EFFECT OF THE WELDING PARAMETERS ON THE HARDFACING ABRASIVE WEAR*

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One of possible ways of increasing service life is hardfacing. Hardfacing should be developed with different electrodes using required welding parameters in minimal and maximal limits. Welding parameters influence geometry of the weld bead, dilution, and mechanical properties of the reinforcement overlay. This article is focused on optimizing the welding parameters with the aim to provide longer service life. Service life is represented by weight loss and reinforcement of the hardfacing. The results show that the procedure using factorial experimental design and regression analysis for the mathematical development can be used for optimizing determination.

service life; optimizing, analysis of variance; weld deposit; volume loss

INTRODUCTION

Weld surfacing techniques are employed mainly to extend or improve the service life of engineering components and to reduce their cost either by repeated rebuilding or fabricating in order to produce a well defined composite material as in screw line presser, mining tools, and agriculture tools. Other desired and often acquired properties include corrosion resistance, wear resistance, etc. (Chotěborský et al., 2008). Some studies show that hardfacing is one of possible ways of increasing the service life of ploughshares (Horvat et al., 2008) or that it can be used for developing a bionic shape of agriculture tools (Chirende et al., 2010).

High chromium electrodes are often used for the hardfacing development. Their structure should be hypoeutectic, eutectic or hypereutectic after weld depositing. Abrasive wear resistance of the high chromium hardfacing deposits depends on the structure (Kazemipour et al., 2010), and it is usually limited (Chotěborský et al., 2011a). Hardfacing alloys with special carbides in the structure should be used if a higher wear resistance is required (Correa et al., 2007). In the soil conditions the abrasive wear rate is influenced by soil type and moisture content (Natsis et al., 2008) and it is also influenced by abrasive particles size (Chotěborský et al., 2009).

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 for optimizing the welding process is the Response Surface Methodology (RSM). This can be used to approximate the unknown parameters using appropriate empirical models and the function representing this method is called the Response Surface Model. Identifying and fitting a good Response Surface Model from experimental data requires knowledge on statistical experimental design, basic regression modelling 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; Chotěborský et al., 2011b).

The objective is to explore the application of 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, geometry, and wears resistance of hardfacing.

MATERIAL AND METHODS

The research included the following planned activities:

• identifying the important process control variables

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•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, determination of optimal parameters

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: open-circuit voltage (U), arc current (I), and welding speed (S). The experiments were conducted by laying a single of electrode positive without preheating and nozzle-to-plate measured distance of 18 mm. The experiments were conducted with positive involvement electrode in single wiring 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.

Developing the design matrix

The selected design matrix shown in Table 1 was a factorial design consisting of 13 sets of coded conditions and comprising a full replication of 2^3 (8) factorial design plus five centre points.

Conducting the experiment according to the design matrix

An automatic surfacing system Mini 2A, designed and fabricated by ESAB (Wamberk, Czech Republic) was employed. The experiments were conducted according to the design matrix at random to protect the effects from systematic errors creeping into the system. OK Tubrodur 15.82 tube wire of 1.6 mm diameter (MOG type) ((ESAB) was used in the deposition onto structural steel plate S235JR of 15 mm thickness. Positive polarity and electrode at an angle of 90° was set. Five to seven weld beads of 150 mm length were deposited (Fig. 1). Base material without preheating was used.

Specimens for the abrasive wear tests were cut off from the samples according to the modified dry rubber wheel test ASTM G65 (Fig. 2). Abrasive wear test (repeated five times per each sample) was carried out in a dry rubber wheel machine (Fig. 2) using 0.2–0.3 mm sand particles. The normal load was 30 N and wear distance was 250 m per a specimen. The rubber wheel was 130 mm in diameter and 10 mm wide. Before testing, all specimens were cleaned in ultrasonic bath and rinsed with warm air. The abrasive wear resistance was determined from the weight loss (WL) results measured with a 0.1 mg resolution.

Recording of the responses

The plates were cross-sectioned at their mid points to obtain the test specimens. These specimens were then prepared by usual metallurgical methods (grinding and polishing) and etched with 4% Nital (4% solution of HNO_3 in ethanol). The reinforcement (*h*) of the weld beads (Fig. 1) was measured using optical microscopy. The experiments were done in five replicates. The observed values of *h* and WL are given in Table 1.

Development of mathematical models

The factorial function representing any of the weld bead dimensions was expressed as $Z = f(U, I, S)$

and the relationship selected, representing a second-degree factorial Eq. (1), was expressed

$$Y = b_0 + b_1 \times U + b_2 \times I + b_3 \times S + b_{12} \times U \times I + b_{13} \times U \times S + b_{23} \times I \times S \quad (1)$$

where:
Y = response
$b_{0, 1, 2, 3}$ = regression coefficients
U = open-circuit voltage
I = arc current
S = welding speed

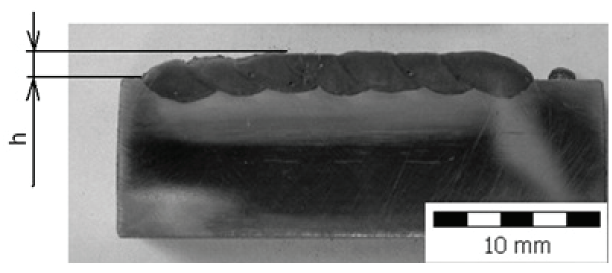

Fig. 1. Weld beads onto base material

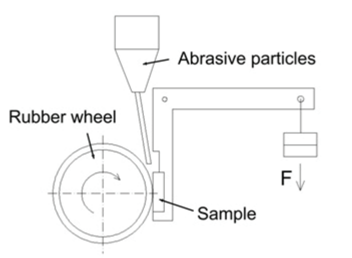

Fig. 2. Schema of the dry rubber wheel tester

Table 1. Experimental design matrix and observed responses

U (V)	I (A)	S ($mm.min^{-1}$)	Weight loss (mg)	Standard deviation (mg)	Reinforcement - h (mm)
26	180	300	24.5	1.35	2.44
26	180	500	16.77	1.45	1.93
26	260	300	19.2	1.67	3.15
26	260	500	13.7	1.12	2.2
30	180	300	21.3	1.92	1.81
30	180	500	15.83	1.32	1.44
30	260	300	16.97	1.47	2.9
30	260	500	10.11	0.76	2.1
28	220	400	15.33	0.54	2.32
28	220	400	15.7	1.21	2.28
28	220	400	16.2	1.16	2.35
28	220	400	15.9	1.05	2.32
28	220	400	16.1	1.45	2.4

Evaluation of the coefficients of the models

The coefficients were calculated by regression with the help of STATISTICA software (Version 10, 2011). A computer programme was also developed to calculate the value of these coefficients for different responses.

RESULTS

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 *F* ratio of the model developed does not exceed the standard tabulated value of *F* ratio for the desired level of confidence (95%) and the calculated value of *R* ratio of the model developed exceeds the standard tabulated value of *R* ratio for the desired level of confidence (95%), then the model may be considered adequate within the confidence limit. The obtained results presented in Table 2 show that all of the models are adequate.

Table 2. Statistical data for the mathematical models

		h	WL
Sum of squares	regression	2.19	136
	residual	0.084	9.61
Degrees of freedom	regression	3	2
	residual	9	10
Mean squared error	regression	0.73	68
	residual	0.0094	0.96
F-ratio		70.2	70.8
P		0.001 <	0.001 <
R^2 (%)		96.3	93.4
Adjusted R^2 (%)		95.1	92.1
Adequate		yes	yes

h = reinforcement, WL = volume loss

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 task. 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.

Development of the final models

The final mathematical models determined based on the above analysis are shown below:

$$h = 6.21 - 0.208 \times U + 0.000529 \times U \times I - 0.0000155 \times I \times S \quad (2)$$

$$WL = 42.8 - 0.032 \times S - 0.00216 \times U \times I \quad (3)$$

where:
h = reinforcement
WL = weight loss
U = open-circuit voltage
I = arc current
S = welding speed

The graphical form of the correlation between the observed values of reinforcement and the predicted values of reinforcement using the mathematical model Eq. (2) is presented in Fig. 3. The points are near the 45° line showing that the model is correct. The graphical form of the correlation between the observed values of weight loss and the predicted values of weight using mathematical model Eq. (3) is presented in Fig. 4. The points are near the 45° line indicating that this model can be used as well.

DISCUSSION

The study shows that *h* decreased according to the increasing U. There was no significant effect on the welding parameters. However, if U and I increase at the same time, *h* increases accordingly. It was found out that the interaction between U and I is significant the same as the interaction between I and S, but with negative influence on the reinforcement. It is also evident that WL decreased due to increasing S and other direct effect of welding parameters was not determined as significant. If U increases along with I, WL lowers. It is clear that the interaction between U and I is significant. Other studies (Murugan et al., 1993; Kim, 2003; Kim et al., 2003) are focused only on mathematical description of the weld bead and lack mathematical description between welding parameters and wear resistance.

Eq. (4), based on Eq. (2) and Eq. (3), determines optimal welding parameters. This model can be used to enhance the service life of hardfacing wear resistance.

$$Wt = h\ WL^{-1} \qquad (4)$$

where:
Wt = service life-time
WL = volume loss (mm^3)
h = mass of hardfacing

It is important to note that according to Eq. (4) density is the same for all hardfacing samples hence weight loss is calculated in mg.

The limited conditions are values derived by the mathematical models given in Eq. (2) and Eq. (3) which are presented in the experimental design matrix (Table 1). The optimal welding parameters were determined as maximum of Eq. (4) using Eq. (5):

$$\frac{dWt}{dU} = 0\,; \qquad \frac{dWt}{dI} = 0\,; \qquad \frac{dWt}{dS} = 0 \qquad (5)$$

By Eq. (5) the first, second, and third general determinants of the second order partial derivative matrix Eq. (6) were derived. The optimal welding parameters were also verified.

$$A = \begin{pmatrix} \frac{d^2Wt}{dU^2} & \frac{d^2Wt}{dUdI} & \frac{d^2Wt}{dUdS} \\ \frac{d^2Wt}{dIdU} & \frac{d^2Wt}{dI^2} & \frac{d^2Wt}{dIdS} \\ \frac{d^2Wt}{dSdU} & \frac{d^2Wt}{dSdI} & \frac{d^2Wt}{dS^2} \end{pmatrix} \qquad (6)$$

The optimum welding conditions were determined as U = 29 V, I = 260 A, S = 450 $mm.min^{-1}$.

The abrasive wear resistance of the hardfacing alloys is influenced by structure, volume, and size of the phases. Currently, relationships between structures and wear resistance of the hardfacing (Correa et al., 2007; Chotěborský et al., 2008, 2011a) and welding parameters influence primary conditions of crystallization and therefore the structure of the hardfacing layer. This study was not focused on the relationships between the conditions of formation of the phases. However, different descriptive ways for a simple optimization process of hardfacing were considered.

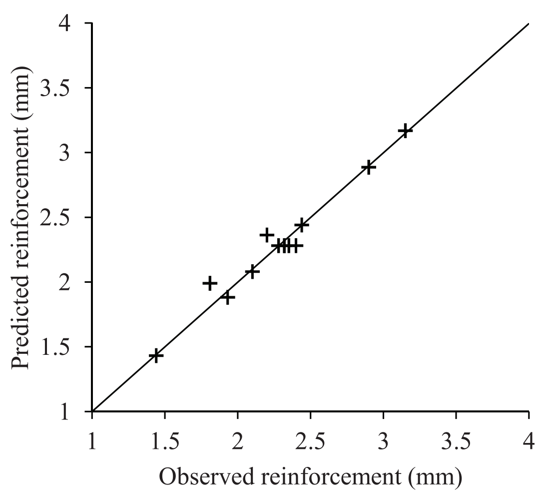

Fig. 3. Correlation between observed and predicted values of reinforcement h

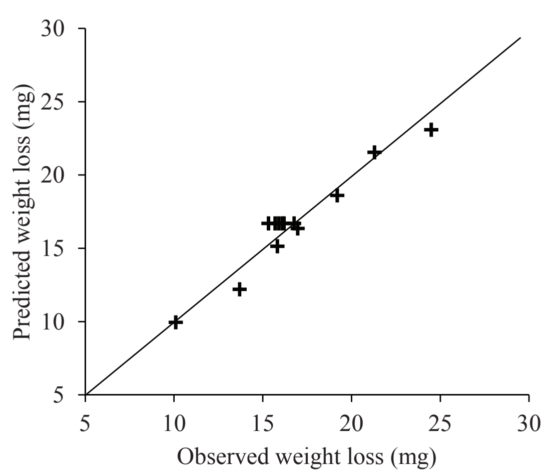

Fig. 4. Correlation between observed and predicted values of weight loss WL

CONCLUSION

The results showed that for the determination of optimal welding conditions the factorial design matrix can be used as an experimental program. Optimizing procedures are very important for material consumption minimizing.

Reinforcement of hardfacing was influenced by welding parameters including arc current and weight loss. However, weight loss of hardfacing is one of significant welding parameters. The optimizing process brings about the question on what is more appropriate – whether the construction of a thick overlay with low abrasion resistance or a thinner overlay with high abrasion resistance. The answer is not simple and it depends on greater gap effects like heat input limit in the real base material, maximal limit for thickness, etc. It was also found out that with highly increasing welding parameters weight loss decreases. Reinforcement can be used to improve the service life of hardfacing which is influenced by open circuit voltage and welding speed negativity and by arc current positivity. The parameters of 29 V, 260 A, and 350 mm.min^{-1} were assessed to fit the optimization process.

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