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An experimental study on the prediction of back-bead geometry in pipeline using the GMA welding process

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ABSTRACT

Purpose: of this research paper is to select optimal welding condition for a root-pass welding for pipeline and to provide a best process for desirable welding quality.

Design/methodology/approach: In this study, a variety of welding experiments were carried out to optimize an automated welding process using a GMA (Gas Metal Arc) process, these has been applied for root-pass welding. Welding current, welding speed, wire feed speed and torch angle were chosen as input parameters, while back-bead geometry representing quality of root-pass welding as output parameter.

Findings: Based on the results from welding experiments, optimal welding conditions were selected after analyzing correlation between welding parameters and back-bead geometry such as back-bead width and back-bead height. Moreover, not only effectiveness of empirical models developed was compared and analyzed. The optimized empirical models were finally developed for predicting back-bead geometry by analyzing the main effect of each factor and their influence on interaction.

Research limitations/implications: This research was concentrated on the developed empirical models that can predict back-bead width and height for root-pass welding in pipeline.

Originality/value: This study is intended to define correlations between process parameters and back-bead geometry as welding quality and eventually select optimal welding condition by performing root-pass welding experiment under various conditions.

Keywords: Welding; GMA - Gas Metal Arc

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

The welding process has extensively been employed as a joining technique to fabricate various metallic structures including ships, airplanes, automobiles, bridges, pressure vessels, etc. It provides better performance when compared with other joining techniques in joint efficiency, mechanical properties, and field adaptability.

Since the first appearance of welded ships traded in the United State during the Second World War, the shipbuilding can be considered as one of the first industrial fields taking advantage of the most economic benefits from the development of welding technology. The welding process is the best technique for joining of all the structural members composing modernized metallic's. Remarkable advancements in welding technology and development of welding consumables provide high quality and improve the productivity in ship building industries.

Robotic welding processes have replaced human welders in many welding applications and reasonable seam tracking systems are commercially available, but fully adequate process control systems have not been developed. This is due to a lack of reliable sensors and mathematical models that correlate process parameters to the bead geometry for the automated welding process.

The demand in automation of welding process for the pipe structure has recently been increased to improve the productivity and accuracy in the fields such as marine structures, pipeline and steel towers. The welding process for pipeline generally consists of root-pass welding and fill-pass welding. The root-pass by method of GTA (Gas Tungsten Arc) welding is so far performed by the skilled workers due to possibility for defect welded, while the fill-pass is mainly welded by method of GMA welding.

In general, GTA welding is a welding method which has been used for many years to produce high quality joints in a wide variety of materials, while the process is sometimes called TIG (Tungsten Inert Gas shield) welding by IIW (International Institute of Welding) [1]. It is normally used at low welding currents to weld the relatively thin materials and is a very "clean" process because no flux is used. But GTA welding has the disadvantage of high equipment costs and low welding speed then that of GMA welding.

Recently, productivity improvement is a major focus for the welding industry and its associated research community, especially in the push for higher weld quality and reduced manufacturing cost. Weld quality is dependent on arc stability and changes in the operating condition commonly occurring during the welding process. Therefore, recent trends of welding system have been focused on the development of new process in order to achieve better quality, higher productivity and cost savings in welding.

The capabilities of application to a wide range of metals and thickness, high production, and adaptable to robotic application, GMA welding is currently one of the most popular welding methods, especially in a broad range of industrial environments. In GMA welding, heat source is an arc created and maintained between a consumable bare wire electrode and the work piece. The weld is formed by melting and solidification of the joint edges together with filler metal transferred from the electrode. A flow of inert gas shields the weld metal from the surrounding atmosphere. Short-circuit GMA welding process has emerged for a root-pass welding process. The extensive use of the GMA welding in pipeline applications has been limited due to the difficulty for choosing the optimal process parameters and making the automatic welding process.

In order to solve this problem, many attempts have been made to estimate the effect of process parameters experimentally. Sosnin et al. [2,3] developed the experimental models for searching the optimum welding conditions of plasma welding with a penetrating arc. Gaillard et al. [4] proposed the methods for optimizing the preheat temperature to avoid cracking of the resultant weld. Kikushima et al. [5] developed the system generating the optimal process parameter for the arc welding based on a heat conduction analysis. For the above cases, an optimization technique was not used to determine the optimal process parameter for pipeline welding.

To achieve the high quality and welding performance, an interrelationship between back-bead geometry and welding parameters requires to be developed. Many efforts have been done to develop the analytical and numerical models to study these relationships. Kim et al. [6] proposed a method for determining the near-optimal settings of welding process parameters to obtain the desired weld bead geometry in GMA welding using a CRS (Cyclic Redundancy Check) algorithm which is similar to the GA (Genetic Algorithm). Raveendra et al. [7] and Yang et al. employed multiple regression techniques to establish the empirical models for various arc welding processes. Datta et al. [9] developed three empirical models for predicting bead volume of submerged arc butt welding. Also, Gunaraj et al. proposed empirical models for prediction and optimization of weld bead for the SAW process. Furthermore, Gunaraj et al. highlighted the use of RSM (Response Surface Method) by designing a central composite rotatable design matrix to develop empirical models for predicting weld bead quality in SAW (Submerged Arc Welding) for pipelines.

As stated above, the existing researches have aimed to develop regression equation for bead geometry, and find out the optimal conditions using regression equation developed. However, there is still a lack of researches on concrete visualization of back-bead geometry and improvement of prediction performance through statistical approach to regression equation developed. Besides, there is little research on selection of welding conditions according to each position of pipeline, and a lack of researches on root-pass welding for pipe welding.

Objective of this research paper is to select optimal welding condition for a root-pass welding for pipeline and to provide a best process for desirable welding quality. In this point, this study is intended to define correlations between process parameters and back-bead geometry as welding quality and eventually select optimal welding condition by performing root-pass welding experiment under various conditions. Furthermore, an empirical model for back-bead geometry has been developed so as to provide an algorithm for prediction of back-bead geometry.

2. Experimental works

GMA welding has been applied for root-pass welding in 3 types of welding positions (0°, 90° and 180°). Welding current, welding speed, wire feed speed and torch angle are chosen as input parameters compared to back-bead geometry representing quality of root-pass welding as output parameter. Based on the result from 38 welding experiments, the empirical model was developed and correlations between process parameters and back-bead geometry were analyzed.

2.1. Experiment procedure

Welding parameters such as the capacity, type of equipment, material dimensions and composition may be relatively fixed, while primary adjustable parameters may be altered during the arc welding process. Therefore, in this study, welding current, welding speed, wire feed speed and torch angle were chosen to be the welding parameters for the experimental work. Fig. 1 shows a schematic diagram for the welding parameters and quality characteristics for experiment.

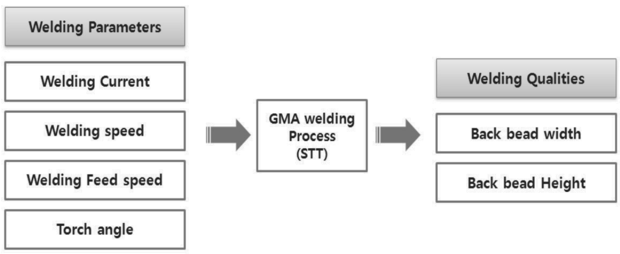


Fig. 1. Schematic diagram for the welding parameters and quality characteristics for experiment

In this study, experiments preferentially were performed on a plate, instead of a pipe welding. Welding directly to the pipe for selecting the optimum conditions requires expensive equipment, much of the cost and manpower is needed. Therefore, surface-bead geometry is kept constant. It was noticed that the surface-bead height deviation is approximately 0.0381 mm if 250 mm diameter pipe is being welded with 2° rotation as shown in Fig. 2 [7]. For the above reason, welding experiment was carried out on flat specimen.

Furthermore, the experiment conducted in this research chooses basic welding conditions that required for the back-bead geometry in flat position. For vertical and overhead positions, additional experiment was planned for selecting mechanical conditions (torch angle, welding speed) of welding carriage. For flat position, the experimental design was performed using a CCD method which is not only convenient to study main effects and interaction, but also to correlate independently controllable process variables. This method is also effective to minimum process combination having n-element in the full factorial experiment. The process variables included in this study were three levels of peak current, three levels of background current, three levels of wire feed speed. Experiments for vertical and overhead position were not use any special experimental design method because it was possible enough to conduct an experiment for all of vertical position and overhead position with two factors and three levels. For that reason, experiment for vertical and overhead position have only been conducted total of 9 welding experiments about each position as shown in Fig. 3.

Table 1.
Process parameter and level for flat position

Process parameter	Symbol	Unit	Level		
			-1	0	1
Peak current	C_p	Ampere	330	360	390
Background current	C_b	Ampere	50	60	70
Wire feed speed	W_f	cm/min	250	300	350

In this study, experiment was carried out on the base materials 500×200×15.9 mm API X-65 plates with 70°groove and 2.5 mm root-gap, 1-1.5 mm root-face as shown in Fig. 4.

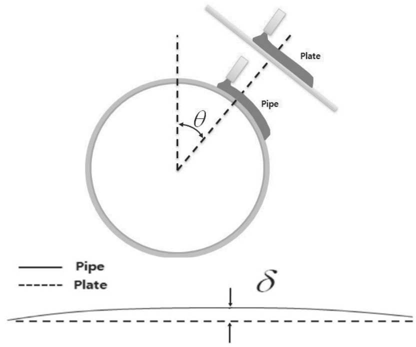


Fig. 2. Comparison pipe with plate

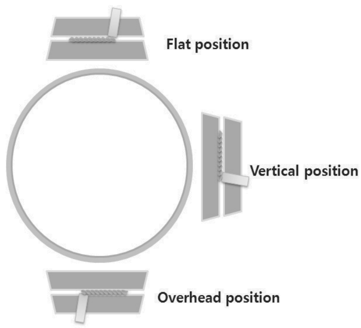


Fig. 3. Schematic of pipe weld experiment with different welding position

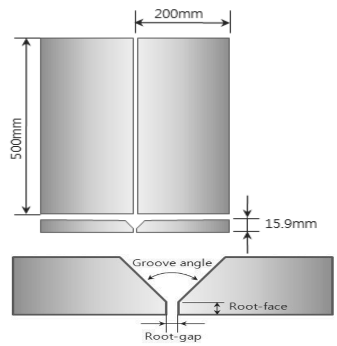


Fig. 4. Configuration of welding specimen

The selection of the electrode wire should be based principally upon matching the mechanical properties and physical characteristics of the base metal. Secondary consideration should be given to items such as the equipment to be used, the weld size and existing electrode inventory. The 1.2 Ø solid wire diameters and 100% CO_2 shielding gas was employed in experiment.

Table 2.
Results of back-bead geometry measured

No.	C_p	C_b	W_f	W_b	H_b
1	410	60	330	4.39	0.94
2	360	60	385	4.19	0.76
3	360	76	300	3.17	0.19
4	360	60	215	2.17	0.20
5	330	70	350	2.35	0.35
6	360	43	300	3.24	1.33
7	330	50	250	3.33	0.90
8	330	70	250	3.55	0.62
9	360	60	300	3.45	0.97
10	390	50	250	3.19	1.34
11	390	70	250	3.51	0.76
12	390	50	350	4.84	0.99
13	390	70	350	3.9	0.65
14	309	60	300	2.99	1.52
15	360	60	300	3.37	0.74
16	330	50	250	2.64	0.90
17	390	50	250	2.85	1.30
18	330	70	250	2.51	0.49
19	390	70	250	3.54	0.61
20	330	50	350	3.58	1.46

Table 3.
Results of back-bead geometry measured each positions

No	Position	W_s	T_a	W_b	H_b
1	Vertical position	10	70	3.72	0.68
2		15	70	4.76	0.4
3		20	70	3.18	0.08
4		10	60	2.56	0.72
5		15	60	4.1	0.44
6		20	60	2.72	0.36
7		10	50	2.1	0.2
8		15	50	3.32	0.52
9		20	50	3.84	0.36
10	Overhead position	10	70	2.95	0.58
11		15	70	3.08	0.24
12		20	70	4.04	0.14
13		10	60	3.58	0.72
14		15	60	3.18	0.44
15		20	60	3.12	0.32
16		10	50	4.48	0.56
17		15	50	4.5	0.6
18		20	50	3.94	0.56

2.2. Experiment results and select the optimal condition

Welding experiment have been carried out 38 times for each welding position. To measure back-bead geometry, the experiment specimen were cut in 60×30 mm sizes horizontally from the middle by laser cutting machine and polished. To make the experiment specimen's bead geometry clearly visible, 3% HNO_3 and H_2O Nital solution were applied for etching of the cross-section of specimens. Also, optimal microscope system was used for accurate measurement of back-bead geometry and actually measured 38 cross sectional back-bead geometries. Among 38 welds measured, back-bead width and height measured in flat welding experiment are shown in the Table 2. Flat position welding resulted in stable welding and convex back-bead geometry. For vertical and overhead positions, welding was stable as depicted in the Table 3. However, several experimental result were dents owing to gravity. Results from the experiment were applied for correlations between process parameters, back-bead geometry and used to develop a model that is designed to optimize welding process.

Through welding experiment of flat position, basic welding conditions required for back-bead formation are chosen. Whereas, vertical and overhead welding that are generally affected by torch angle and welding speed. In order to choose a optimal welding condition at each welding position, this research could verify the back-bead width and height using contour line plot among the RSM (Response Surface Method). Figs. 6-7 shows contour lines per each parameter related to the back-bead width and height in flat position. While Tables 4-5 describes the target values of back-bead geometry and corresponding welding conditions. Appropriate back-bead geometry of 3-5 mm width and 0.5-1.5 mm height is chosen.

Out of several RSM, satisfaction function estimates overall satisfaction level of a solution on every response at response optimization. Satisfaction level can be either individual or integrated level with 0-1 range; 1 for ideal case and 0 for one or more responses be out of range. Fig. 5 summarizes the satisfaction function.

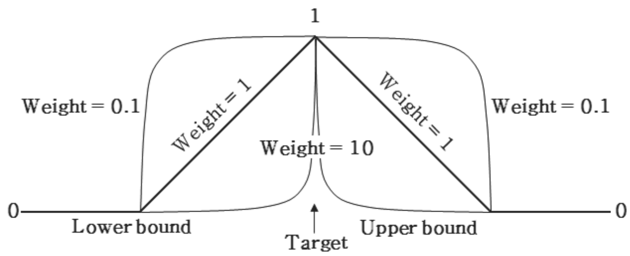


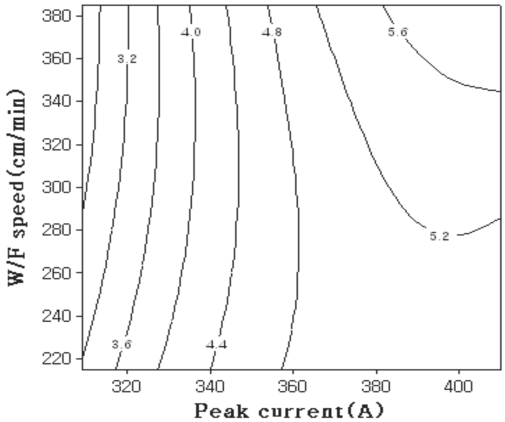
Fig. 5. Concept of satisfaction function

Table 4.
The target value of the optimal back-bead determined

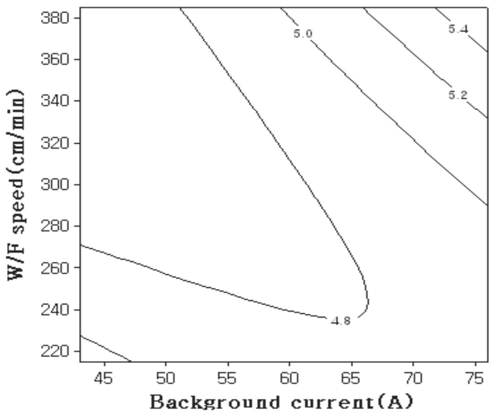
	Min.	Target	Max.	Weight	Significance
W_b	3	4	5	1	1
H_b	0.5	1.0	1.5	1	1

Table 5.
The optimal value of process parameters predicted

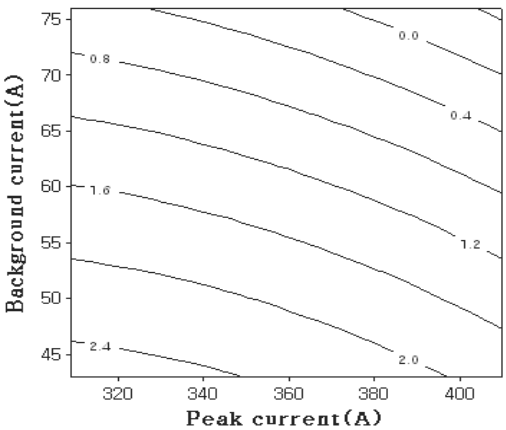
Predicted response		Optimal conditions Flat position		
W_b	H_b	C_p	C_b	W_f
4	1.0	397.5	57.46	315



(a) Back-bead width, W/F speed, peak current

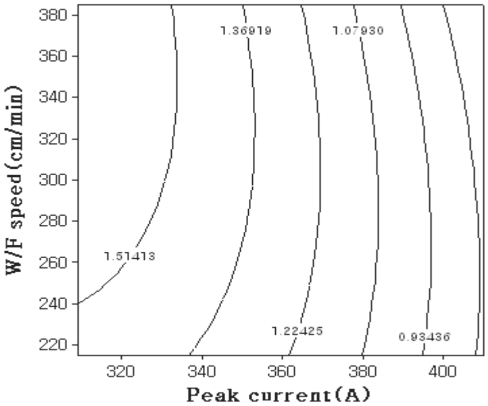


(b) Back-bead width, W/F speed, background current

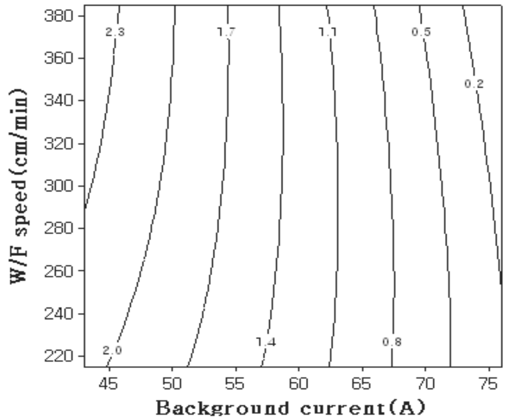


(c) Back-bead width, background current, peak current

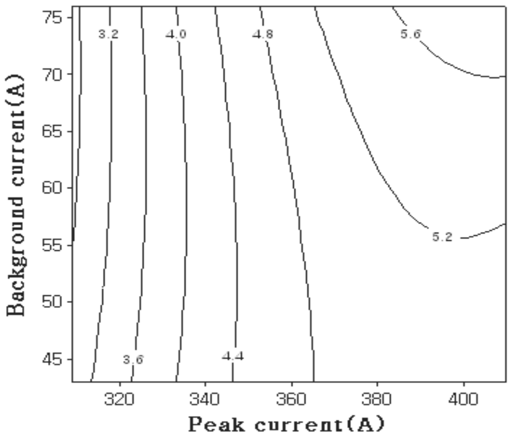
Fig. 6. Contour line for back-bead width



(a) Back-bead height, W/F speed, peak current



(b) Back-bead height, W/F speed, background current



(c) Back-bead height, background current, peak current

Fig. 7. Contour line for back-bead height

3. Experimental analysis and discussion

3.1. Development of empirical models

To analyse the effect of process variables on the back-bead geometry for root-pass welding in butt GMA welding process, a new models based on the experimental results have been developed. In general, the response function can be represented as follows;

For 2nd-order interaction model;

$$Y_f = a_0 + a_1 C_P + a_2 C_b + a_3 W_f + a_4 C_P^{\ 2} + a_5 C_b^{\ 2} + a_6 W_f^{\ 2} + a_7 C_P C_b + a_8 C_P W_f + a_9 C_b W_f \quad (1)$$

$$Y_{o/v} = a_0 + a_1 T_a + a_2 W_s + a_3 T_a^{\ 2} + a_4 W_s^{\ 2} + a_5 T_a W_s \quad (2)$$

These analysis were carried out using a standard statistical package program, Minitab in the PC. Based on the regression analysis using the least square method from experimental results (back-bead width and height) and significance at the 1% level on Fisher's F-ratio that represents the actions and interactions shown to be important. Coefficients of the mathematical model are shown in Table 6. The developed coefficient were analyzed by R-square and sum of square error (SEE).

Table 6.
Estimated regression coefficients of empirical model for back-bead geometry parameters

Coeff.	Flat position	
	W_b	H_b
a_0	16.727	10.730
a_1	-0.1059	-0.1117
a_2	0.1069	0.0243
a_3	-0.0020	0.0694
a_4	0.0001	0.0001
a_5	0.0001	-3.0783
a_6	0.0001	-0.0001
a_7	0.0003	0.0001
a_8	0.0001	-0.0001
a_9	0.0001	-0.0001

Coeff.	Flat position		Overhead position	
a_0	-16.8467	-9.2177	36.7511	-1.6888
a_1	-0.1640	0.2373	-0.8565	0.0873
a_2	1.1966	0.1433	-0.3216	0.0009
a_3	0.0036	-0.0011	0.0053	-0.0001
a_4	-0.0104	-0.0017	0.0009	0.0005
a_5	-0.0057	-0.0019	0.0040	-0.0011

Table 7.
Variance test for developed empirical models

Developed models		SSE	R-Square
Flat position	W_b	1.540	0.819
	H_b	0.467	0.842
Vertical position	W_b	0.548	0.901
	H_b	0.046	0.864
Overhead position	W_b	3.620	0.882
	H_b	0.020	0.931

Coefficient of determination means a proportion of a section which is explained by X (Welding parameter), of the whole variables of subordinate measure, Y(Experimental results). Normally this proportion marked as R^2 is called R-square. R^2 value may be adjacent to 1, if results of each case are similar to regression values, then numerator and denominator are almost same. Also, coefficient of determination has the scope of $0 \le R^2 \le 1$ since it means a proportion and its R^2 is an absolute value of correlation between subordinate variable and independent variable. As shown in Table 7 as a whole, a very good predictive performance is considered as a model.

3.2. Modification of empirical models

Since a main effects or interactions factor have little effect on a response value, there are 3 methods to determine whether to screen or not. First, there are T-value (statistical test value for the test coefficient) and P-value (probability of the T-value) method. Second, there are regular probability chart and pallet chart for comparison of relative sizes of the effects and statistical analysis for assessment of the effect on the response value. Third, there is visualization of the factors, which visualizes how the response values interact with one or more factors using main and interaction effect charts and assesses relative sizes of the effects.

The T-test assesses whether the means of two groups are statistically different from each other. This analysis is appropriate whenever you want to compare the means of two groups, and especially appropriate as the analysis for the posttest-only two-group randomized experimental design.

This study has discussed factors that has effects on response values, main factors' correlation assessment, P-value, regular probability chart, main and interaction effects, and so on. Tables 8-10 describes main effect and interaction effect of those factors related to back-bead geometry in each welding position.

As indicated in the Tables 8-10, based on the P-value that represents the extent of a corresponding factor's that affect the result, a factor is to be meaningful if P-value ≤ 0.1. Otherwise, it is meaningless. A modified mathematical model was developed based on the meaningful factor and meaningless factors to enhance accuracy of the model's prediction.

In flat welding case, most meaningful factor that affects a back-bead height is peak current with P-value of 0.004. Furthermore, P-value for interaction between background current and wire feed speed turned out to be 0.022 while P-value for interaction between peak current and wire feed speed was 0.51. In addition, other factors can be thought of as no-effect factors.

In the back-bead width case, as shown in the Table 8, it was verified that background current, as a single factor had P-value of 0.004 and thus was the most meaningful factor. Also, peak current and background current had little effect on the back-bead width.

Table 8.
Estimated effects and coefficients of back-bead for flat position

Terms		Results			
		SE Coeff.	Coeff.	T	P
W_b	Constant	0.2764	3.4150	12.356	0.000
	C_p	0.1601	0.6058	3.784	0.004
	C_b	0.1618	-0.2302	-1.422	0.185
	W_f	0.1610	0.6291	3.907	0.003
	C_p^2	0.3556	0.1718	0.483	0.639
	C_b^2	0.3605	-0.1139	-0.316	0.758
	W_f^2	0.3668	-0.1423	-0.388	0.706
	C_pC_b	0.3146	0.2801	0.890	0.394
	C_bW_f	0.3200	0.7081	2.213	0.051
	C_pW_f	0.3306	-0.8971	-2.713	0.022
H_b	Constant	0.2764	3.4150	12.356	0.000
	C_p	0.1601	0.6058	3.784	0.004
	C_b	0.1618	-0.2302	-1.422	0.185
	W_f	0.1610	0.6291	3.907	0.003
	C_p^2	0.3556	0.1718	0.483	0.639
	C_b^2	0.3605	-0.1139	-0.316	0.758
	W_f^2	0.3668	-0.1423	-0.388	0.706
	C_pC_b	0.3146	0.2801	0.890	0.394
	C_bW_f	0.3200	0.7081	2.213	0.051
	C_pW_f	0.3306	-0.8971	-2.713	0.022

Table 9.
Estimated effects and coefficients of back-bead for vertical position

Terms		Results			
		SE Coeff.	Coeff.	T	P
W_b	Constant	0.3186	3.8200	11.990	0.001
	T_a	0.1745	0.4000	2.292	0.106
	W_s	0.1745	0.2267	1.299	0.285
	T_a^2	0.3023	0.3600	1.191	0.319
	W_s^2	0.3023	-1.0400	-3.441	0.041
	T_aW_s	0.2137	-0.5700	-2.667	0.076
H_b	Constant	0.09247	0.54222	5.864	0.010
	T_a	0.05065	0.01333	0.263	0.809
	W_s	0.05065	-0.13333	-2.632	0.078
	T_a^2	0.08773	-0.13333	-1.520	0.226
	W_s^2	0.08773	-0.05333	-0.608	0.586
	T_aW_s	0.06203	-0.19000	-3.063	0.055

In case of back-bead width at vertical welding, it is shown in the Table 9 that two-factor interaction is greater than single factor. For a back-bead height, torch angle (single factor) and welding speed (two-factor interaction) have little effects as depicted in Table 9.

In overhead welding case, torch angle has the greatest effect on the back-bead width with 44.8% of total Seq SS value as shown in the Table 10. For a back-bead height, welding speed has substantial effect with P-value of 0.025. Through P-value, an empirical model excluding those factors with low effects was developed, therefore developing more precise prediction model of back-bead geometry. Modified cofficient of empirical model per each position is as shown Table 11.

Table 10.
Estimated effects and coefficients of back-bead for overhead position

Terms		Results			
		SE Coeff.	Coeff.	T	P
W_b	Constant	0.2549	3.22778	12.662	0.001
	T_a	0.1396	-0.47500	-3.402	0.042
	W_s	0.1396	0.01500	0.107	0.921
	T_a^2	0.2418	0.53833	2.226	0.112
	W_s^2	0.2418	0.09833	0.407	0.712
	T_aW_s	0.1710	0.40750	2.383	0.097
H_b	Constant	0.06093	0.45778	7.514	0.005
	T_a	0.03337	-0.12667	-3.796	0.032
	W_s	0.03337	-0.14000	-4.195	0.025
	T_a^2	0.05780	-0.04667	-0.807	0.479
	W_s^2	0.05780	0.05333	0.923	0.424
	T_aW_s	0.04087	-0.11000	-2.691	0.074

Table 11.
Variance test for modified empirical models

Developed models			SSE	R-Square
Flat position	Empirical model	W_b	1.540	0.819
		H_b	0.467	0.842
	Modified model	W_b	1.787	0.892
		H_b	0.888	0.867
Vertical position	Empirical model	W_b	0.548	0.901
		H_b	0.046	0.864
	Modified model	W_b	0.807	0.854
		H_b	0.088	0.743
Overhead position	Empirical model	W_b	3.620	0.882
		H_b	0.020	0.931
	Modified model	W_b	0.370	0.875
		H_b	0.030	0.897

Table 11 indicates comparison results of variance test between modified curvilinear model and non-modified curvilinear model. Normally, adjusted R-Square value of modified one is higher than that of the non-modified one. It is evidence that the fitting of modified curvilinear models are better than those of linear and curvilinear models. Figs. 8-13 shows graphs comparing the error percentages between the modified curvilinear models and curvilinear models. As the graphs shows, the modified curvilinear model has much lower error percentage, compared to the curvilinear models. However, as shown in Fig. 10, the curvilinear model is more appropriate than the modified curvilinear one for the back-bead width in a vertical position welding.

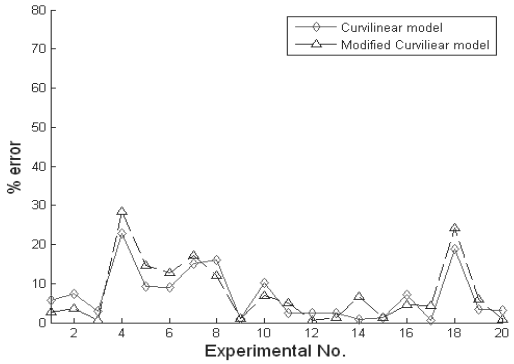


Fig. 8. The accurate prediction of two developed models for back-bead width (flat position)

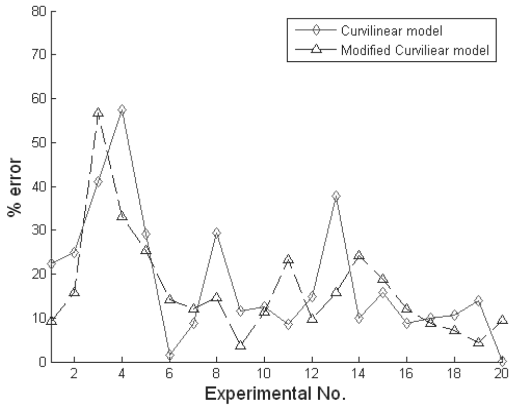


Fig. 9. The accurate prediction of two developed models for back-bead height (flat position)

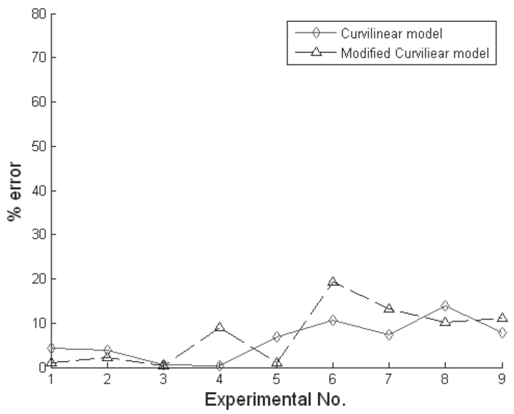


Fig. 10. The accurate prediction of two developed models for back-bead width (vertical position)

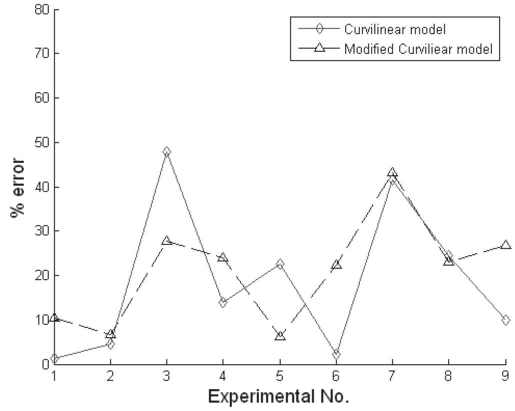


Fig. 11. The accurate prediction of two developed models for back-bead height (vertical position)

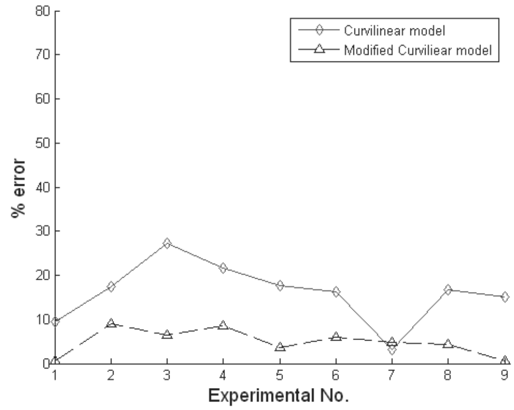


Fig. 12. The accurate prediction of two developed models for back-bead width (overhead position)

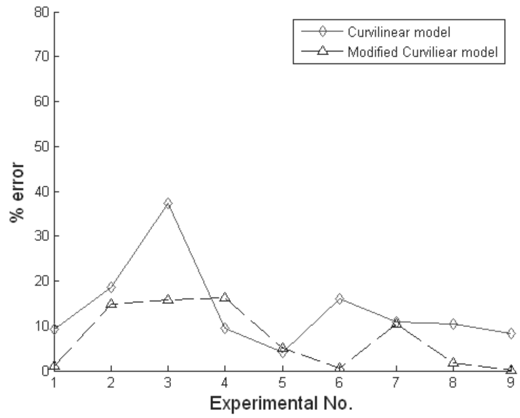


Fig. 13. The accurate prediction of two developed models for back-bead height (overhead position)

Vertical position, unlike the flat position accuracy did not improve. Using the same method to modify the model, but the differences is in the number of parameters. Using statistical methods to improve the accuracy of the mathematical model should be sufficient for the number of parameters. In flat position, the number of parameters sufficient accuracy of the revised model is expected to be improved.

4. Conclusions

This research was concentrated on the developed empirical models that can predict back-bead width and height for root-pass welding in pipeline. In addition, four kinds of quadratic function were compared by curve-fitting toolbox of Matlab, in order to express the back bead geometry. Within this research, the following conclusions have been reached:

- GMA welding has been applied for root-pass welding in 3 types of welding positions(0°, 90° and 180°). Welding current, welding speed, wire feed speed and torch angle are chosen as input parameters compared to back-bead geometry as a welding quality.
- Results of experiment has been used to develop three empirical model, so it can be confirmed that curvilinear model has a reliable fitting on the experimental data and the prediction capabilities on back-bead width and height than linear model at each position.
- In order to choose a optimal welding condition at each welding position, this research could verify the back-bead width and height using contour line plot among the RSM (Response Surface Method).
- In this study, response effects of welding parameters were relatively analyzed in order to improve accuracy of the curvilinear model developed. Although, it was found that the curvilinear model which was modified by eliminating uninfluential factors. Using T-value of test statistics and P-value that is a percentage regarding test statistics, had very precise prediction abilities, compared to modified curvilinear model and general curviliear model. The curvilinear model had higher precision than the modified curvilinear model for vertical welding positions. Using statistical methods to improve the accuracy of the mathematical model should be sufficient for the number of parameters flat position, even if the number of parameters sufficient accuracy of the revised model is expected to be improved.

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