile. The main objective of the investigation is to develop a linear and a nonlinear regression model for predicting weld bead width and penetration using different welding variables (such as frequency, EN ratio, current, and welding velocity) in AC square SAW of heat resistant steel. Subsequently, a comparison in between the two approaches is aimed to improve the accuracy in predication. The results of both the models are corroborated with the experimental results in terms of model adequacy and percentage error prediction. Finally, the effect of welding variables on weld penetration profile is discussed.

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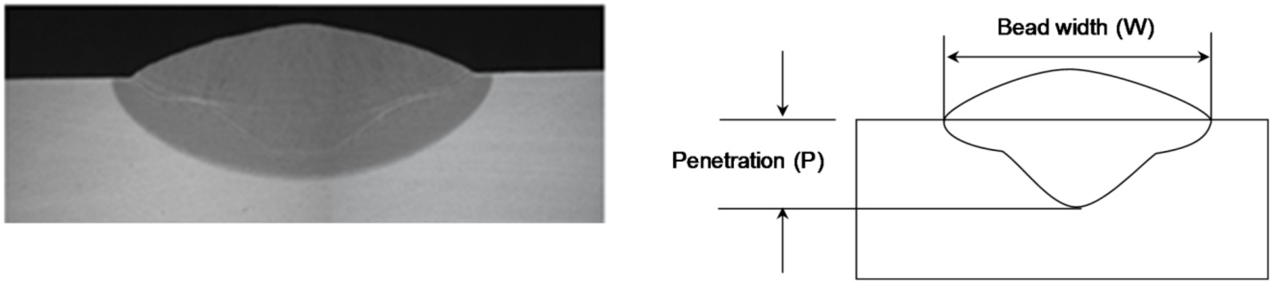
2. 0 EXPERIMENTAL PROCEDURE

The bead on plate welding were performed using 2¼Cr-1Mo steel plates of 600 mm length, 80 mm width and 10 mm thickness. The experiments were conducted as per the design of experiments (L16) by taking four-factor and four-level of input variables. In addition, ten additional experiments were conducted for validation purpose. The frequency, EN ratio, welding current, and welding velocity used as input variables whereas other factors remained constant. The heat input is measured during the experiments by capturing the real time current and voltage using a data acquisition system. The weld sample were obtained by cutting the bead normal to the torch travel direction. Polishing of the sample was done with different grade (i.e. From 200 grit size to 2000 grit size) of emery paper. The polished samples were etched with 5% nital solution to obtain macrograph. The macrograph of a representative weld sample is shown in **Fig. 1(a)**. The response of penetration profile was measured from the macrograph as shown in **Fig. 1(b)**. The process variables and the penetration profile attributes are shown in **Table 1**.

Table 1 : Process Variables and Responses

Exp. No.	Process Variables				Response of penetration profile	
	F (Hz)	E	I (A)	V (cm/min)	W (mm)	P (mm)
1	60	0.50	500	30	23.91	4.19
2	60	0.50	700	30	27.12	7.58
3	60	0.50	400	30	19.48	3.54
4	60	0.50	600	30	26.51	5.88
5	60	0.50	500	20	30.54	4.94
6	60	0.50	500	40	19.76	5.04
7	60	0.50	500	50	16.69	5.28
8	60	0.75	500	30	22.48	4.2
9	60	0.40	500	30	24.43	4.64
10	60	0.25	500	30	26.90	5.14
11	20	0.50	500	30	24.88	4.54
12	40	0.50	500	30	24.68	4.74
13	80	0.50	500	30	25.52	4.84
14	20	0.25	500	20	29.12	4.94
15	40	0.40	500	40	19.92	5.44
16	80	0.75	500	50	19.34	5.35
17	40	0.25	700	30	31.95	8.9
18	80	0.50	700	20	33.29	8.54
19	60	0.75	700	40	23.67	6.74
20	20	0.40	700	50	20.45	8.34
21	80	0.40	400	30	19.94	3.94
22	60	0.25	400	50	13.98	4.04
23	20	0.75	600	30	26.27	6.14
24	60	0.40	600	20	32.49	6.64
25	80	0.25	600	40	23.11	7.94
26	40	0.50	600	50	19.10	5.84

F- Frequency; E - EN ratio; I – Current; V - Welding velocity; W - Bead width; P - Penetration



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(a) (b)

Fig.1 : Representation of weld sample (a) Macrograph (b) Responses

3.0 STATISTICAL MODELING

3.1 Mathematical Model

The bead width and penetration establish the relationship among frequency, EN ratio, welding current, and velocity and expressed as follows:

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

In this study, Y (bead width and penetration) is analyzed by both linear regression and nonlinear regression. A second order equation is used for linear regression analysis, whereas an exponential function is used in the nonlinear regression. The details of each regression are given below.

Case-1: Linear regression

The second order polynomial used to represent Y is given by

$$Y = b_0 + \sum b_i X_i + \sum b_{ii} X_i^2 + \sum b_{ij} X_i X_j \quad (2)$$

The expansion of the polynomial using four variables is expressed as follows:

$$Y = b_0 + b_1 F + b_2 E + b_3 I + b_4 V + b_{11} F^2 + b_{22} E^2 + b_{33} I^2 + b_{44} V^2 + b_{12} FE + b_{13} FI + b_{14} FV + b_{23} EI + b_{24} EV + b_{34} IV \quad (3)$$

where, Y is the predicted value, b_0 is the intersection, bi's are the linear coefficients, b_{ii}'s are the quadratic coefficients, and b_{ij}'s are the interaction coefficients. The values of coefficients are obtained with Minitab software. The co-efficients are obtained by setting α value as 0.15 at 95% confidence interval in stepwise regression.

Case-2 : Nonlinear regression

In nonlinear regression, an exponential function is used. The nonlinear regression equation used to represent the responses is given by

$$Y = K_1 e^{K_2 F} + K_3 e^{K_4 E} + K_5 e^{K_6 I} + K_7 e^{K_8 V} \quad (4)$$

where, K_1, K_3, K_5, K_7 are the coefficients of exponential terms. K_2, K_4, K_6, K_8 are the exponents. The values of the coefficients are calculated using a coded form of input variable in 'Minitab software'. The main attributes set in the Levenberg-Marquardt (LM) methods are the maximum number of repetitions : 20000, limit of convergence : 0.00001 and Confidence interval : 95%.

3.2 Model Adequacy

The analysis of variance (ANOVA) result of linear and nonlinear regression are given in **Table 2-3**. The models are validated by obtaining coefficient of determination (R^2). If R^2 is more than 90%, then the model is considered adequate while a large value of R^2 may lead to overfitting, i.e., the model learns the error and sacrifices its accuracy in prediction. From the ANOVA results, it is confirmed that the developed models using linear regression and nonlinear regression techniques are adequate.

After checking the adequacy of the models and obtaining the reduced model through linear regression and nonlinear regression methods, the final models are expressed as follows:

Model expression using linear regression

$$W = 23.93 - 0.11F - 0.76E + 4.36\,I - 5.61V - 1.66\,I^2 - 1.28\,FI + 1.76\,EV - 2.04\,IV \quad (5)$$

$$P = 5.40 + 0.16F - 0.60\,E + 2.20\,I + 0.27V + 0.57F^2 - 0.48\,EI - 0.45\,IV \quad (6)$$

Model expression using nonlinear regression

$$W = 4.80 \times 10^{-13}\, e^{27.85F} + 1.55 \times 10^{-13}\, e^{-29.41E} + 11.44\, e^{0.30I} + 10.79\, e^{-0.54V} \quad (7)$$

$$P = 1.85 \times 10^{-9}\, e^{19.69F} + 0.47\, e^{-1.02E} + 4.68\, e^{0.45I} + 0.04\, e^{1.85V} \quad (8)$$

Table 2 : ANOVA of linear regression

Bead geometry	Regression			Residual Error Terms			F-ratio	P	R^2(%)
	SS	DF	MS	SS	DF	MS			
W	525.97	8	65.75	10.58	12	0.838	78.44	0.00	98.12
P	51.951	7	7.422	1.696	13	0.1304	56.90	0.00	96.84

Table 3 : ANOVA of nonlinear regression

Bead geometry	Residual Error Terms			S	R^2(%)
	SS	DF	MS		
W	31.75	12	2.6455	1.627	93.49
P	2.52	12	0.21	0.458	96.03

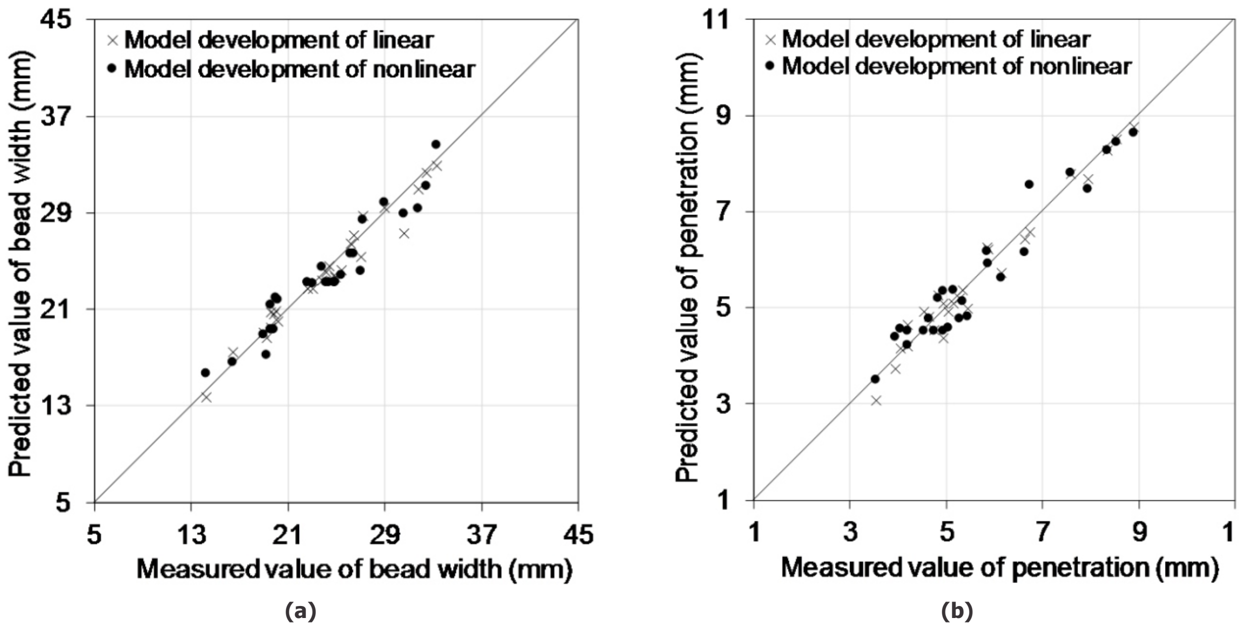

Fig. 2 : Comparison between predicted and measured width and penetration

3.3 Validation of Model

Fig. 2 shows a comparison between measured and predicted value of width and penetration for both the models. The measured and predicted values are in good agreement. The models are validated by obtaining maximum absolute percentage error (MAPE). The value of MAPE is calculated using the experimental result as shown in **Table 1** and predicted result (using Eq. 5-8). From the linear regression results, the MAPE value for bead width and penetration are found to be 10.69% and 13.15%, respectively.

Similarly, in case of the nonlinear regression, the MAPE value of bead width and penetration are obtained as 10.49% and 12.83% respectively. Since MAPE value of the nonlinear regression model is less, therefore, it is a more efficient technique for predicting the penetration profile of heat resistant steel.

4.0 RESULTS AND DISCUSSION

4.1 Effect of Process Variables on Width and Penetration

Mathematical models are used to estimate the bead penetration profile of 2¼Cr-1Mo steel welds for different input parameters. The results are presented in graphical form, as shown in **Fig. 3**. The graphs are used to understand the variability of frequency, EN ratio, current, and welding velocity. The bead width follows similar trend irrespective of the type of regression model at a different frequency as shown in **Fig. 3(a)**. However, the linear regression method is less efficient in identifying the minor variations due to the inherent complex nonlinear relation in between process inputs and bead geometry. In both the cases, the width increases with the increase in frequency because at high frequency, narrow arc cone is developed which needs less time to expand. A similar observation is noticed in case of penetration. It also follows the trend like bead width. The weld penetration in the case of linear regression is over predicted due to lack of non-linearity despite the availability of second order term in the regression equation (Eq. 3). **Fig. 3(b)** depicts the interplay between penetration profile and EN ratio at a constant frequency, current, and velocity. Both, the penetration and width, decreased as EN ratio increases. Similar results are observed in the earlier investigation of AC pulse GMAW [17-18]. The

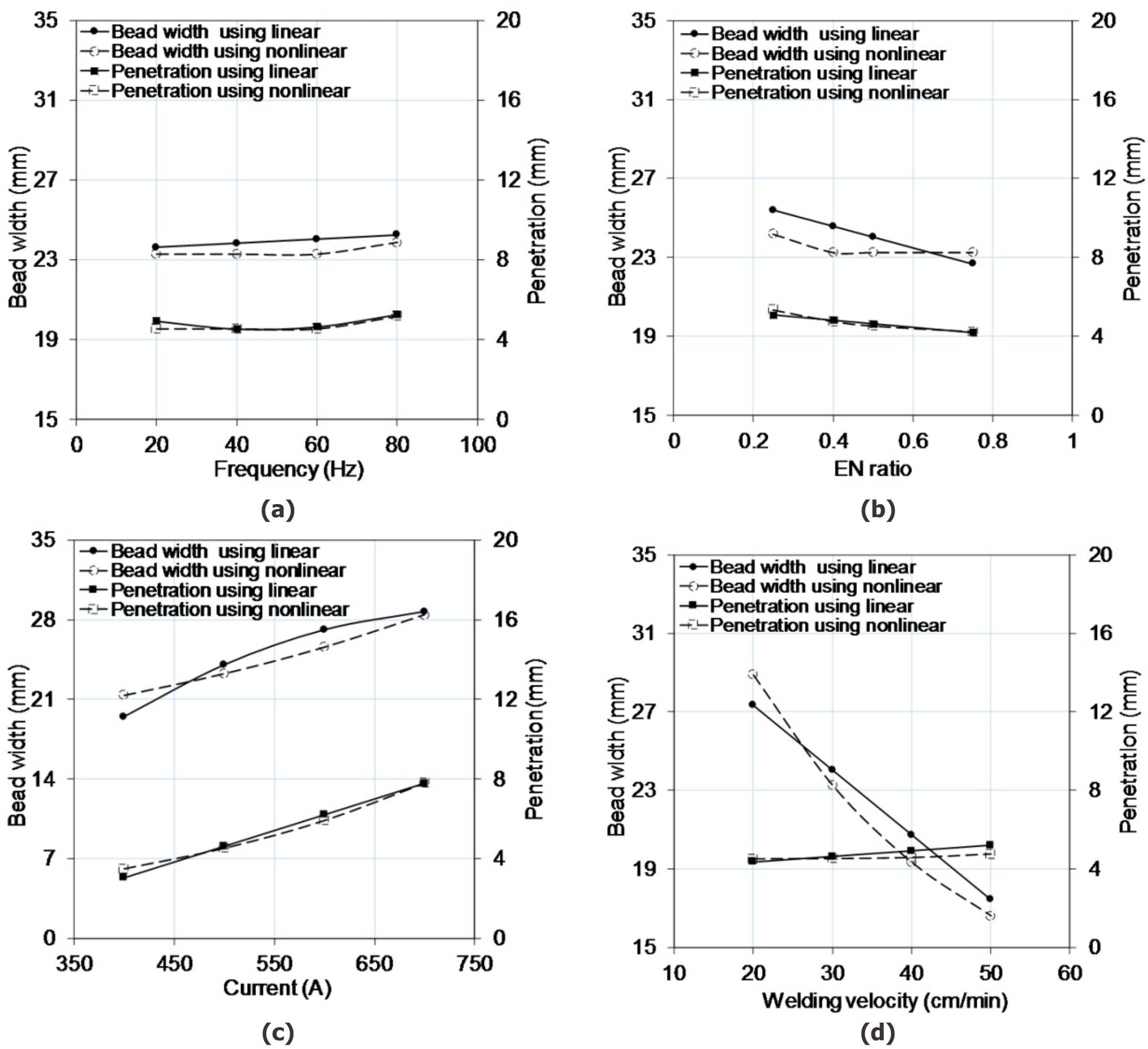

Fig. 3 : Effect of (a) frequency at E=0.5, I=500 A and V=30 cm/min (b) EN ratio at F=60 Hz, I=500 A and V=30 cm/min, (c) current at F=60 Hz, E=0.5 and V=30 cm/min (d) welding velocity at F=60 Hz, E=0.5 and I=500 A on bead width and penetration.

welding current has a strong impact on penetration profile of heat resistant steel. A small increase in current results in considerable change in penetration profile, as shown in **Fig. 3(c)**. This is due to higher deposition and the fluidity of molten metal because of the enhancement in the welding with increase in current at constant F, E, and V. The effect of welding velocity on the width and penetration of bead in both linear regression and nonlinear regression is shown in **Fig. 3(d)**. A careful examination of the predicted results shows that increase in welding velocity reduces the bead width and increases the penetration. The rate of reduction in bead width depends on welding velocity, i.e. when welding velocity increases, then the electrode travels faster, which reduces the deposition rate per unit length of the plate. On the other hand, when welding velocity increases, then the cooling time of the material decreases, which results in softer fusion material that enhances the penetration [19].

4.2 Effect of Process Variables on Penetration Shape Factor

The penetration shape factor (PSF, i.e. ratio of penetration to weld width) is an important measure to understand the overall impact on the weld bead. The nonlinearity in bead width and penetration, interestingly compensate each other that results in almost a linear variation in PSF, as shown in **Fig. 4**. The effect of the process parameters on the penetration shape factor is analyzed and related with the welding heat input. It can be seen in **Fig. 4 (a)** and **(b)** that frequency and EN ratio,

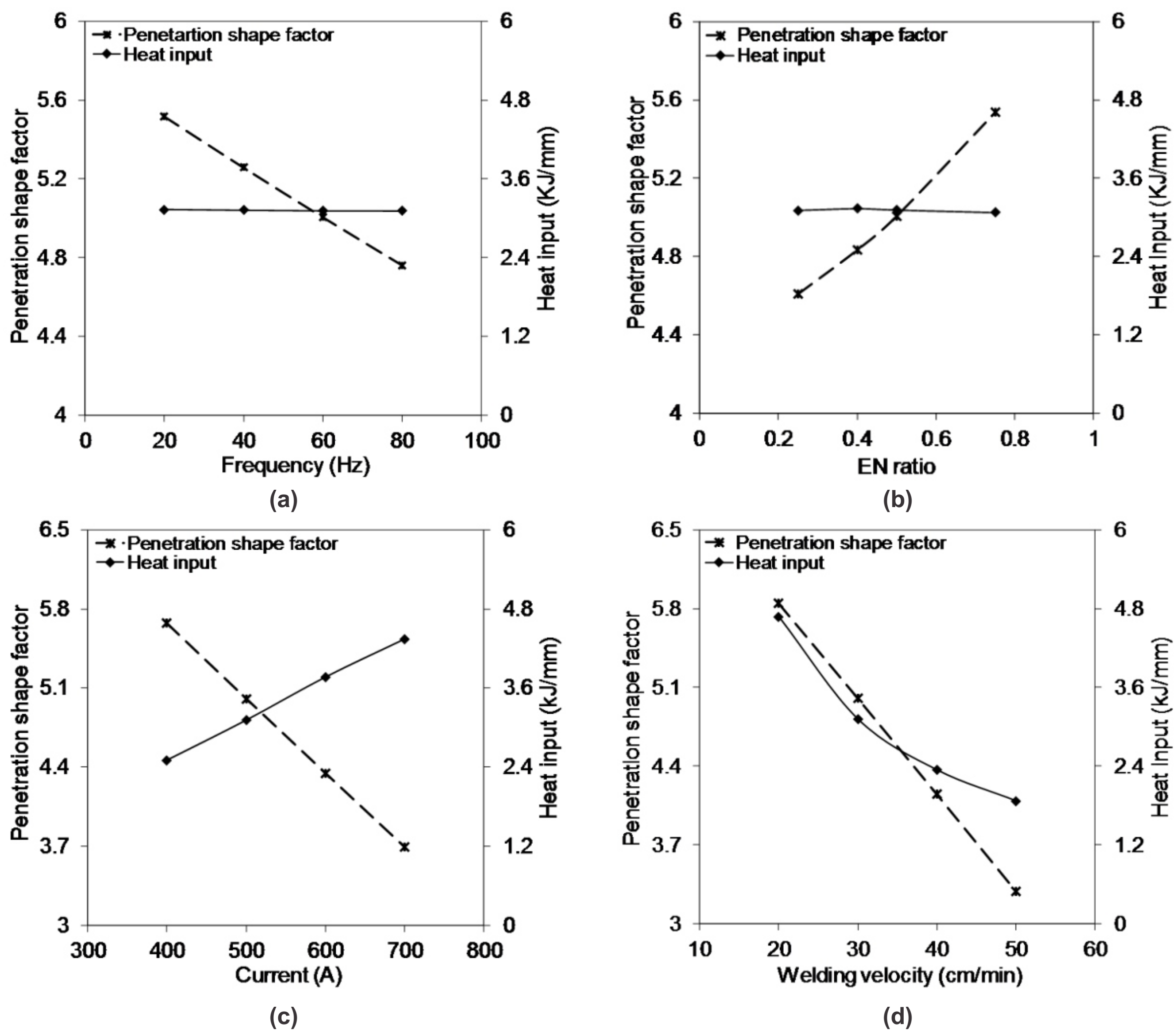

Fig. 4 : Effect of (a) Frequency at E=0.5, I= 500 A and V=30 cm/min (b) EN ratio at F=60 Hz, I=500 A and V=30 cm/min, (c) Current at F=60 Hz, E=0.5 and V=30 cm/min (d) Welding velocity at F=60 Hz, E=0.5 and I=500 A on penetration shape factor.

though do not affect the heat input, but the penetration shape factor is influenced by the change in frequency and EN ratio. This indicates that the parameters have the capability to change the spatial distribution of heat.

The heat input in **Fig. 4(c)** increases with the increase in current which also increases the penetration and bead width. The rate of increase in penetration is more than the bead width. Therefore, the PSF shows a decreasing trend with change in current. The comparable observations are reported by Roy et al. [10] in SAW of mild steel. As welding velocity is inversely proportional to heat input so the quantity of heat input is low at high welding speed, as observed in **Fig. 4(d)**. **Fig. 4(d)** also shows decreasing trend in variation of the PSF because at higher welding velocity the weld pool becomes smaller and penetration is reduced which cause a decrease in dilution as well as PSF.

This investigation shows the efficacy of nonlinear regression analysis in identifying the inherent non-linearity in the relationship between weld penetration profile and welding variables. The linear regression analysis has limited flexibility as it can only adopt linear or possible to transform in the linear form type of regression equations. On the other hand, nonlinear regression can accommodate any form of an equation and find the characteristic coefficients by iterative schemes as Levenberg-Marquardt, thereby, becomes generic to be horizontally deployed to a variety of welding processes.

5.0 CONCLUSIONS

This work compares models for prediction of weld bead attributes in heat resistant steel using linear and nonlinear regression. The main conclusions are as follows:

1. The prediction trends of weld bead attributes as a function of welding variables remain same with linear and nonlinear regression analysis. However, nonlinear regression gives better results in terms of accuracy in prediction.
2. The second order polynomial, in spite of having second order terms in the parent regression equation, more often fails to capture the nonlinear relationship in between welding parameters and bead geometry.
3. Among frequency, EN ratio, current, and welding velocity, the current and EN ratio are the most significant factors that affect both bead width and penetration.
4. The penetration shape factor is influenced by the variation of welding process parameters. The process parameters influence the spatial distribution of welding heat even though some of them (e.g. frequency and EN ratio) do not affect on heat input.
5. The nonlinear model developed in this work is a generic that can be applied to other welding process to obtain bead geometry.

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