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로봇 아아크 용접에서 비드 형상에 공정변수들을 예측하기 위한 새로운 알고리즘

(A New Algorithm for Predicting Process Variables on Welding Bead Geometry for Robotic Arc Welding)

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ABSTRACT

With the trend towards welding automation and robotization, mathematical models for studying the influence of various parameters on the weld bead geometry in Gas Metal Arc (GMA) welding process are required. The results of bead-on-plate welds deposited using the GMA welding process has enabled mathematical relationships to be developed that model the weld bead geometry. Experimental results were compared to outputs obtained using existing formulae that correlate process input variables to output parameters and subsequent modelling was performed in order to better predict the output of the GMA welding process. The aim of this work was to explain the relationships between GMA welding variables and weld bead geometry and thus, be able to predict input welding conditions calculated from required weld bead size. The relationships can be usefully employed for open loop process control and also for adaptive control provided that dynamic sensing of process output is performed.

1. INTRODUCTION

GMA welding involves large number of interdependent variables that can affect product quality, productivity and cost effectiveness. The relationships between GMA welding variables and weld bead geometry is complex because of the number of parameters and their interrelationships involved. Variables such as capacity and type of equipment and material composition are considered to be fixed, while primary adjustable variables such as welding voltage, arc current and welding speed can be altered during GMA welding process. Many attempts have been made to predict and understand the effect of the arc welding variables on the weld bead geometry. These include the entirely theoretical studies based on heat flow theory[1-6] and the empirical methods based on studies of actual welding applications[7-15]. An early approach to procedure optimisation called, "tolerance box approach", was developed to optimise welding procedure selection[8-9]. Welding variables were optimised using the tolerance to process variations and production rate, but this approach is difficult to implement in process control situations when dealing with more than three process input variables.

The above mentioned work has been summarized by Shinoda and Doherty[10]. McGlone[11], and McGlone and Chadwick[12] have reported a mathematical analysis correlating arc welding variables and weld bead geometry for the submerged-arc welding of square edge close butts. Process variables in these studies included welding current, arc voltage, welding speed, bevel angle and electrode diameter. Similar mathematical relationships between arc welding variables and fillet weld geometry for GMA welding using flux-cored wires have also been reported[13].

Chandel[14] extended his study of GMA welding process modelling to include the effects of electrode polarity and its effect on the weld joint penetration, melting rate and bead size. Yang, et al.[15] further extended this study to the weld deposit area and presented the effects of electrode polarity, extension and diameter, and welding current, arc voltage, travel speed, power source setting and flux basicity on the weld deposited area.

To make effective use of automated and robotic arc welding, it is imperative that mathematical models are developed which can be programmed easily and fed to the robot controller having a high degree of confidence in predicting the weld bead geometry and shape relations to accomplish the desired mechanical properties of the weldment. They should also cover a wide range of material thicknesses and be applied for all position welding. For the automatic, open loop control, welding system to use this data, the data must be available in the form of mathematical equations. It was in the light of these concluding remarks and suggestions for further developments outlined by previous researchers that the work in this paper was undertaken.

The objectives were to model weld bead geometry, to compare the experimental results to outputs obtained using the sets of the existing formulae in the literature relating input variables to output parameters, remodel the mathematical equations to better predict the output of the GMA welding process and develop a mathematical model explaining the relationship between GMA welding variables and weld bead geometry of bead-on-plate welds.

2. EXPERIMENT PROCEDURES

The 3^n experimental factorial design provided the smallest number of treatment combinations where n factors were studied in a complete factorial arrangement, and not only the main effect of each factor, but also the interactions between these factors[16]. In this study, results were used only for fitting the response curve. The chosen factors are wire diameter (D), welding voltage (V), arc current (I) and welding speed (S). The response is bead width (W), bead height (H) and penetration (P). The 2×3^3 factorial design provided the main effect and interaction effects of four variables at two or three levels. The factorial design required 54 weld runs for fitting each equation. The welding variables and limits are given in Table 1.

Table 1 Welding variables and limits

Variables	Units	Limits		
		Low	Middle	High
D	mm	1.2		1.6
V	Volt	20	25	30
S	cm/min	25	33	41
I	Ampere	180	260	360

The welding facility at the Control Lab. in Mokpo National University was chosen as the basis for the data collection and evaluation. The facility consists of a Gas Metal Arc welding unit which includes a welding power source, welder remote control unit and wire torch, and a six-axis robot manipulator that has a robot control unit and robot teach box. Torch positioning and motion control were obtained using the robot controller (M6060II). The selection of the welding electrode wire was based principally upon matching the mechanical properties and physical characteristics of the base metal, weld size, and existing electrode inventory.

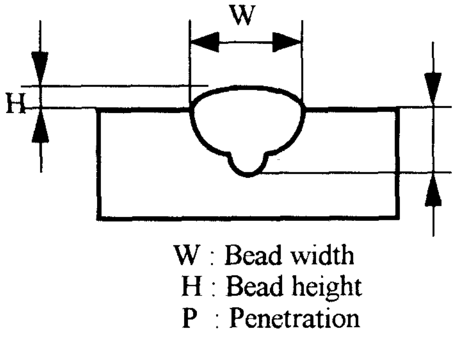

Figure 1 Weld bead geometry

Steel wires of 1.2 and 1.6 mm diameter with composition C 0.07-0.15 %, Mn 1.00-1.50 %, Si

0.60-0.85 %, S 0.035 % max, P 0.025 % max and Cu 0.5 % max, were used. To achieve equilibrium during GMA welding process, two samples were taken for observation after discarding 50 mm on each side to eliminate the end effects. Welding was carried out on experimental plates of $200 \times 75 \times 6mm$ mild steel flats adopting the bead-on-plate technique. Experimental test plates were located in the fixture jig by the robot controller and the required input weld conditions were fed for the particular weld steps in the robot path. With welder and argon shield gas turned on, the robot was initialised and welding was executed. This procedure was followed until the factorial experimental design runs were completed. After 54 welds, the plates were cut using a power hacksaw and the end faces were machined. Specimen end faces were polished and etched using a 2.5% nital solution to reveal grain boundaries and display the depth of penetration. A profile projector with the image magnification of 10 and 20 times was used to accurately measure the weld bead geometry. The results of the experiment were analysed on the basis of the relationships between input variables and output parameters of GMA welding process. Figure 1 defines the weld bead geometry studied.

3. ANALYSIS OF RESULTS

Comparison with Previous Models

The empirical equations reported by Chandel for the GMA welding process[14] were used to predict weld bead geometry characteristics. The process input conditions used to produce the 54 weld runs for fitting each equation were input into the Chandel's equations to provide theoretical results for bead height, bead width and penetration accordingly. This allowed the accuracy of Chandel's equations to be validated using experimental findings extracted during the course of this study.

Results were plotted using a scatter graph for each weld bead width, height and penetration. Three graphs (Figures 2 to 4) were produced for experimental vs theoretical results using Chandel's equations. The line of best fit for the plotted points was drawn using regression computations.

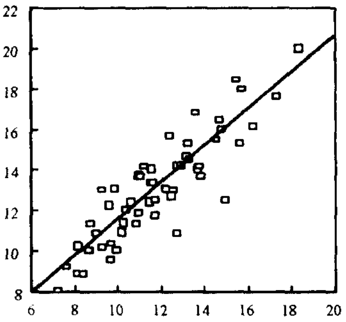

Figure 2 Weld bead model analysis graph for bead width

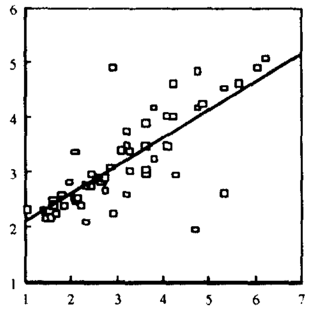

Figure 3 Weld bead model analysis graph for bead height

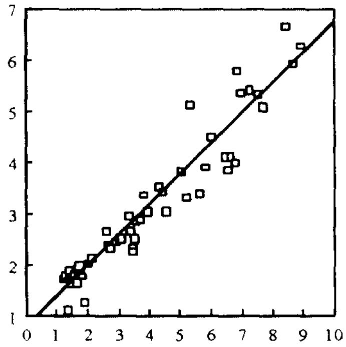

Figure 4 Weld bead model analysis graph for penetration

It is evident from these results that the model's accuracy is questionable and its universal applicability is limited. However, when these values were plotted as data points in a scatter graph, a definite correlation appeared. This means that the mathematical equations required remodelling to suit the GMA welding process with argon shield gas and the wire material type and diameter used. The rationale to remodel the mathematical equations centres on the fact that the equations suggested by Doherty and McGlone[9] and The Welding Institute[11] can be adjusted to suit a particular welding process. They can take the same form as the general straight line relationship. From the straight lines plotted using the original equations, the slope "K0" and the Y intercepts "K1" of these lines were measured and then fed into the original equations. The new equations, when plotted, produced straight lines which intersected the origin and lied at 45 degrees. Most important, the equations are capable of predicting experimental results with an improved accuracy. Using the general equation for a straight line, the modified Chandel's equations were obtained as follows;

$$W = (D^{0.567}\ L^{0.0106}\ I^{0.181}\ V^{0.86}\ S^{-0.614}) \times 0.5707 + 1.8946 \qquad (1)$$

$$H = (D^{-1.36}\ L^{0.38}\ I^{1.2}\ V^{-0.69}\ S^{-0.45}) \times 0.02127 + 1.5926 \qquad (2)$$

$$P = (D^{-0.86}\ L^{-0.063}\ I^{2.05}\ V^{-0.142}\ S^{-0.53}) \times 0.00005542 + 0.75715 \qquad (3)$$

To evaluate the accuracy of the new equations and observe the spread of the values, the results were again plotted using the scatter graph.

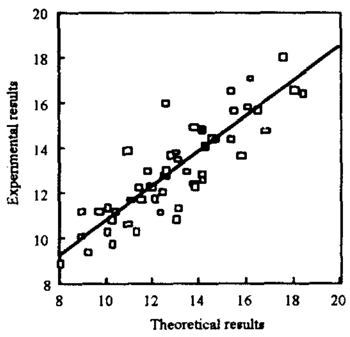

Figure 5 Weld bead model analysis graph for bead width

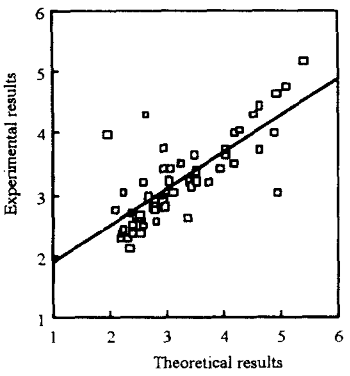

Figure 6 Weld bead model analysis graph for bead height

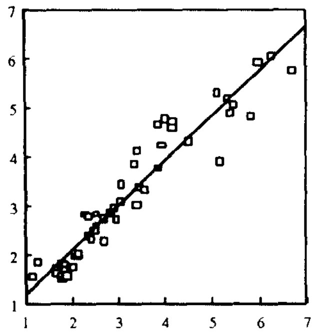

Figure 7 Weld bead model analysis graph for penetration

These graphsof experimental vs theoretical values of weld bead geometry are presented in Figures 5 to 7. As seen in Figures 6 and 7, the bead hight and penetration predictions of Chandel's modified equations produced data points which are located in a close proximity to the line of best fit. The results for bead width depicted in Figure 5, however, exhibited a degree of scatter believed to be due to the permissible amount of fluctuation in the wire travel speed and arc current recorded during the GMA welding process.

Development of Adjusted Mathematical Models

In order to quantitatively evaluate the effect of process variables on the weld bead geometry, the following adjusted mathematical relationships between process variables and weld bead geometry have been developed. In general, the response function can be represented as follows;

$$Y = f(D, V, I, S) \tag{4}$$

Assuming a linear relationship for the narrow range and considering all the main effects together with the two factor interactions, the above equation suggested by McGlone and Chadwick[12] can be expressed as follows;

$$y = a\,(D)^{b}\,(V)^{c}\,(I)^{d}\,(S)^{\epsilon} \tag{5}$$

where a, b, c, a and ϵ are constants.

The values of a, b, c, a and ϵ were computed by the method of regression[16-18]. The following equations correlating experimental welding process input parameters and weld bead geometry were obtained from the data;

$$W = (\,D^{0.4294}\ V^{0.7083}\ I^{0.3518}\ S^{-0.4590}\ 10^{-0.0905}) \tag{6}$$

$$H = (\,D^{-0.1255}\ V^{-0.7183}\ I^{0.6387}\ S^{-0.2395}\ 10^{0.3339}) \tag{7}$$

$$P = (\,D^{-0.5668}\ V^{0.0130}\ I^{1.4005}\ S^{-0.3641}\ 10^{-2.3098}) \tag{8}$$

The adequacy of the models and the significance of coefficients were tested by applying the analysis of variance technique and student's test 't' respectively.

Table 2 Analysis of variance tests for model

Model no.	SEE	R	100R^2
Width(W)	0.85437	0.9398	0.9259
Height(H)	0.73431	0.9037	0.8960
Penetration(P)	0.67543	0.9056	0.8979

Table 2 shows the standard error of estimates (SEE), coefficients of multiple correlations (R), and coefficients of determination (R^2) for the above mentioned models, respectively. The mathematical models that determine a given weld bead geometry and provide useful guidelines for systems which control weld bead geometry, automatically over a limited range of welding conditions, were used to calculate the results of regression analysis and to compare the experimental results measured with theset of existing empirical findings reported by Chandel, the set of modified empirical equations and finally the sets of theoretical formula. To ensure the accuracy of the new equations and survey the spread of the values, results were again plotted using the scatter graph.

These graphs of experimental vs theoretical values of weld bead dimension are presented in Figures 8 to 10 for bead width, bead height and penetration respectively.

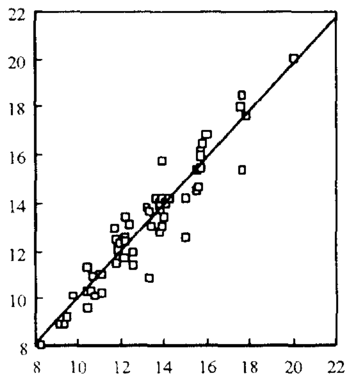

Figure 8 Weld bead model analysis graph for bead width

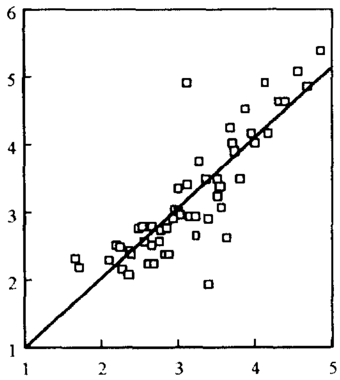

Figure 9 Weld Bead model analysis graph for bead height

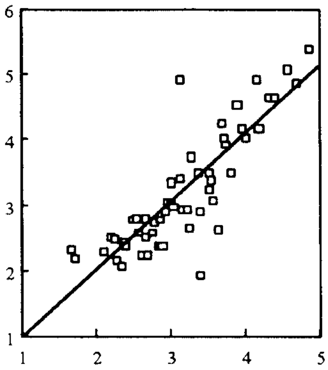

Figure 10 Weld bead model analysis graph for penetration

During analysis of the results, it was observed that the mathematical models yielded more accurate weld bead geometry and provided better predictions of the dimensions such as bead width, bead height and penetration.

4. CONCLUSIONS

The effect of welding process input parameters on weld bead geometry when bead-on-plate welds are deposited using GMA welding process has been studied and the following conclusions reached.

1. The universality of results obtained after using empirical equations taken from existing models developed by Chandel proved to be limited in predicting experimental bead shapes for the GMA welding process. After the equations were adjustedand the process was remodelled, the accuracy of weld bead dimension substantially improved.
2. Results from redefining the mathematical models should be put into perspective with equipment, consumables and test plates employed to conduct the experimental work.
3. Mathematical models developed from the observed data in thachieve desired weld bead geometry outcomes and indeed weld quality.

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