Prediction and Optimization of Weld Bead Volume for the Submerged Arc Process — Part 2

Analytic models were developed to establish a relationship between process parameters and weld bead quality

BY V. GUNARAJ AND N. MURUGAN

ABSTRACT. As a part of a study and analysis on the effects of process parameters on weld bead volume in submerged arc welding (SAW) of pipes, mathematical models were developed to relate the process parameters and the weld bead quality parameters. Further, the optimization of weld bead volume was carried out using the optimization module available in the *MATLAB* version 4.2b software package. The mathematical models thus developed for optimization are also helpful in predicting the weld bead quality parameters and in setting process parameters at optimum values to achieve the desirable weld bead quality at a relatively low cost with a high degree of repeatability and increased production rate. Total volume of the weld bead, an important bead parameter, was optimized (minimized), keeping the dimensions of the other important bead parameters as constraints, to obtain sound and superior quality welded pipes. Sensitivity analysis was also carried out to predict the direct and few interaction effects of important bead parameters on the total volume of the weld bead, and the results are presented in graphical form. The results of the sensitivity analysis are very useful in understanding the interdependence of various weld bead quality parameters in controlling the volume of the weld bead, to improve weld quality, to increase productivity with the available welding facilities and to minimize the total welding cost.

Introduction

Submerged arc welding is widely employed as one of the major fabrication processes in industry due to its inherent advantages of deep penetration, smooth bead and superior quality (Ref. 1). In SAW of pipes, engineers are often faced with the problems of relating the process variables to the weld bead quality and optimization of the bead parameters. Also, welding is done with the aim of achieving a sound joint at a low cost. But without optimization, it is impossible to achieve low-cost welding. The design and optimization process is iterative, requiring the repeated use of the same set of calculations (Refs. 2, 3). Until recently, cost and time-intensive trial and error methods were used to determine the optimum process parameters for a required bead quality. Since any welding process is a multi-objective problem (maximum penetration, minimum reinforcement, minimum heat input, minimum width, minimum dilution, low cost, maximum production rate), the optimum solution is a compromise (Ref. 4). Selection of an appropriate weld bead parameter is also equally important because if the selected parameter is the one determined and controlled by most of the other important bead parameters, then the optimization of that parameter will obviously include all the other parameters. Total volume of the weld bead is one of those important bead parameters controlled by most of the other bead parameters. Hence, the total volume, if optimized (minimized), obviously minimizes most of the other bead quality parameters such as heat input, dilution, reinforcement, bead width and penetration. But for a sound and strong weld, bead penetration should be maximized. Hence, in optimizing the total volume of the weld bead, the penetration, included as a constraint, should be set at its maximum value.

Minimizing the size of the weld bead reduces the welding cost through 1) reduced consumption of consumables such as electrodes and flux; 2) reduced heat input and energy consumption and 3) increased welding productivity through a high welding speed. Because of these advantages, the total volume of the weld bead should be optimized, having other bead parameters as constraints, rather than optimizing all the bead parameters individually. The total volume of the weld bead is the area of the weld bead cross section multiplied by the length of the weld bead. To reduce the complexity of the problem, the length of the bead is assumed as unity, which simplifies the equation. Now the total vol-

KEY WORDS

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Bead Width

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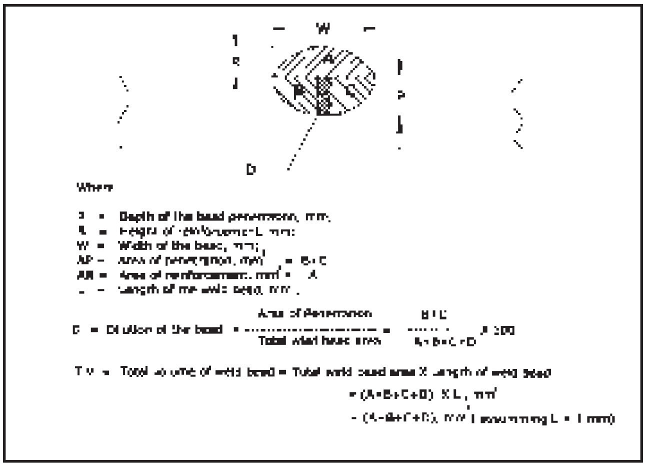

Fig. 1 — Cross section of a weld bead.

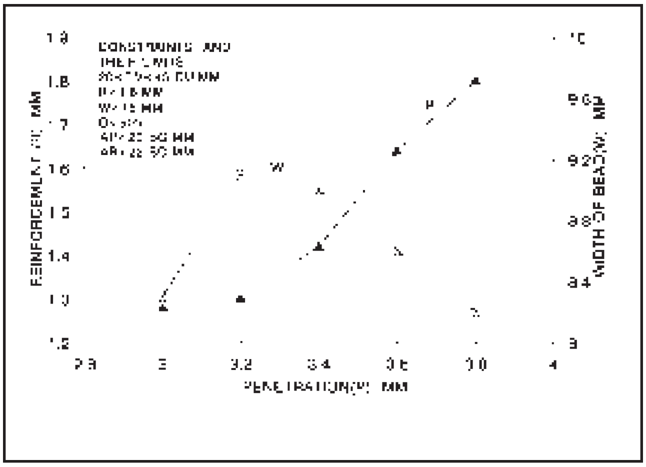

Fig. 2 — Direct effect of penetration (P) on reinforcement (R) and bead width (W).

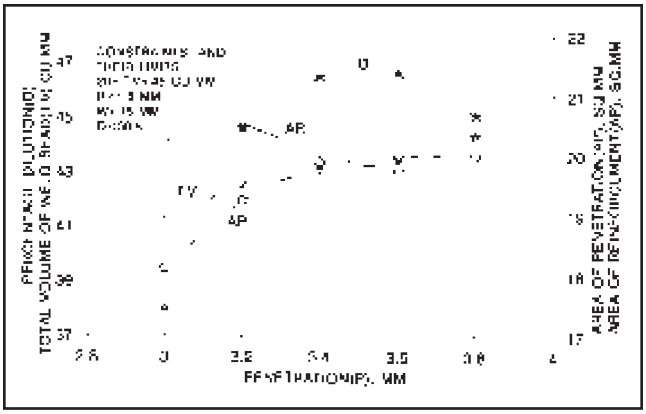

Fig. 3 — Direct effect of penetration (P) on percentage of dilution (D), area of penetration (AP), area of reinforcement (AR) and total weld bead volume (T.V.).

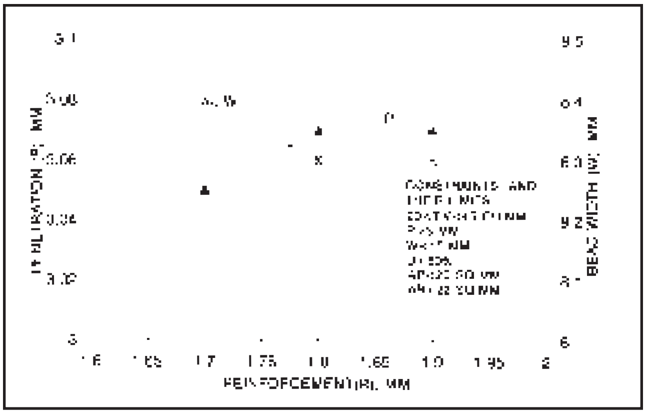

Fig. 4 — Direct effect of reinforcement(R) on penetration (P) and bead width (W).

ume is equal to the total area of the weld bead. Hence, the optimization of the total area of the weld bead cross section, subject to minimum reinforcement, minimum bead width, minimum dilution and maximum penetration, is the objective of this study. In order to do this, mathematical models were developed to establish the relationship between process parameters and the weld bead quality parameters. To achieve these objectives, the following three steps of methodology were used (Ref. 5):

1) Development of mathematical models, involving several steps to relate the response and the process parameters.

2) Model building, which involves selection of the objective function, along with one or several constraints with limits. This facilitates the optimization process.

3) Optimization, which includes the actual minimization or maximization of the objective function, subject to the constraints already specified.

As the amount of data generated in the iterative process for optimization were enormous and each design cycle requires substantial calculations, the optimization module available in the tool box of the *MATLAB* version 4.2b software package was used.

To achieve the objective, a study of the SAW process used for longitudinal welding of pipe was conducted to determine the effects of SAW process parameters on the dimensions of the important weld bead quality parameters. Statistically designed experiments based on the factorial technique (Ref. 6) were used to reduce the cost and time, as well as to obtain the required information about the main and interaction effects of the process variables on the weld bead quality parameters. The cross section of a weld bead showing important weld bead quality parameters is given in Fig. 1.

The mathematical models developed and optimized for weld bead parameters are very useful to predict the optimum weld bead geometry for the proposed input variables, to select the optimum combination of input variables for the desired weld bead quality and to atomize the SAW process through the development of a computer program. Also, this will be helpful in setting the process variables at the correct and optimum levels to obtain superior quality welded joints at a relatively high production rate with low manufacturing cost. Also, it is very important to study the benefit of relaxing the constraints associated with the total volume in understanding the influence of one bead parameter on the other. So, sensitivity analysis was also carried out.

Experimental Work

The experiment was conducted at M/s. Sri Venkateswara Engineering Corporation, Coimbatore, India, with the following setup: ADORE semiautomatic welding equipment joined IS 2062 carbon steel plates 300 x 150 x 6 mm thick; ESAB SA1

(E8) copper-coated wire 3.15 mm in diameter and ESAB basic fluoride type (equivalent to DIN 8557) granular flux were used. The plates were joined in the flat position using a narrow square-groove butt joint with 1-mm root opening.

Development of Mathematical Models

The detailed step-by-step procedure of the development of mathematical models was presented in Part 1, Mathematical Modeling to Predict Weld Bead Quality for SAW of Pipes, published in the October 2000 issue of the *Welding Journal*. A central composite rotatable design (Ref. 7), a factorial design, was used to develop mathematical models. The selected process control parameters with their limits and levels are shown in Table 1. The final mathematical models developed with all process parameters in coded form are given below.

$$\text{Penetration, mm} = 3.57 - 0.113V + 0.33F - 0.217S - 0.001N + 0.048V^2 + 0.1F^2 + 0.03S^2 - 0.01N^2 - 0.05VF + 0.03VS + 0.04VN - 0.01FS - 0.01FN + 0.08SN \tag{1}$$

$$\text{Reinforcement, mm} = 1.27 - 0.08V + 0.16F - 0.18S - 0.03N + 0.03V^2 + 0.07F^2 + 0.15S^2 + 0.01N^2 + 0.03VF + 0.03VS - 0.014VN - 0.001FS - 0.02FN + 0.03SN \tag{2}$$

$$\text{Width of weld bead, mm} = 10.76 + 1.19V + 0.45F - 1.9S + 0.23N + 0.41V^2 - 0.17F^2 + 0.29S^2 + 0.12N^2 - 0.04VF - 0.64VS - 0.15VN - 0.35FS + 0.091FN - 0.29SN \tag{3}$$

$$\text{Area of penetration, mm}^2 = 21.56 + 1.05V + 1.85F - 1.61S - 0.212N + 0.041V^2 + 0.29F^2 - 0.097S^2 + 0.15N^2 + 0.14VF - 0.21VS + 0.056VN - 0.24FS - 0.16FN - 0.16SN \tag{4}$$

$$\text{Area of reinforcement, mm}^2 = 21.44 + 0.44V + 0.187F - 1.76S + 2.11N + 1.39V^2 - 0.39F^2 + 1.22S^2 + 0.62N^2 + 0.41VF - 0.047VS + 0.14VN - 0.94FS + 0.77FN - 0.33SN \tag{5}$$

$$\text{Percentage of dilution} = 47.27 + 0.74V + 2.51F - 0.25S - 2.23N - 1.31V^2 - 0.71F^2 - 1.31S^2 - 0.44N^2 - 0.09VF - 0.3VS - 0.31VN + 0.43FS - 0.90FN + 0.17SN \tag{6}$$

$$\text{Total weld bead volume, mm}^3 = 45.78 + 1.58V + 2.2F - 3.5S + 2.0N + 1.67V^2 + 0.17F^2 + 1.34S^2 + 0.97N^2 + 0.28VF - 0.21VS + 0.48VN - 0.87FS + 0.64FN - 0.77SN \tag{7}$$

Optimization

Selection of Function and Constraints

The objective function selected for optimization was the total volume of the weld bead. The area in which the solution for the function lies decreases as the number of constraints increases. Therefore, only the parameters penetration, reinforcement, bead width and percentage of dilution were given as constraints in their equation form. In optimization, generally the constraints with their upper limits should be given in such a way that their value will be less than or equal to zero. Also, the function, as well as the constraint functions, will usually be minimized. To obtain a strong weld in any application, it is always desirable to have maximum depth of penetration with minimum reinforcement, width and dilution without sacrificing other bead qualities. To maximize a function, the function should be multiplied by –1. The process

Table 1 — Process Parameters and Their Limits

Parameters	Units	Notation	Limits –2	–1	0	+1	+2
Welding voltage	volts	V	24	26	28	30	32
Wire feed rate	m/min	F	0.70	0.93	1.16	1.39	1.62
Welding speed	m/min	S	0.43	0.51	0.59	0.67	0.75
Nozzle-to-plate distance	mm	N	30.00	32.50	35.00	37.50	40.00

Table 2 — Results of the Sensitivity Analysis

S. No	Parameters varied and their limits	Optimum Process Variables: V volts	F m/min	S m/min	N mm	Optimum Values of the Bead Parameters: P mm	R mm	W mm	AP mm^2	AR mm^2	D %	T.V mm^3
1	R = 1.7 mm	28	0.69	0.64	34.5	3.05	1.28	8.4	18.07	20.19	37.9	41.31
2	R = 1.8 mm	28	0.70	0.64	34.6	3.07	1.28	8.3	18.13	20.21	38.0	41.33
3	R = 1.9 mm	28	0.70	0.64	34.6	3.07	1.28	8.3	18.13	20.21	38.0	41.33
4	R = 2.0 mm	28	0.70	0.64	34.6	3.07	1.28	8.3	18.13	20.21	38.0	41.33
5	P = 3.0 mm	28	0.70	0.64	34.6	3.07	1.28	8.3	18.13	20.21	38.0	41.33
6	P = 3.2 mm	28	1.02	0.66	33.6	3.20	1.28	9.1	19.25	20.53	44.6	42.48
7	P = 3.4 mm	28	1.17	0.68	33.3	3.40	1.42	9.0	19.89	20.03	46.5	42.98
8	P = 3.6 mm	27	1.28	0.71	33.5	3.60	1.64	8.6	20.00	19.72	46.6	43.38
9	P = 3.8 mm	27	1.40	0.72	34.7	3.80	1.80	8.2	20.00	20.30	45.1	44.44
10	W = 8 mm	27	0.70	0.67	35.6	3.07	1.38	8.0	17.54	21.37	36.3	41.58
11	W = 8.5 mm	28	0.70	0.64	34.6	3.07	1.28	8.5	18.13	20.21	38.0	41.33
12	W = 9 mm	28	0.70	0.64	34.6	3.07	1.28	9.0	18.13	20.21	38.0	41.33
13	W = 10 mm	28	0.70	0.64	34.6	3.07	1.28	9.0	18.13	20.21	38.0	41.33
14	D = 35%	28	0.70	0.63	35.3	3.04	1.47	7.9	17.14	22.00	35.0	42.51
15	D = 36%	27	0.70	0.60	35.4	3.05	1.40	8.0	17.40	21.64	36.0	41.68
16	D = 37%	27	0.70	0.66	35.1	3.06	1.34	8.1	17.74	20.89	37.0	41.43
17	D = 38%	28	0.70	0.64	34.7	3.07	1.28	8.3	18.13	20.21	38.0	41.33
18	AP = 18 mm^2	29	0.70	0.65	34.8	3.06	1.30	8.2	18.00	20.16	37.7	41.33
19	AP = 20 mm^2	28	0.70	0.64	34.7	3.07	1.28	8.3	18.13	20.21	38.0	41.34
20	AR = 20 mm^2	28	0.70	0.63	34.6	3.07	1.27	8.5	18.27	20.00	38.3	41.33
21	AR = 22 mm^2	28	0.70	0.64	34.7	3.07	1.28	8.3	18.13	20.21	38.0	41.34

For the values of the bead parameters P, R, W, AP, AR and D, other than that tabulated above, it was found that the value of objective function, namely, total volume of the weld bead, is either unaltered or it had no feasible solution.

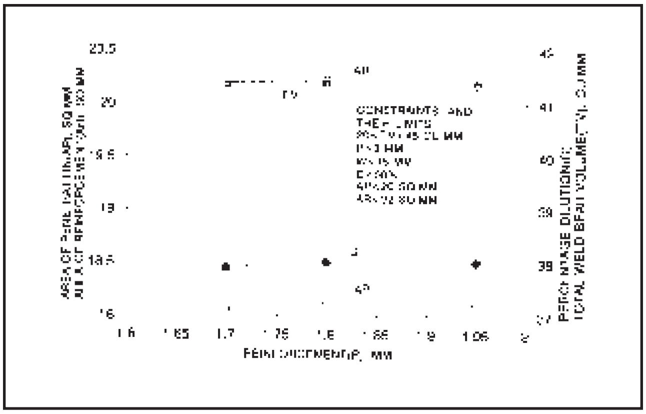

Fig. 5 — Direct effect of R on D, AP, AR and T.V.

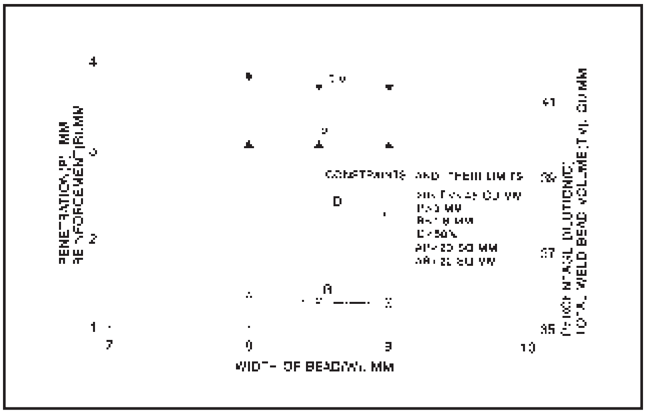

Fig. 6 — Direct effect of W on P, R, D and T.V.

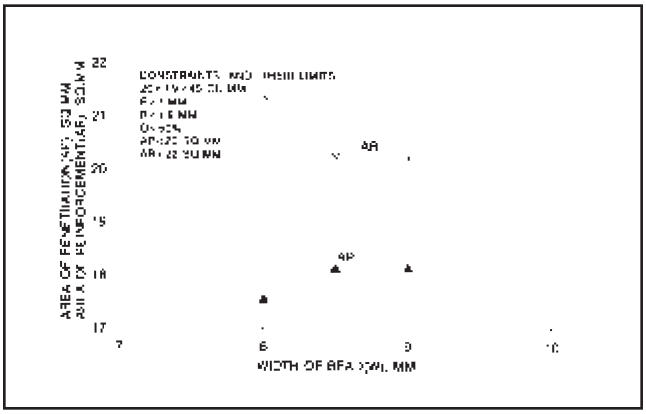

Fig. 7 — Direct effect of W on AP and AR.

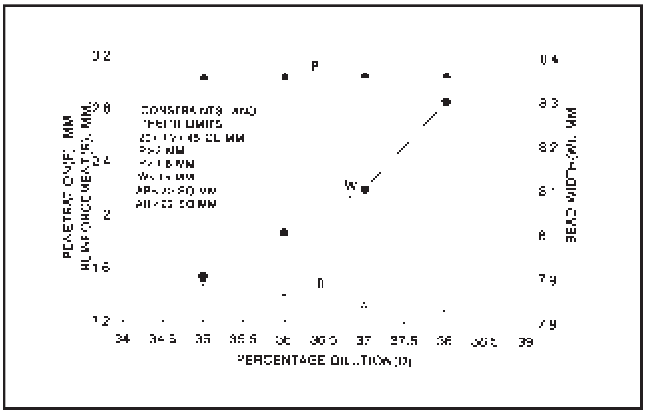

Fig. 8 — Direct effect of D on P, R and W.

variables and their notations used in writing the M-file using *MATLAB* software are given below.

X (1) = welding voltage (V)
X (2) = wire feed rate (F)
X (3) = welding speed (S)
X (4) = nozzle-to-plate distance (N).

Optimization of the Objective Function

The main purpose of this study is to minimize the total volume of the weld bead using other important bead parameters with their limits as constraints. The model is a nonlinear equation with constraints. The step-by-step procedure of minimization of total volume using the optimization module available in the tool box of the *MATLAB* version 4.2b software package is given below. The constrained minimum of a scalar function of several variables at an initial estimate, which is referred as "constrained nonlinear optimization," is mathematically stated as the following:

Minimize f(X) subject to
$G(X_1,X_2,X_3,....X_n) < 0$

where, X and G(X) represent the matrices of the objective and constraint functions, respectively, and f(X) is a scalar function. In optimization, the value of the constraints should be < 0 (Ref. 8). To satisfy this condition, the upper limit of each of the constraints, except for penetration, is included in the constraint equation so that each of the constraints is kept below or equal to the limit. But the penetration of the weld bead has to be fixed at the maximum possible value. Therefore, the penetration is specified as a constraint in such a way that it is multiplied by –1 and its minimum limit is included so that it becomes –P + 3 <0 (where 3 mm is its minimum value). Therefore, the value of the penetration as a constraint will be above 3 mm. The limits of the other constraints (*i.e.,* reinforcement, width, area of penetration, area of reinforcement and the dilution of the weld bead) were established by data obtained from past experience with a view that they should provide a sound and defect-free welded joint along with a feasible solution to the objective function. Also, the constraints were given in the form of equations. Several numerical methods are available for optimization of nonlinear equations with constraints. A quasi-Newton method is the most efficient and quickest one, and this method was used to determine the optimum total weld bead volume (Ref. 9).

Step 1: Writing M-file: Function (f, g) = f(x)

f(X) = 45.78 + 1.58*X(1) + 2.2*X(2) – 3.5*X(3) + 2.0*X(4) + 1.67*X(1)^2 + 0.17*X(2)^2 + 1.34*X(3)^2 + 0.97*X(4)^2 + 0.28*X(1)*X(2) – 0.21*X(1)*X(3) + 0.48*X(1)*X(4) – 0.87*X(2)*X(3) + 0.64*X(2)*X(4) – 0.77*X(3)*X(4); Total weld bead volume.

g(1) = 1.27–0.08*X(1) + 0.16*X(2) – 0.18*X(3) – 0.03*X(4) + 0.03*X(1)^2 + 0.07*X(2)^2 + 0.15*X(3)^2 + 0.01*X(4)^2 + 0.03*X(1)*X(2) + 0.03*X(1)*X(3) – 0.014*X(1)*X(4) – 0.001*X(2)*X(3) – 0.02*X(2)*X(4) + 0.03*X(3)*X(4) – 1.8; Reinforcement and its upper limit in mm.

g(2) = –[3.57 – 0.113*X(1) + 0.33*X(2) – 0.22*X(3) – 0.001*X(4) + 0.05*X(1)^2 + 0.1* X(2)^2 + 0.03*X(3)^2 – 0.01*X(4)^2 – 0.05*X(1)*X(2) +

Table 3 — Comparison of Observed and Predicted Values of Conformity Test

	Process parameters				Penetration, mm			Dilution, %			Total Volume, mm^3		
S. No.	V Volts	F m/min	S m/min	N mm	Observed Value	Predicted Value	Error %	Observed Value	Predicted Value	Error %	Observed Value	Predicted Value	Error %
1	27	0.70	0.67	36	3.00	3.08	+2.60	36.48	35.45	+2.91	41.66	41.50	2.21
2	27	1.39	0.75	35	3.70	3.75	–1.33	46.23	44.98	+2.84	44.34	44.11	2.85
3	28	0.70	0.61	35	3.20	3.10	+3.20	39.17	38.05	+2.94	42.25	43.14	2.06
						Average	2.38			2.89			2.40
			Error =										

$$\% \text{ Error} = \frac{\text{Observed value-predicted value}}{\text{Predicted value}} \times 100$$

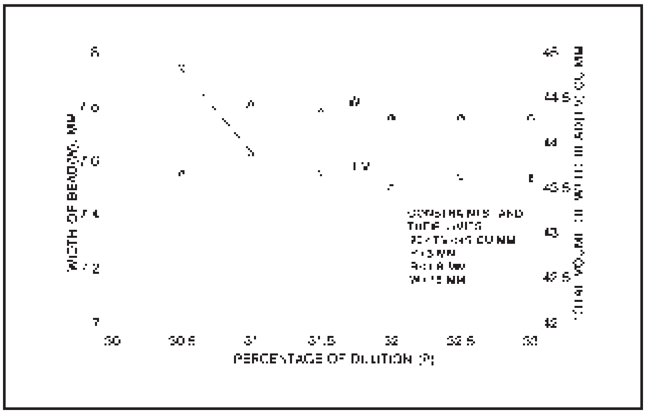

Fig. 9 — Direct effect of P on W and T.V.

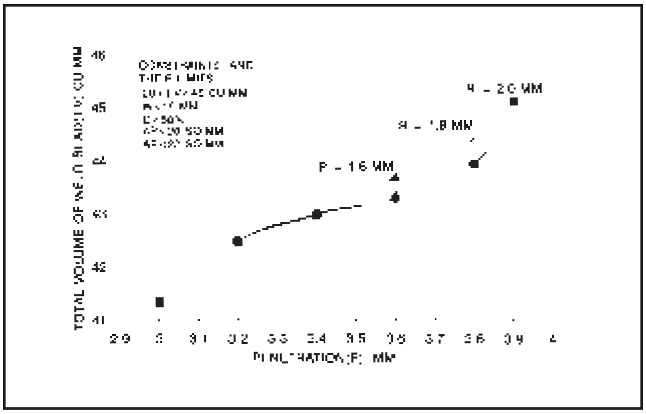

Fig. 10 — Interaction effect of P and R on T.V.

0.03*X(1)*X(3) + 0.04*X(1)*X(4) – 0.01*X(2)*X(3) – 0.01*X(2)*X(4) + 0.08*X(3)*X(4)] + 3.0; Penetration and its lower limit in mm.

g(3) = 10.76 + 1.19*X(1) + 0.45*X(2) – 1.9*X(3) + 0.23*X(4) + 0.41*X(1)^2 – 0.17*X(2)^2 + 0.29*X(3)^2 + 0.12*X(4)^2 – 0.04*X(1)*X(2) – 0.64*X(1)*X(3) – 0.15*X(1)*X(4) – 0.35*X(2)*X(3) + 0.091*X(2)*X(4) – 0.29*X(3)*X(4) – 15.0; Bead width and its upper limit in mm.

g(4) = 47.27 + 0.74*X(1) + 2.51*X(2) – 0.25*X(3) – 2.23*X(4) – 1.31*X(1)^2 – 0.71*X(2)^2 1.31*X(3)^2 – 0.44*X(4)^2 – 0.09*X(1)*X(2) – 0.3*X(1)*X(3) – 0.31*X(1)*X(4) + 0.43*X(2)*X(3) – 0.90*X(2)*X(4) + 0.17*X(3)*X(4) – 50; % Dilution and its upper limit.

g(5) = 21.56 + 1.05*X(1) + 1.85*X(2) – 1.61*X(3) – 0.212*X(4) + 0.041*X(1)^2 + 0.29*X(2)^2 – 0.097*X(3)^2 + 0.15*X(4)^2 + 0.14*X(1)*X(2) – 0.21*X(1)*X(3) + 0.056*X(1)*X(4) – 0.24*X(2)*X(3) – 0.16*X(2)*X(4) – 0.16*X(3)*X(4) – 20; Area of penetration and its upper limit.

g(6) = 21.44 + 0.44*X(1) + 0.187*X(2) – 1.76*X(3) + 2.11*X(4) + 1.39*X(1)^2 – 0.39*X(2)^2 + 1.22*X(3)^2 + 0.62*X(4)^2 + 0.41*X(1)*X(2) – 0.047*X(1)*X(3) + 0.14*X(1)*X(4) – 0.94*X(2)*X(3) + 0.77*X(2)*X(4) – 0.33*X(3)*X(4) – 22; Area of reinforcement and its upper limit.

g(7) = f – 45; upper limit of total weld bead volume is 45 mm^3.

g(8) = – f + 20; lower limit of total weld bead volume is 20 mm^3.

Step 2: Invoke an optimization routine (R-file)

X_0 = [–1, –1,1,1] (guess of initial solution)

Options = [ ] (change in the default setting if any)

V_{lb} = [–2, –2, –2, –2] (lower boundaries of the variables)

V_{ub} = [2, 2, 2, 2] (upper boundaries of the variables)

X = Constr (‘f(X)’ X0; options; V_{lb}, V_{ub})

Step 3: Running the M-file.

After running the M-file and retrieving the constraints, the optimum values of the process variables are the following:

X(1) = welding voltage (V) = 28 volts;
X(2) = wire feed rate (F) = 0.7 m/min;
X(3) = welding speed (S) = 0.64 m/min
X(4) = nozzle-to-plate distance (N) = 34.6 mm.

The results of optimization are given below.

T.V. = total volume of the weld bead = 41.33 mm^3
R = reinforcement = 1.28 mm;
P = penetration = 3.07 mm;
W = width of the bead = 8.33 mm;
D = dilution of the bead = 38%;
AP = area of penetration = 18.13 mm^2;
AR = area of reinforcement = 20.21 mm^2.

Sensitivity Analysis

Sensitivity analysis, also known as the post optimality analysis, is the study of what happens to the value of the objective function if the limit of each of the constraints is changed from optimum value. Optimum solution for any function lies in a boundary or zone and, hence, it is not a single constant value (Ref. 10). This provides a flexibility in fixing the limits for the constraints. Also, for every value of each of the constraints there is a possibility for change in the value of the objective function as well as other constraints.

Therefore, it is very important to know the impact of relaxing the limits of each constraint on the value of the objective

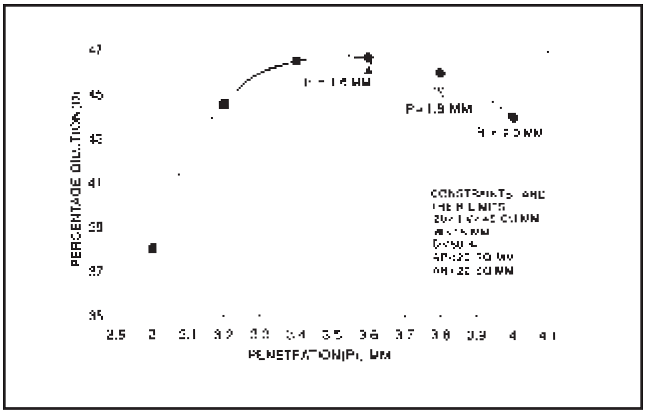

Fig. 11 — Interaction effect of P and R on D.

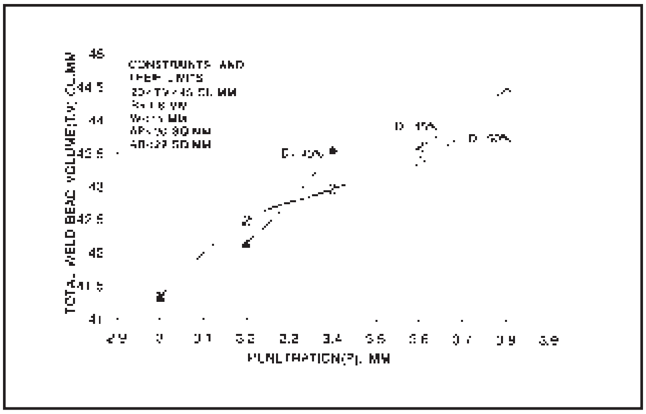

Fig. 12 — Interaction effect of P and D on T.V.

function and other constraints before fixing the correct limits for the constraints to produce a sound and strong weld at relatively low cost with a high degree of repeatability. Sensitivity analysis was carried out for the total volume of the weld bead by varying the limit of one of the constraints at a time, and the effect of the change in the constraint limit on the value of the total volume and other constraints were recorded and given in Table 2. To find the interaction effect of the constraints, limits of two constraints were changed and their effects were also noted.

Confirming Test

To check and confirm the validity of the optimization results, test runs were conducted in a manufacturing facility with the same experimental setup. The process parameters were assigned values nearest to the optimum values selected from Table 2 after confirming the equipment could produce them and the results were recorded. For the same set of parameters, optimization of T.V. was done with other bead parameters as constraints with the same limits. The objective function, as well as the constraints, were substituted in their natural scale. A comparative study between the actual and predicted results with a percentage of deviation of the results was carried out. The results of this comparative study are presented in Table 3.

Results

The mathematical models furnished above can be used to predict the weld bead geometry by substituting the values, in coded form, of the respective factors. Also, knowing the weld bead volume is very useful 1) to minimize the various weld defects due to high heat input, 2) to increase productivity and 3) to minimize the total welding cost for the required quality. The sensitivity analysis improves the understanding of the direct and interaction effects of various bead parameters on weld bead size and volume. The responses calculated for each set of coded welding variables are represented graphically in Figs. 2–12.

For bead parameter values, P, R, W, AP, AR and D, other than that tabulated above, it was found the value of the objective function, namely, total volume of the weld bead, is either unaltered or has no feasible solution.

Discussion

The main effects of each of the weld bead parameters on the other bead parameters and on the total weld bead volume predicted from the sensitivity analysis using the mathematical models developed are depicted in Figs. 2–12.

Direct Effects of Bead Parameters

Direct Effect of Penetration on the Other Bead Parameters

Figure 2 shows the effect of increasing the lower limit value of the penetration (P), a constraint, on reinforcement (R) and bead width (W) in the process of optimizing the total volume of weld bead. For the given constraints and limits, the maximum penetration is 3.8 mm. For all values of P greater than 3.8 mm, no feasible solution was possible and for P less than 3 mm, the values of R and W remain unchanged. From Table 2, it is noted that as P is increased from 3 to 3.2 mm, V and S increase marginally but N drops from 34.6 to 33.6 mm and F increases considerably from 0.7 to 1.02 m/min. As F has a positive effect on all the bead parameters and N has a negative effect on R but a positive effect on W, the increase in P from 3 to 3.2 mm results in an increase in R from 1.28 to 1.30 mm and W from 8.3 to 9.1 mm. The increase in P beyond 3.2 mm results in a drop in V from 28 to 27 V, an increase in F from 1.02 to 1.40 m/min, an increase in S from 0.66 to 0.7 m/min and an increase in N from 33.6 to 34.7 mm. This shows the increase in R from 1.30 to 1.80 mm as P is increased beyond 3.2 mm is mainly due to an increase in F. Therefore, F has the predominant effect on R for all values of P compared to that of other bead parameters. The decrease of W is mainly due to an increase in S as P is increased beyond 3.2 mm. Therefore, S has the predominant effect on W for all values of P >3.2 mm compared to other bead parameters.

Figure 3 shows the effect of P on other bead parameters, namely, area of penetration (AP), area of reinforcement (AR), total weld bead volume (T.V.) and percentage of dilution (D). From the figure, it is clear AP generally increases with the increase in P. But this increase of AP decreases gradually because of a decrease in W as P is increased beyond 3.2 mm — Fig. 2. AR has a mixed trend with the increase in P. As P is increased from 3 to 3.2 mm, AR increases from 20.21 to 20.53 mm^2 because both R and W increase for this range of values of P. As P is increased from 3.2 to 3.6 mm, AR decreases from 20.53 to 19.72 mm^2. This is mainly due to the drop in W for this range of values of P. For further increase in P, AR increases from 19.72 to 20.30 mm. This may be due to the predominant effect of an increase in R rather than the decrease in W on AR. T.V. also generally increases with an increase in P. The increasing rate of T.V. is not steady. This is because of a mixed trend of R in spite of an increasing trend of AP. D increases from 38% to 46.6% as P is increased from 3 to 3.6 mm. D drops from 46.6% to 45.1%. This is because the increasing rate of AP compared to T.V. with the increase in P from 3 to 3.6 mm is more. Therefore, D increases. For the increase in P from 3 to 3.6 mm, AP remains at the same value of 20 mm^2 but T.V. increases from 43.38 to 44.44 mm^3. Therefore, D drops. For all the other values of P, the values of R, W, D, AP, AR and T.V. either remained unaltered or no feasible solution is possible.

Direct Effect of Reinforcement on the Other Bead Parameters

Figures 4 and 5 show the effect of changing the value of R, a constraint in optimization, on bead parameters P, W, AP, AR, T.V. and D. From Fig. 4, it is apparent as R is increased from 1.7 to 1.8 mm, P increases from 3.05 to 3.07 mm, but W drops from 8.4 to 8.3 mm. These effects are mainly due to the increase in the value of F as R increases. As F has a positive effect on P and W, they increase with the increase in R. For a further increase in R beyond 1.8 mm, there is no change in the values of the process parameters, and hence, in the values of P and W. For other values of R, no feasible solution was possible.

From Fig. 5, it is clear as R is increased from 1.7 to 1.8 mm, V and F increase, and, therefore, AP, AR, T.V. and D increase. For a further increase in R beyond 1.8 mm, all the bead parameters remain unaltered. For other values of R <1.7 mm, no feasible solution was possible.

Direct Effect of Bead Width on the Other Bead Parameters

Figure 6 shows the effect of varying the value of the upper limit of W on other bead parameters, namely, P, R, D and T.V. From the figure, it is apparent the range of values of W for which a feasible solution is possible is very narrow and is 8 to 8.5 mm only. For all the other values of W, the values of bead parameters were either unaltered or no feasible solution was possible. As W is increased from 8 to 8.5 mm, P remains at the same value of 3.07 mm, but R drops from 1.38 to 1.28 mm. The decrease in R is due mainly to increase in S and N as W is increased. As S and N have a negative effect on R, R decreases. As P is unaltered and R decreases, T.V. drops when W is increased. Because T.V. drops, D increased from 36.3% to 38% as W increased.

From Fig. 7, it is noted AP increases from 17.54 to 18.13 mm^2 with the increase in W. This is because P is unaltered when W is increased from 8 to 8.5 mm. Also, as W increases from 8 to 8.5 mm, R drops from 1.38 to 1.28 mm, and AR drops from 21.37 to 20.21 mm^2. For the other values of W, the values of AP and AR either remain unaltered or no feasible solution was possible.

Direct Effect of Percentage of Dilution on the Other Bead Parameters

Figure 8 shows the effect of D on P and R and W. The figure shows P increases slightly from 3.04 to 3.07 mm but R decreases gradually from 1.47 to1.28 mm and W increases from 7.9 to 8.3 mm as D is increased from 30% to 38%. The increase in P is mainly due to the decrease in N as D increased — Table 2. The decrease in R is due to the increase in S. The decrease in R is compensated by the increase in W as D increases. For the other values of D, the value of P, R and W are either unchanged or no feasible solution was possible.

Figure 9 shows the effect of changing the value of D, a constraint in optimization of T.V., on AP, AR and T.V. From the figure, it is apparent AP increases but both AR and T.V. decrease as D increases from 35% to 38%. The increase in AP is due mainly to an increase in P and W as D increases. A decrease in AR, in spite of an increase in W, is due to the decrease in R as W increases. The decrease in T.V. is due to the fact D increases when either AP increases or the total area decreases. In this case, AP increases and T.A. decreases. Therefore, T.V. decreases.

Interaction Effects of Bead Parameters

Interaction Effect of Penetration and Reinforcement on Total Volume of the Weld Bead

Figure 10 shows the interaction effect of P and R on T.V. The figure shows the value of T.V. is the same for all values of R as P increases from 3 to 3.4 mm. The minimum value of T.V. (about 41.3 mm^3) is at the minimum value of P and R. Total value of T.V. is maximum (about 45.4 mm^3) at maximum values of P and R. Total area and the total volume of the weld bead generally increase when the areas of penetration and reinforcement increase. The areas of penetration and reinforcement increase as P and R are increased, keeping W either constant or increasing W. The total area and the total volume of the weld bead depends on the values of P, R and W. From the figure, it is noted that even though T.V. increases for all values of R when P is increased, this increasing trend of T.V. decreases gradually as R is increased from 1.6 to 2.0 mm. But T.V. is supposed to increase as R is increased. As T.V. is influenced by W, this decrease in the increasing trend of T.V. as R is increased may be due to the increase in the value of W.

Interaction Effect of Penetration and Reinforcement on Dilution of the Bead

Figure 11 shows the interaction effect of P and R on D. From the figure, it is apparent D increases as P increases from 3 to 3.4 mm for R = 1.6 and 1.8 mm, respectively. For R = 2.0 mm, D increases as P is increased from 3 to 3.6 mm. Beyond this value of P, D decreases for all values of R. Also, the value of D for any given value of R is the same as P is between 3 and 3.4 mm. This indicates P has a stronger effect on D compared to R. As P increases, AP increases, and D increases. For all values of P >3.4 mm, the value of D is more for the higher value of R. For this range of P (P = 3.4 to 4.0 mm), the effect of R is greater than P. As R increases, AR increases, T.A. increases and D decreases.

Interaction Effect of Dilution and Penetration on Total Volume of Weld Bead

Figure 12 shows the interaction effect of D and P on T.V. From the figure, it is clear the value of T.V. is minimum (41.3 mm^3) at minimum value of P and D (= 40%). This is because when P is minimum, AP is minimum for the same value of W, and T.A. and T.V. are minimum. As P increases, T.V. also increases for all values of D. For all values of P between 3.4 and 3.8 mm, the value of T.V. is more for a lesser value of D (= 45%). This is due to the fact that for this range of values of P, the increase in AP is less than that of T.A. Therefore, T.A. and T.V. are more for a lesser value of D.

Conclusions

The following were concluded from this investigation:

The *MATLAB* software package can be effectively employed for the optimization of weld bead parameters and finding the corresponding optimum process variables.

The sensitivity analysis reveals the effect of constraint limits on the value of the objective function.

The bead width has no effect on other bead parameters including total area during optimization and sensitivity analysis. The penetration has a considerable positive effect on the dilution. At a maximum penetration of 3.8 mm, the dilution is also maximum at 46.6%.

The reinforcement has very little effect on total volume of the weld bead and other bead parameters.

The percentage dilution has a negative effect on the total volume of the weld bead. At the lower dilution of 35%, the total volume is maximum and equal to 43 mm^3, and at a higher value of dilution (38% and above), the total volume is a low 41%.

The comparison of predicted and actual results shows the predicted results are accurate by about 97%.

The value for penetration and dilution as constraints for which the objective function and other parameters are sensitive is considerable, while it is narrow for other bead parameters.

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