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Control of welding process for BV-AH 32 steel

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ABSTRACT

Purpose: The GMA welding process involves large number of interdependent variables, which may affect product quality, productivity and cost effectiveness. With the combination of sensors and mathematical models, increased effectiveness in control of the automatic welding process was achieved. In this study, it focuses on development of mathematical models for the selection of process parameters using BV-AH32 steel for shipbuilding industry.

Design/methodology/approach: The base material used for this study was the BV-AH32 steel with 12 mm in thickness for multi-pass butt welding. A curvilinear regression analysis was performed with the predictors that were found to be statistically significant against bead geometry based on the results from the above factorial design. The adequacy of the models and the significance of coefficients were tested by applying the analysis of variance technique and T-test respectively.

Findings: From the above resultant equation for estimation of bead geometry, the sensitivity equations are obtained by differentiation with respect to process parameters of interest such as arc current, welding voltage and welding speed that are explored.

Practical implications: Sensitivity analysis has been investigated to represent the effectiveness of the processing parameters on these empirical equations and showed that the change of process parameters affects the bead width and bead height more strongly than penetration relatively.

Originality/value: These models are extended to shielding gas composition, weld joint position, polarity and many other parameters which are not included in this research in order to establish a closed loop feedback control system to minimize possible errors from uncontrolled variations.

Keywords: Welding quality; Mathematical model; Sensitivity analysis; Weld bead geometry; Welding process control

MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

The GMA welding process involves large number of interdependent variables, which may affect product quality, productivity and cost effectiveness. Variables such as the capacity and type of equipment, material dimensions and composition may be relatively fixed, while primary adjustable variables that are characterized by welding voltage, arc current and welding speed may be altered during the welding process. A major process optimization should define a welding process, which can be shown to be the best with respect to some standard and chosen combination of process parameters, which give an acceptable balance between production rate, and the extent of defects for a given situation. Generally, bead geometry, including bead height, bead width and penetration depth is import information about a weldment. Also, the bead cross-sectional area together with its height and width influences the total shrinkage, which determines largely the residual stresses and thus distortion [1].

Automation without closed loop control processes the same components contained within the grey region of this figure, except that the manual welding equipment is replaced with automatic welding equipment. The operator must also utilize experience or modeling to select the necessary input parameters to achieve the desired output parameters. As a result of these short-comings, much research and development work have concentrated on sensing and control methods to enhance the automated arc welding.

With the combination of sensors and mathematical models, increased effectiveness in control of the automatic welding process was achieved. Through-the-arc sensing has been applied from width control and seam tracking [2], to sensing of the GTA welding weld pool motion [3] and detection of the GMA welding metal transfer models [4]. Vision sensing has been utilized for joint tracking [5], weld bead profile sensing and control of electrode extension [6]. Other forms of sensing include infrared that has been used in the estimation of penetration [7] as well as seam tracking [8], and ultrasonic sensing which has been applied to weld bead monitoring and inspection [9].

Sensitivity analysis, a method to identify critical parameters and rank them by their order of importance, is paramount in model validation where attempts are made to compare the calculated output to the measured data. This type of analysis can study which parameters must be most accurately measured, thus determining the input parameters exerting the most influence upon model outputs. It differs considerably from the usual approach of perturbing a process parameter of a known amount and evaluating the new results.

2. Experimental work

This paper focuses on development of mathematical models for the selection of process parameters and the prediction of bead geometry (top-bead width, top-bead height, back-bead width and back-bead height) in robotic GMA welding. A sensitivity analysis has been conducted and compared the relative impact of three process parameters on bead geometry in order to verify the measurement errors on the values of the uncertainty in estimated parameters.

A number of problems related to the robotic GMA welding process include the modelling, sensing and control of the process. Statistically designed experiments that are based upon factorial techniques, reduce costs and provide the required information about the main and interaction effects on the response factors. Experiments were designed for developing a new mathematical model to correlate independently controllable process parameters. The process parameters included in this study were three levels of pass number (2, 3 and 4), three levels of welding current (170, 220 and 270 A), three levels of arc voltage (23, 26 and 28 V) and 12 to 50 cm/min of welding speed that depends on weld quality. All other parameters except these parameters under consideration were fixed. The welding facility was chosen as the basis for the data collection and evaluation.

The base material used for this study was the BV-AH32 steel with 12 mm in thickness for multi-pass butt welding. This plate was cut into 300×200mm pieces, and both surfaces were sand blasted to remove dirt and oxides. GMA/CO_2 welding system and an automatic travelling unit were combined to make an automatic process system. The shielding gas composition was Ar 80%+CO_2 20%. Experimental test plates were located in the fixture jig by the robot and the required weld conditions were fed for the particular weld steps in the robot path. With power supply and argon shield gas turned on, the robot was initialised and welding was executed.

This process continued until experimental runs were completed. To measure bead geometry, the transverse sections of each weld were cut using a power hacksaw from the mid-length position of welds, and the end faces were machined. Specimen end faces were polished and etched using a 2.5% nital solution to display top-bead width. The schematic diagrams of top-bead width employed were made using a metallurgical microscope interfaced with an image analysis system. Images are represented by a 256 level gray scale to identify top-bead width. The fractional factorial matrix was assumed to link the mean values of the measured results with changes in the four process parameters for determining top-bead width. The experimental results were analyzed on the basis of relationships between process parameters and top-bead width in robotic GMA welding process.

3. Results and discussion

3.1. Development of empirical models

Based on the results from the above factorial design, a curvilinear regression analysis was performed with the predictors that were found to be statistically significant against bead geometry. The commercial statistical package SAS [7] was utilized for all the multiple regression analyses in this research. The procedure employed for obtaining the predictive equation for bead geometry is shown below for the equation;

Top-bead width:

$$W_T = 10^{2.906} V^{-2.180} S_2^{1.275} S_3^{-0.233} \tag{1}$$

Top-bead height:

$$H_T = 10^{17.365} V^{-16.928} S_2^{6.798} S_3^{-2.271} \tag{2}$$

Back-bead width:

$$W_B = 10^{-4.864} C^{-4.276} V^{11.517} S_1^{-0.583} \tag{3}$$

Back-bead height:

$$H_B = 10^{-7.140} C^{1.146} V^{5.170} S_1^{-2.14} \tag{4}$$

The adequacy of the models and the significance of coefficients were tested by applying the analysis of variance technique and student's (T) test respectively. Table 1 shows the standard error of estimates (SEE), coefficients of multiple correlations (R), and coefficients of determination ($100R^2$) for the above models respectively. It is evident that all models were adequate.

Table 1.
Analysis of variance tests for mathematical models for bead geometry

Bead geometry	Std. error of estimate	Coefficient of multiple relation	Coefficient of determination (%)
Top-bead width	0.96	0.918	86.8
Top-bead height	0.22	0.974	94.9
Back-bead width	0.12	0.981	96.2
Back-bead height	0.052	0.863	74.5

3.2. Sensitivity analysis of empirical equation for bead geometry

From the above resultant equation for estimation of bead geometry, the sensitivity equations are obtained by differentiation with respect to process parameters of interest such as arc current, welding voltage and welding speed that are explored here. Table 2 and Fig. 1 show the sensitivity of bead geometry (top-bead width, top-bead height, back-bead width and back-bead height) for various welding conditions. The bead width and bead height are more sensitive in low arc current region but sensitivity of the penetration increases high arc current region. The sensitivities of welding voltage on bead geometry are represented in Fig. 2. These results reveal that the top-bead height and back-bead width are more sensitive than the others. It means that the varying of welding voltage causes small change of penetration and large changes of bead height and bead width. Figs. 3-4 are the results of sensitivity analysis of welding speed and welding current on bead geometry. Generally, the sensitivity values of bead width are higher than bead height and penetration. It means that the welding speed affects the bead width more strongly than bead height and penetration. Fig. 3 shows the sensitivities of bead shape parameters (back-bead width, back-bead height) for process parameters, which are arc current, welding voltage and welding speed. The sensitivities of welding voltage on bead width are positive value, but sensitivities of welding voltage on bead height are negative value. Since the sensitivity of welding voltage on bead width and bead height is higher greatly than those of arc current and welding speed, the change of welding voltage is more useful in control of bead width and bead height. The penetration is less sensitive than other bead shape parameters (bead width and bead height). It appears that the change of process parameters affects the bead width and bead height more strongly than penetration relatively. The sensitivities of welding current on bead geometry are represented in Fig. 4.

Table 2.
Sensitivities of curvilinear equations at average welding conditions

Sensitive of	S1	S2	S3	C	V
W_T		0.991	-0.194		-1.988
H_T		0.352	-0.126		-1.029
W_B	-0.068			-0.069	1.574
H_B	-0.034			0.003	0.096

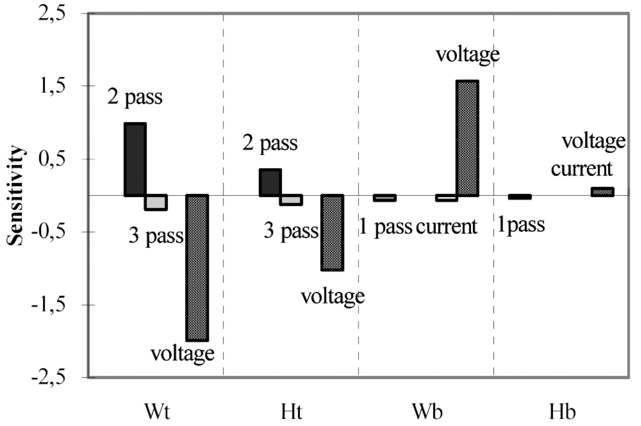

Fig. 1. Bead-geometry sensitivities of process parameters for curvilinear equations

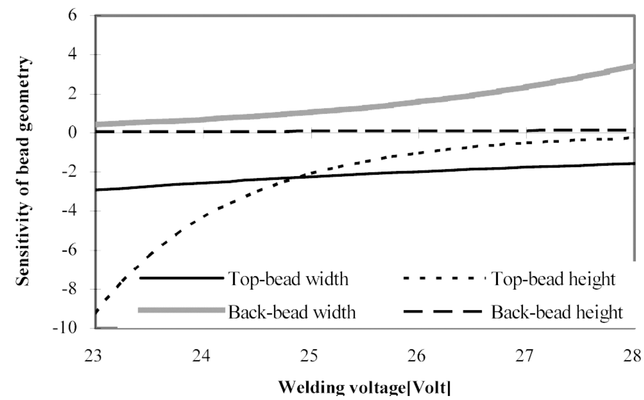

Fig. 2. Sensitivities of bead geometry on welding voltage

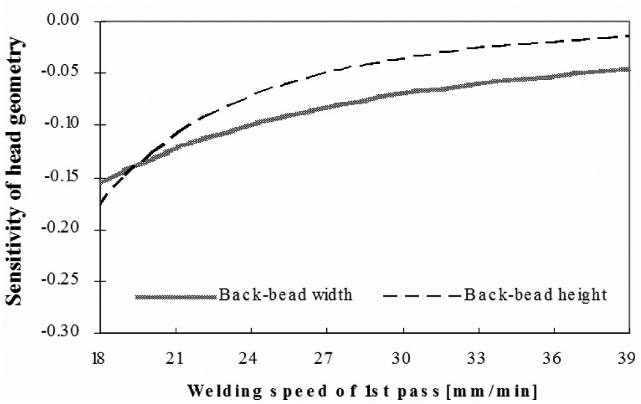

Fig. 3. Sensitivities of bead geometry on 1^{st} welding speed

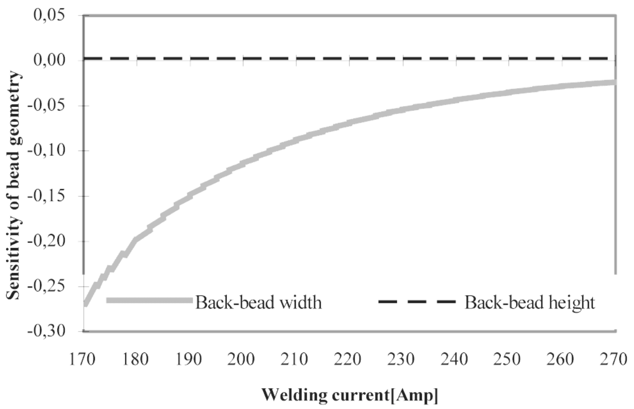

Fig. 4. Sensitivities of bead geometry on welding current

4. Conclusions

In this study, the effects of the process parameters for GMA welding with bead geometry using sensitivity analysis have been reported. The optimal bead geometry is top-bead width, top-bead height, back-bead width and back-bead height. Curvilinear empirical models developed from experimental results can be used to investigate the relationship between process parameters and bead geometry and to predict the bead dimensions (top-bead width, top-bear height, back-bead width and back-bead height) with reasonable accuracy. The comparison of coefficient of multiple correlations curvilinear, regression equations correlating process parameters to bead dimensions for GMA welding process make no difference, which indicates that all equations are reasonably suitable. Sensitivity analysis has been investigated to represent the effectiveness of the processing parameters on these empirical equations and showed that the change of process parameters affects the bead width and bead height more strongly than penetration relatively.

The empirical models based on experimental results are valid for current process parameters and bead geometry. It is proposed that the these models are extended to shielding gas composition, weld joint position, polarity and many other parameters which are not included in this research in order to establish a closed loop feedback control system to minimize possible errors from uncontrolled variations.

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