Effects of MIG process parameters on the geometry and dilution of the bead in the automatic surfacing

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Abstract

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Automatic weld surfacing is being employed increasingly in the process, mining and power industries. Gas metal arc welding has become a natural choice for automatic surfacing due to its important properties. These include: high reliability, all positions capabilities, ease of use, low cost and high productivity. With increasing use of gas metal arc welding in its automatic mode, the use of mathematical models to predict the dimensions of the weld bead has become necessary. The development of such mathematical equations using a four factor central factorial technique to predict the geometry of the weld bead in the deposition of OK Tubrodur 15.43 electrode onto structural steel S235JR is discussed. The models developed have been checked for their adequacy and significance by using the *F* test and the Student's *t* test, respectively.

Keywords: gas metal arc welding; weld bead; dilution; response surface methodology

Weld surfacing techniques are employed mainly to extend or improve the service life of engineering components and to reduce their cost either by rebuilding repeatedly or by fabricating in such a way as to produce a well defined composite material as in screw line presser. Other desired properties often obtained include corrosion resistance; wear resistance, etc. (Chotěborský et al. 2008).

The experimental optimization of any welding process is often a very costly and time consuming task due to many kinds of nonlinear events involved. One of the most widely used methods to solve this problem is the Response Surface Methodology (RSM), in which the experimenter tries to approximate the unknown mechanism with an appropriate empirical model and the function representing this method is called a Response Surface Model. Identifying and fitting a good Response Surface Model from experimental data requires some knowledge of statistical experimental design, bases of regression modeling techniques and elementary optimization methods (Thorpe 1980; Ellis, Garrett 1986; Murugan et al. 1993; DuPont, Marder 1996; Doumanidis, Kwak 2002; Kim 2003; Kim et al. 2003; Correia et al. 2005; Palani, Murugan 2007).

The goal of this article is to explore the RSM technique in the determination of gas metal arc welding (GMAW) process parameters, welding voltage (U), arc current (I) and welding speed (S). However, the search for mathematical models depends on process parameters and geometry of weld bead.

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MATERIALS AND METHODS

The activities planned for the research include the following:

- identifying the important process control variables,
- finding the upper and lower limits of the control variables,
- developing the design matrix,
- conducting the experiments according to the design matrix,
- recording the responses,
- developing the mathematical models,
- calculating the coefficients of the polynomials,
- checking the adequacy of the models developed,
- testing the significance of the regression coefficients and arriving at the final mathematical models,
- presenting the main effects and the significant interaction between different parameters in graphical form,
- analysis of results.

Identification of the process variables

The independently controllable process parameters were identified in order to carry out the experimental work and to develop the mathematical models, namely: the open-circuit voltage (U), the arc current (I) and the welding speed (S). The experiments were conducted by laying one bead of electrode positive without preheating and nozzle-to-plate measured distance of 18 mm. The responses were measured after cross-section of the overlay at its mid-point.

Finding the limits of the process variables

Trial runs were carried out by varying one of the process parameters whilst keeping the rest of them at constant values. The working range was selected by inspecting the bead for a smooth appearance and the absence of any visible defects such as surface porosity, undercut, etc. The upper limit factor was coded as +2 and the lower limit as –2 according to central composite rotatable factorial design. The coded values for the intermediate values were calculated from the relationship below (1):

$$X_i = \frac{2 \times \left[2 \times X - \left(X_{\max} - X_{\min}\right)\right]}{\left(X_{\max} - X_{\min}\right)} \qquad (1)$$

where:

X_i – required coded value of a variable X

X – any value of the variable from $X_{\min} - X_{\max}$

$X_{\min}$ – lower level of the variable

$X_{\max}$ – upper level of the variable

The selected levels of the process parameters for 1.6 mm diameter OK Tubrodur 15.43 tube wire, together with their units and notations, are given in Table 1.

Developing the design matrix

The selected design matrix, shown in Table 2, was a central composite rotatable factorial design consisting of 21 sets of coded conditions and comprising a full replication of 2^3 (8) factorial design plus seven centre points and six star points. All welding variables at the intermediate (0) level constitute the centre points whilst combination of each welding variables either at its lowest value (–2) or its highest value (+2) with the other three variables of the intermediate levels constitute the star points. Thus the 21 experimental runs allowed the estimation of linear, quadratic and linear-linear interactive effects of the welding variables on the geometry of the bead.

Conducting the experiment according to the design matrix

An automatic surfacing system, designed and fabricated in the ESAB (Mini 2A), was employed in the

Table 1. Control parameters and their levels

Parameter	Units	Notation	Factor levels				
			–2	–1	0	1	2
Open circuit voltage	volt	U	28	30	32	34	36
Arc current	ampere	I	180	200	225	250	270
Welding speed	cm/min	S	20	30	40	50	60

Table 2. Design matrix and the observed values of the bead dimensions

Specimen No.	Design matrix			Geometry of weld bead			
	U	I	S	penetration	height	width	dilution
1	30	200	30	1.28	1.82	10.95	25.1
2	30	200	50	1.11	1.33	9.05	27
3	30	250	30	1.37	2.21	11.85	29.5
4	30	250	50	1.59	1.72	9.82	30.6
5	34	200	30	1.19	1.65	11.86	25.6
6	34	200	50	1.28	1.24	9.65	28.7
7	34	250	30	1.5	1.89	12.63	30.2
8	34	250	50	1.62	1.6	10.48	32.1
9	28	225	40	1.38	1.86	9.88	25.1
10	36	225	40	1.21	1.41	11.49	27.5
11	32	180	40	0.98	1.4	9.91	26.1
12	32	270	40	1.62	2.1	11.19	34.6
13	32	225	20	1.47	2.3	13.8	26.4
14	32	225	60	1.66	1.35	9.15	35
15	32	225	40	1.11	1.65	9.25	29
16	32	225	40	1.13	1.61	9.22	28.9
17	32	225	40	1.09	1.64	9.22	28.7
18	32	225	40	1.1	1.68	9.18	29.2
19	32	225	40	1.12	1.6	9.26	29.1
20	32	225	40	1.1	1.61	9.23	29.2
21	32	225	40	1.1	1.65	9.18	28.7

conducting of the experiments. The experiments were conducted according to the design matrix at random to avoid the effects from systematic errors creeping into the system. OK Tubrodur 15.43 tube wire of 1.6 mm diameter (MOG type) was used in the deposition onto structural steel plate S235JR of 25 mm thickness. Keeping positive polarity and an electrode to work angle of 90° degrees, one bead of 150 mm length was deposited. Base material without preheating was used.

Recording of the responses

The plates were cross-sectioned at their mid points to obtain test specimen. These specimens were then prepared by usual metallurgical polishing (grinding and polishing) methods and etched with 4% Nital (4% solution of HNO_3 in the ethanol). The geometry of the weld beads (Fig. 1) were measured using optical microscopy. The observed values of w, h, p and D are given in Table 2, where D was calculated by Eq. (2):

$$D = \frac{Z}{G + Z} \times 100\% \qquad (2)$$

Development of mathematical models

The response function representing any of the weld bead dimensions was expressed as $Z = f(\text{U, I, S})$ and the relationship selected, representing a second-degree response (3) was also expressed as follows:

$$Y = b_0 + b_1\text{U} + b_2\text{I} + b_3\text{S} + b_{11}\text{U}^2 + b_{22}\text{I}^2 + b_{33}\text{S}^2 + b_{12}\text{UI} + b_{13}\text{US} + b_{23}\text{IS} \qquad (3)$$

Table 3. Calculation of variance for testing of the models

Bead geometry		p	h	w	D
Sum of squares	regression	0.8637	1.521	36.89	134.8
	residual	0.05202	0.0215	0.325	9.805
Degrees of freedom	regression	7	5	6	4
	residual	13	15	14	16
Mean square	regression	0.1234	0.3042	6.148	33.71
	residual	0.004	0.00144	0.0232	0.613
F-ratio		30.83	211.8	264.7	55
P		0.001<	0.001<	0.001<	0.001<
R^2 (%)		94.3	98.6	99.1	93.2
Adjusted R^2 (%)		91.3	98.1	98.7	91.5
Adequate		Yes	Yes	Yes	Yes

Evaluation of the coefficients of models

The values of the coefficients were calculated by regression with the help of STATISTICA software (StatSoft CR, s.r.o., Prague, Czech Republic). A computer programme was also developed to calculate the value of these coefficients for different responses which is presented in Table 2.

Checking the adequacy of the models developed

The adequacy of the models was tested using the analysis of variance. According to this technique, if the calculated value of the F ratio of the model developed does not exceed the standard tabulated value of F ratio for a desired level of confidence (95%) and the calculated value of the R ratio of the model developed exceed the standard tabulated value of R ratio for desired level of confidence (95%), then the model may be considered adequate within the confidence limit. The results obtained that are presented in Table 3 show that all of the models are adequate.

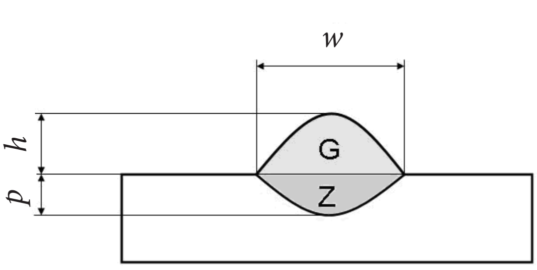

Fig. 1. Scheme of weld bead geometry

Testing the coefficients for significance

The value of the regression coefficients gives an idea as to what extent the control variables affect the responses quantitatively. The less significant coefficients can be eliminated along with the responses which they are associated with, without estimating much accuracy to avoid cumbersome mathematical labour. To achieve this, Student's t-test is used. According to this test when the calculated value of t corresponding to a coefficient exceeds the standard tabulated value for the desired level of probability (95%), the coefficient becomes significant. After determining the significant coefficients, the models were developed using only these coefficients.

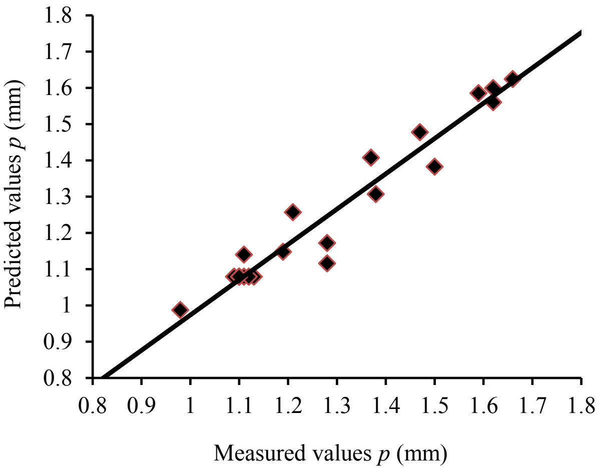

Fig. 2. Typical dependence of measured and predicted values of bead geometry (plot for penetration)

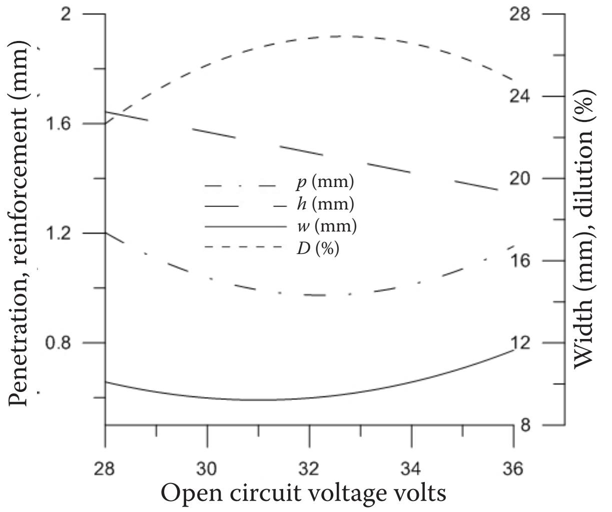

Fig. 3. Effect of open circuit voltage volts on bead geometry (I = 200 A, S = 40 cm/min)

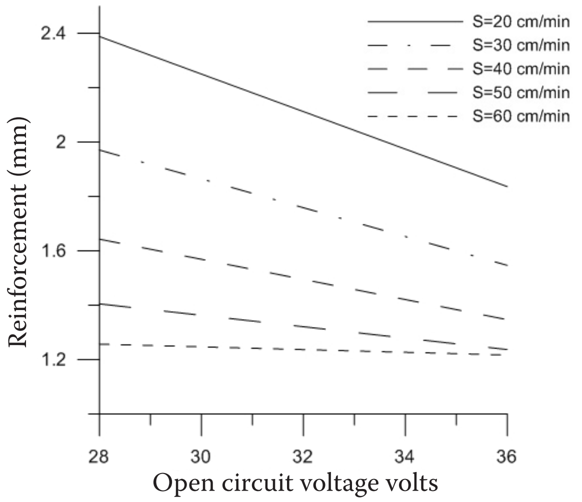

Fig. 6. Interaction effect of voltage and welding speed on reinforcement of bead (I = 200 A)

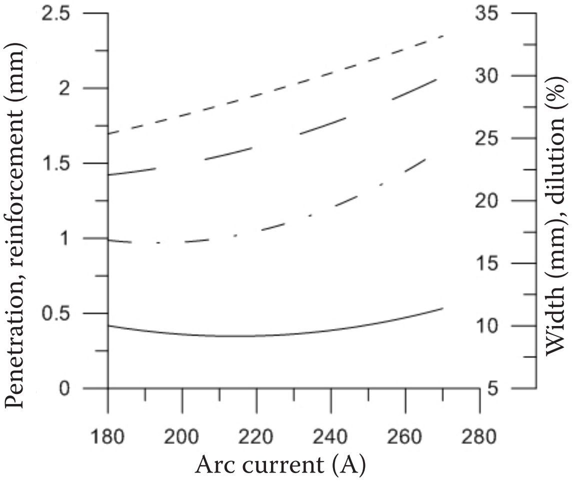

Fig. 4. Effect of arc current on bead geometry (U = 32 V, S = 40 cm/min)

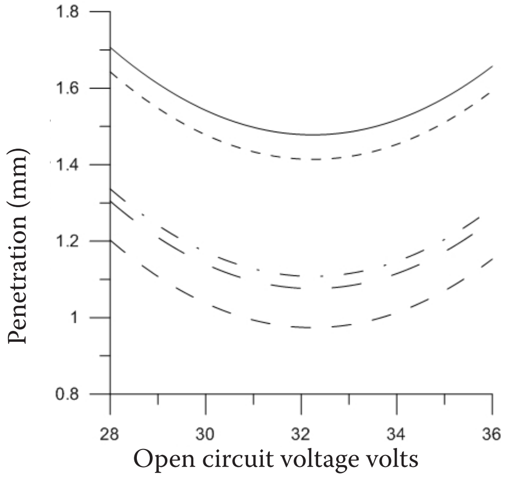

Fig. 7. Interaction effect of voltage and welding speed on penetration (I = 200 A)

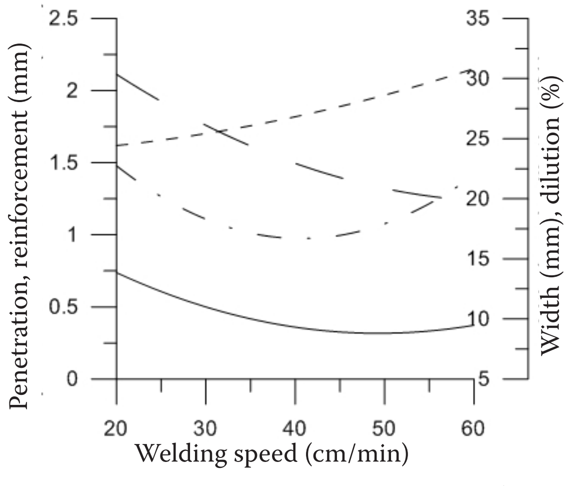

Fig. 5. Effect of welding speed on bead geometry (U = 32 V, I = 200 A)

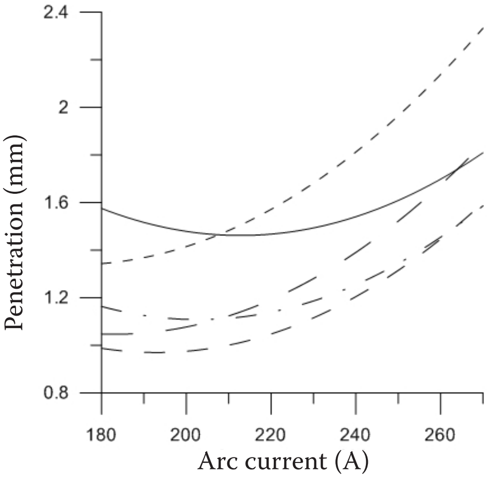

Fig. 8. Interaction effect of arc current and welding speed on penetration (U = 32 V)

Development of the final models

The final mathematical models as determined by the above analysis are shown below:

$$p = 21.75 - 0.819U + 0.0127U^2 - 0.0493I + 0.000106I^2 - 0.138S + 0.00118S^2 + 0.00021IS \quad (4)$$

$$h = 4.237 + 0.0000521I^2 - 0.109S + 0.000449S^2 - 0.000505UI + 0.0016US \quad (5)$$

$$w = 149.3 - 6.034U + 0.0973U^2 - 0.307I + 0.000716I^2 - 0.579S + 0.00587S^2 \quad (6)$$

$$D = -191.2 + 12.68U - 0.194U^2 + 0.000193I^2 + 0.002S^2 \quad (7)$$

Analysis of the results

The mathematical models given above can be employed to predict the geometry of the weld bead and the dilution for the range of parameters used in the investigation by substituting their respective values in the coded form. Based on these models, the main and the interaction effects of the process parameters on the bead geometry were computed and plotted. Also, by substituting the values of the desired bead geometry, the values of the control factors can be obtained.

RESULTS AND DISCUSSION

Typical dependency of the measured values of the geometry weld bead and predicted values using mathematical model is shown in Fig. 2.

The main and interaction effects of the different process parameters on the dimensions of the weld bead predicted from mathematical models are shown in Figs 3–8, showing the general trends between cause and effect.

Direct effect of parameters

From Fig. 3, the penetration (*p*) and width decreased gradually with increase in voltage (U) and reached a minimum value. Also the high value of weld bead (*h*) decreased with increase in U while the dilution (*D*) increased gradually with increase in voltage and reaches a maximum value. From Fig. 4, *D* and *h* increased in the arc current (I) but *w* and *p* decreased with I and reached min value and thereafter increased with I. From Fig. 5, *D* increased with welding speed (S) but *w* and *h* decreased with S and *p* increased with S and reached min value and thereafter increased with S.

Interaction effects of process parameters on the bead dimensions

From Fig. 6, the reinforcement of the weld bead decreased with open circuit voltage, but the value of reinforcement of the weld bead was influenced with arc current and welding speed. With increased welding speed, the reinforcement of the weld bead decreased slowly with increased open circuit voltage.

From Figs 7 and 8, it was also noticed that the penetration of the weld bead increased with arc current but the interaction with welding speed changed to local min.

CONCLUSIONS

The following conclusions were made from the study:

(1) A five-level factorial technique can be employed easily for developing mathematical models for predicting weld bead geometry within the optimal region of control parameters or operating variables for hardfacing.

(2) The models developed can be employed easily in automated or robotic hardfacing in the form of a program for obtaining weld bead of the desired high quality.

(3) Maximum dilution was between 32–33 V and increased with arc current and welding speed.

(4) For high productivity these must be height, width and reinforcement of the weld bead. Thus means that arc current must be high and open circuit voltage must be low.

List of selected symbols:

w – width of weld bead (mm)
h – reinforcement of weld bead (mm)
p – depth of penetration (mm)
D – dilution (%)
S – welding speed (cm/min)
U – welding voltage (V)
I – arc current (A)
RSM – Response Surface Methodology
GMAW – Gas Metal Arc Welding

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