Prediction of Weld Bead Geometry for CO_2 Welding Process by Multiple Regression Analysis

K. Lalitnarayan, M.M.M. Sarcar, K. Mallikarjuna Rao and K. Kameswaran

Abstract—**The purpose of this study is to find a prediction regression equal of the welding process parameters in order to obtain the desired geometry of the back-bead in butt welding, a form of CO_2 arc welding in which a groove gap exists. The regression model equation is obtained from welding process parameters through the correlation of the parameters of the back-bead, to which an inverse transformation is performed. From the parameters of the back-bead, the correlation between the welding process parameters was found in regression model equation. The accuracy of the regression model was proven through the mean error rate for prediction under conditions of data for the analysis level and the verification level respectively. As a result, the maximum prediction error rate in the forward process was under 9.5 per cent, and the prediction error rate in the inverse process, which is the prediction for the welding process parameters, was under 6.5 percent, proving that a regression equation of the model for the prediction system of the back-bead can be obtained through both processes.**

Index Terms— ***CO_2 arc welding, gap of groove, width of back-bead, depth of back-bead, laser vision sensor, image processing, multiple regression analysis, inverse transformation.***

***MSC 2010 Codes* —62A25, 62J05**

I. Introduction

BECASE welding affects not only the quality but also the safety of the structure, welding should be performed under optimal welding conditions. In selecting the optimal welding conditions, the experiments should be repeated many times, as the welding quality may change according to the thickness and shape of the welded part. This requires an immense number of experiments. However, it is not easy to obtain an optimal condition using a trial and error method and to perform so many experiments. Therefore, a method which obtains an optimal condition economically should be considered.

The statistical approach method is used for the efficiency of the welding database. Recently, research has been done which explains the correlation between welding process parameters and bead geometry [Cook, G.E., (1986), Kim, I.S.(1996), Raveendra, J (1987)]. However, this research has not been developed enough to be applied to the parameter prediction system in the case of multi-independent parameters. The use of the multiple regression analysis (MRA) method to solve the correlation between the welding process parameter and welded bead shape has increased [Chandel, R.S. (1988)]. The actual application was initiated by [Yang, L.J. (1993)]. Most of the previous search has been done on bead-on-plate welding [McGlone, J.C. (1980)] and still has not been applied to general welding fields; gaps such as butt welding have been considered.

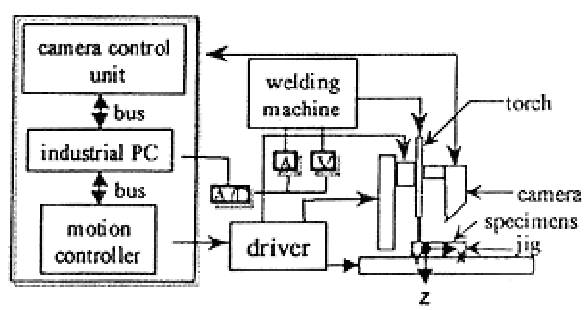

Fig.1 System configuration for the prediction of the back-bead

In this study, a regression model equation was developed using welding process parameters, to effectively control the geometrical shape of a back-bead in but CO_2 welding. Using the inverse transformation of this regression model, the predicting regression equations of welding process parameters are developed for acquiring the desired shape of a back-bead in general welding. In order to test the accuracy of the regression equation, the data obtained through the experiment were applied to the data obtained through the experiment were

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applied to the data for the analysis level and data for the verification level. It is possible to make a prediction system for process parameters that can be applied to general welding, by showing that the mean error rate for prediction of the forward process and backward process are under 10 percent.

II. Experiment

A System configuration

The experimental system consisted of a three-axis robot system, welding machine and measuring system. The three-axis XYZ table is used for the robot system. The CO_2 arc welding machine was used, with 100 per cent CO_2 as the shielding gas. A wire with a diameter of 1.2mm was used for the welding machine. A laser vision sensor was used as the measuring device to detect the groove gap, width and depth of back-bead. The system configuration for the experiment is shown in Fig.1.

B Image processing for obtaining experimental data

The width and depth of the back-bead according to the groove gap are obtained from the data, measured from the laser vision sensor. The laser stripe, which is a form of laser bead acquired from the laser vision sensor, is comprised of 256 pixels, and the group of pixels should be expressed as lines and curves segments for measuring the groove gap, width and depth of the back-bead.

Segment splitting of the profile should be performed to approximate to the contour of the line segment, and the break point should be extracted too obtain satisfactory polygon segments. The segment splitting method is a means of finding break points from both end points.

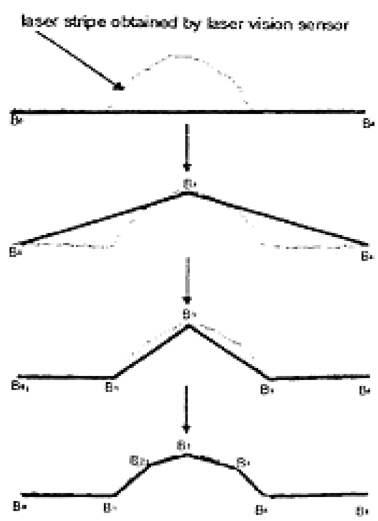

Fig 2 Segment Splitting Method for Stripe Representation

Figure 2 shows the segment splitting method for representing the contour. First, the primary edge point B_0 is connected to the last edge point B_6, forming the line B_0B_6. The furthermost edge point B_3 is found from the line B_0B_6. By repeating the iteration, the edge points of B_1 and B_5, the furthermost edge point B_2 from the line B_1B_3 and the furthermost edge point B_4 from the line B_3B_5 are found. After calculating the orthogonal distance by approximation from the line that connects both edge points, the iteration of the segment splitting method is stopped if the straight distance from every point of the profile is under the tolerance level.

However, if it is not under the tolerance level, the iteration is continued. In this programme, the minimum value of tolerance is placed at 2mm and the maximum number of produced edge points is conditioned to 17.

In this paper, according to image processing for obtaining experimental data, a laser vision sensor with a resolution of 0.05 mm was used for the precise measurement of the width and depth of the back-bead in CO_2 welding.

Table 1.Welding variables and experimental conditions

Parameters	Units	Experimental Conditions
Current	A	130,150,180,200
Voltage	V	15,20,25,30
Speed	mm/sec	2.5, 4.17, 6.77, 9.77

C Experimental Method

The size of the specimen used in the experiment was 90 mm (width) × 100 mm (length) × 6 mm (depth), and butt welding was performed with two parts of SS400 mild steel. The welding parameters of the base metal used in the experiment and the welding conditions are shown in Table 1. The selection standard for Table 1 was based on the optimal welding conditions for the mild steel, which is 6mm thick.

By combining the conditions on Table 1, 36 experiments are performed 3 times each under each condition. From 100 mm of the welding direction of the back-bead, the laser vision sensor measure 80 mm, excluding the first and last 10mm in which the welded part is unstable, thus calculating the groove gap and width and depth of the back bead, which were used as data for predicting the geometry of the back-bead. A schematic diagram of the groove gap and width and depth of the back bead is shown in Fig.3.

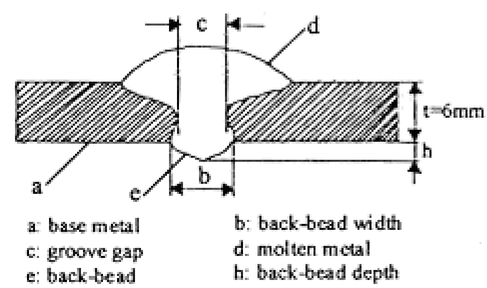

Fig 3 Schematic Diagram of Width and Depth of Back Bead.

Figure 3 shows the cross-section of the welded parts. The upper part of the 6mm SS41 base metal shows the molten pool and the lower part schematically shows the definition of the groove gap and geometry of the back-bead. The laser vision sensor, which was used for measuring profile data, was equipped with a laser diode of 40 mw power and a band-pass filter of 680 nm wavelength. Each profile consists of 256 pixels, and 40 profiles were captured for 1s. The flow rate of shielding was 151/min and the CTWD (contact tip to work piece distance) was fixed at 15 mm.

III. Results and Discussion

A *The correlation between welding process parameters and back-bead parameters*

Arc voltage, welding current and welding speed are welding input parameters in butt CO_2 welding and are thought to be in close correlation with the groove gap, width and depth of the back-bead. In this study, a regression model was made to examine the relationship between these parameters. The stepwise multiple regression analysis, which is a kind of statistical method, was used to consider the regression model in back-bead predictions. Parameters such as arc voltage, welding current and welding speed were used as independent parameters in the regression analysis. The adaptability of the regression model was estimated through data for the analysis level of the five conditions. The SPSS (Statistical Package for Social Science), which is a commercial statistical program, was used in the regression analysis of this study. The correlation coefficients of the geometry of the back-bead and the welding process parameters are shown in Table 2. In Table 3, the independent parameters and dependent parameters were analyzed together.

In Table 1, grove gap, the width of the back-bead and the depth of the back-bead show a high correlation to welding speed, welding current and arc voltage, in descending order. When the significance level of the regression model coefficient is estimated at 0.05, parameters with a probability value of over 0.05 of t-statistical value are excluded, to ensure reliability of the regression analysis, and an approach method to find another adjusted coefficient is used. The model summary and results of multiple regression analysis for groove gap, width and depth of the back-bead are shown in Table 3.

The following equations are expression of the parameters of the back-bead in the form of regression equations:

$$\mathrm{GAP} = 0.849 + (\mathrm{CURRENT} \times 0.617) + (\mathrm{VOLTAGE} \times 0.617) \quad (1)$$

$$\mathrm{WIDTH} = 1.334 + (\mathrm{CURRENT} \times 5.039) + (\mathrm{VOLTAGE} \times 5.981) + (\mathrm{SPEED} \times (-6.671)) \quad (2)$$

$$\mathrm{DEPTH} = 0.458 + (\mathrm{CURRENT} \times 3.306) + (\mathrm{VOLTAGE} \times 2.697) + (\mathrm{SPEED} \times (-3.246)) \quad (3)$$

Where GAP is the groove gap, WIDTH is the width of the back-bead, DEPTH is the depth of the back-bead, CURRENT is welding current, VOLTAGE is arc voltage and SPEED is welding speed.

Table 4 shows the significance level using the multiple regression analysis. In this interpretation, if the significance level is above 0.05, the significance of the independent parameters and dependent parameters decreases. The independent parameters were removed from the regression model equation. Figure 4, 5 and 6 show the groove gap and width and depth of the back-bead by comparing the measured value and the predicted value through the multiple regression analysis. The number of experiments, five a first, provided data for the analysis level and the number of following experiments, five, provided data for the verification level. In table 3, the adjusted coefficient of the model is given as 0.873 and the standard error of the estimate is given as 0.1622, in the case of the groove gap. The error rate of the analysis data is 8.92 percent. The adjusted coefficient of the width of the back bead is shown as 0.913 and the standard error of the estimate is shown as 0.1306, in the case of the width of the back-bead. The error rate of the data for the analysis level is 2.44 percent and the error rate for the data for the verification level is 2.94 percent. Also, in the case of the depth of the back-bead, the adjusted coefficient is 0.984 and the standard error of the estimate is 0.1517. The error rate for the analysis data is 3.48 percent. The adjusted coefficient of the three parameters of the back-bead (groove gap, width and depth of the back-bead) shows levels above 87 percent. Thus, the welding process parameters greatly affected the geometry of the back-bead, and accurate prediction of the back-bead can be performed to a limited degree through the model. As the error rate was below the maximum of 9 percent, the regression model is considered to be very accurate. Of the three results, the groove gap was the most difficult to predict, as it had the lowest adjusted coefficient, and the error rates of the analysis level and verification level were high in comparison to other parameters. For application in general welding, a prediction system for the welding process parameter to obtain the geometry for the back-bead using the regression equation was considered, as the three mean error rates had an accuracy level of over 90 percent in the analysis level and the verification level.

3.2 *Inverse transformation to obtain a desired back-bead geometry from welding process parameters*

In the previous section, back-bead geometry was estimated with the welding parameters in the butt welding process. In this section, a welding process parameters prediction will be investigated in order to obtain the desired bead geometry under various welding conditions in CO_2 welding. Equations (1), (2) and (3) can be expressed as a single equation, as follows:

$$\mathbf{S} = \mathbf{T}_M \mathbf{P} \quad (4)$$

Where S is the bead shape vector, $\mathbf{T}_M$ is the transformation matrix and $\mathbf{P}$ is the welding parametric vector:

$$S = \begin{bmatrix} \mathrm{GAP} & -0.849 \\ \mathrm{WIDTH} & -1.334 \\ \mathrm{DEPTH} & -0.458 \end{bmatrix}$$

$$T_M = \begin{bmatrix} 0.617 & 0.622 & -0.745 \\ 5.039 & 5.981 & -6.671 \\ 3.036 & 2.697 & -3.246 \end{bmatrix}$$

$$P = \begin{bmatrix} \mathrm{CURRENT} \\ \mathrm{VOLTAGE} \\ \mathrm{SPEED} \end{bmatrix} \quad (5)$$

In order to obtain the welding parameters for the desired bead geometry, an inverse transformation should be performed on equation (4), in order to induce a regression model equation to be used in the prediction system for welding process parameters. This can be expressed in one equation as follows:

$$P = T_M^{-1} S \quad (6)$$

Also, the process parameter prediction model equation obtained from equation (6) can be expressed in the following matrix from:

$$P = \begin{bmatrix} \text{CURRENT} \\ \text{VOLTAGE} \\ \text{SPEED} \end{bmatrix} = \begin{bmatrix} -13.9708 & 0.0957 & 3.0098 \\ -38.2656 & 2.5438 & 3.5545 \\ -44.8607 & 2.2031 & 5.4603 \end{bmatrix} \times \begin{bmatrix} \text{GAP} & -0.849 \\ \text{WIDTH} & -1.334 \\ \text{DEPTH} & -0.458 \end{bmatrix} \quad (7)$$

From equation (7), the equations for the welding current, arc voltage and welding speed, which are used for the welding parameters, can be derived, and are expressed as follows:

$$\text{CURRENT} = 10.3551 + (-13.9708 \times \text{GAP}) + (0.0957 \times \text{WIDTH}) + (3.0098 \times \text{DEPTH}) \quad (8)$$

$$\text{VOLTAGE} = 27.4661 + (-38.2656 \times \text{GAP}) + (2.5438 \times \text{WIDTH}) + (3.5545 \times \text{DEPTH}) \quad (9)$$

$$\text{SPEED} = 32.6470 + (-44.8607 \times \text{GAP}) + (2.2031 \times \text{WIDTH}) + (5.4603 \times \text{DEPTH}) \quad (10)$$

In order to evaluate and estimate the reliability of the developed algorithm, the multiple regression model equations to which inverse transformation has been applied were analysed using the five conditions of data for the verification level and the five conditions of data for the analysis level that were used in the previous section. Also, the data for the verification level and the data for the analysis level were compared by the normalized measured values and multiple regression analysis values. Comparison plotting diagrams of the normalized welding current, normalized arc voltage and normalized welding speed are shown in Figs 7, 8 and 9. The error rate for the verification level and the error rate for the analysis level are shown in Table 5. It is possible to predict the process parameters in order to obtain the desired bead geometry from the results of Table 5. This is because the error rate of prediction was below 6.5 percent. The analysis result shows that the normalized welding speed had the highest error rate of prediction, followed by the normalized arc voltage and normalized welding current. As a result, the welding speed was considered the most difficult parameter to predict in making a welding process parameter system.

The objective of this study is to obtain an equation for the welding process parameter prediction regression model in order to obtain the desired back-bead geometry in butt GMAW< which has a random groove gap, and the width and depth of the back-bead obtained through the vision sensor. Thus, the correlation between the parameters of the back-bead and the welding process parameters of the back-bead and the welding process parameters obtained through the statistical multiple regression analysis is analysed and regression equations of welding process parameters are made through inverse transformation.

IV. Conclusion

In gas metal arc welding where a gap exists, regression model questions of welding parameters which were thought to produce the desired geometry of the back-bead can be obtained. Both sides of the process regression model equation of the geometry parameters of the back-bead and welding process parameters are found and, after analysis, the following results are obtained:

1. Whereas the correlation between parameters for the bead shape and welding process parameter has until now been applied generally to bead-on-plate welding, this study extends the range of the research to the geometry prediction of the back-bead in butt welding where a gap exists.
2. In order to obtain the geometry of the back-bead using the welding process parameters, the multiple regression analysis is modelled into a linear equation. The error rate of analysis had a maximum value of 9.5 percent. Also, the groove gap had the largest error rate for prediction, followed by the depth of the back-bead and the width of the back-bead. Thus, the groove gap was thought to be the most difficult parameter to predict.
3. The multiple regression analysis of the welding process parameters which were though to produce the desired back-bead was modeled into a linear equation and the error rate of analysis was under 6.5 percent. Also, the normalized welding speed had the largest error rate for prediction, followed by the normalized arc voltage and the normalized welding current. In this case, the welding speed was thought to be the most difficult parameter to predict.

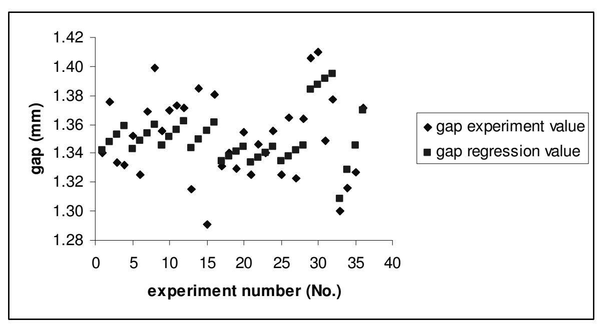

Fig 4: Gap comparison of measured values and multiple regression analysis values

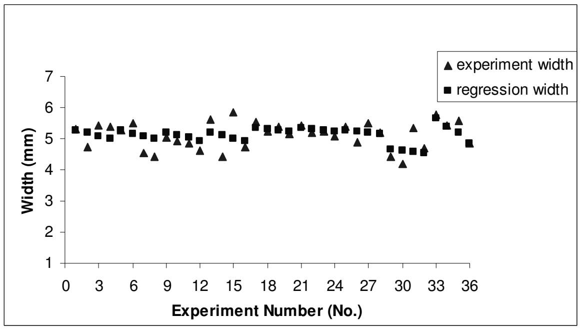

Fig.5: Width Comparison of experimental values and regression values

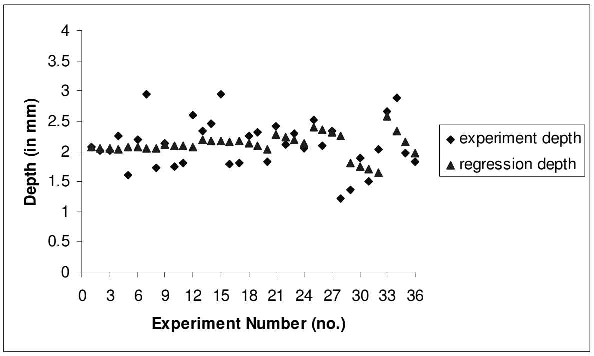

Fig.6: Depth Comparison of experiment values and regression values

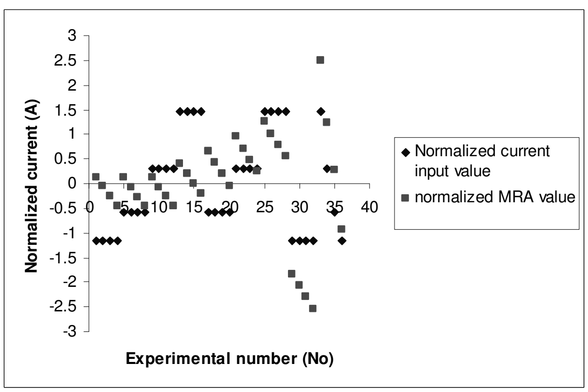

Fig 7: Comparison of Normalized current between normalized input values and normalized MRA values

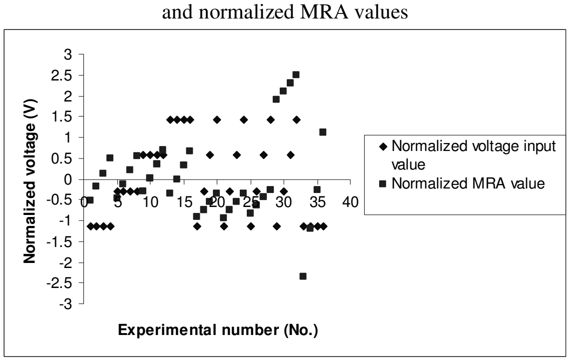

Fig 8: Comparison of Normalized voltage between normalized input values and normalized MRA

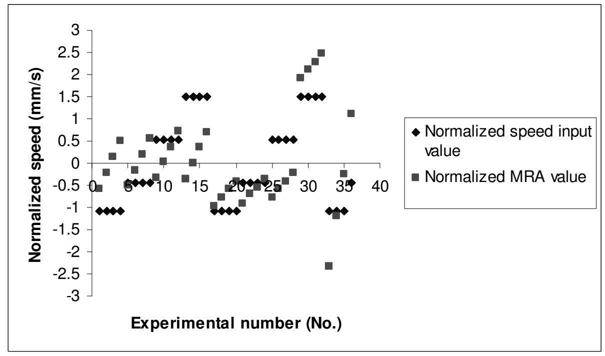

Fig 9: Comparison of Normalized speed between normalized input values and normalized MRA values

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Table 2: Correlation Coefficient between Welding Parameters and Shape Parameters of the Back-Bead

	Current	**Voltage**	**Speed**	**Gap**	**Width**	**Depth**
Current	1					
Voltage	-0.037	1				
Speed	0.018	0.014	1			
Gap	0.836	0.783	-0.890	1		
Width	0.812	0.765	-0.932	0.879	1	
Depth	0.858	0.751	-0.887	0.876	0.880	1

Table 3: Model summary and prediction errors

Dependent parameters	Model Summary	Prediction errors
Groove Gap	Adjusted R^2 Standard error of the estimate Error rate of data for the verification level (%) Error rate of data for the analysis level (%)	0.873 0.1622 8.92 6.53
Width of back-bead	Adjusted R^2 Standard error of the estimate Error rate for analysis or training (%) Error rate for verification or test (%)	0.913 0.1306 2.44 2.94
Depth of back-bead	Adjusted R^2 Standard error of the estimate Error rate for analysis or training (%) Error rate for verification or test (%)	0.984 0.1517 3.48 3.68

Table 4: Significance level of regression model coefficient

	Constant	**Current**	**Voltage**	**Speed**
p-value of gap	0.021	0.043	0.004	0.012
p-value of width	0.013	0.011	0.032	0.003
p-value of depth	0.019	0.009	0.023	0.017

Table 5: Dependent parameter and prediction errors

Dependent parameters	**Analysis error**	**Prediction errors**
Normalized welding current	Error rate for the verification level Error rate for the analysis level	4.56 2.84
Normalized arc voltage	Error rate for the verification level Error rate for the analysis level	5.38 3.66
Normalized welding speed	Error rate for the verification level Error rate for analysis level	6.35 4.67