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ORIGINAL ARTICLE

Optimization of weld bead geometry in plasma transferred arc hardfaced austenitic stainless steel plates using genetic algorithm

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Abstract Plasma transferred arc hardfacing has attracted increasing attention for its effective protection against corrosion, thermal shock, and abrasion. The quality of hardfaced components depends on the weld bead geometry and dilution, which have to be properly controlled and optimized to ensure better economy and desirable mechanical characteristics of the weld. These objectives can be fulfilled by developing mathematical equations to predict the dimensions of the weld bead. This paper highlights the development of such mathematical equations using multiple regression analysis, correlating various process parameters to weld bead geometry in PTA hardfacing of Colmonoy 5, a nickel-based alloy over stainless steel 316 L plates. The experiments were conducted based on a five factor, five level central composite rotatable design matrix. A genetic algorithm (GA) was developed to optimize the process parameters for achieving the desired bead geometry variables.

Keywords PTA hardfacing · Regression analysis · Dilution · Optimization · Genetic algorithm

1 Introduction

In the manufacturing industries, wear and corrosion have been persistent problems that need to be solved through various techniques. PTA hardfacing has been a widely accepted technique to combat wear and improve the properties of material surfaces by forming composite wall sections [1]. It produces a very high quality deposit offering optimal protection with minimal dilution or deformation of the base material. It is a process that deposits very precise coatings of perfectly controlled alloys on mechanical parts that are subject to harsh environments, significantly extending their service life. In the recent years, PTA hardfacing finds extensive use in applications such as valve industries, aircrafts, hydraulic machineries, mining industries, earth-moving equipment, chemical, nuclear, and thermal power plants, etc. H. Eschnauer reviewed the use of various hard materials and alloy powders for plasma surface coating and reported that PTA hardfacing was a suitable processing technique for nickel- and cobalt-based alloys [2]. According to L.C. Lim et al., borides and carbides are the common hard phases present in such nickel-based alloys [3]. They are either added in the form of composite powders or precipitate during processing. In the present study, Colmonoy 5, a nickel-based alloy (Ni-Cr-B-Si-C) has been chosen for its excellent performance under conditions of abrasion, adhesion, corrosion, and elevated temperature. Also, like many researchers, Kaul et al. reported that in nuclear applications, nickel-based Colmonoy alloys were preferred in the place of more widely used cobalt based stellite alloys due to its less induced radioactivity in hard-faced deposits [4–6]. In this way, Colmonoy alloys have gained more popularity owing to their fine performance and importance [7] and led to more investigations to be carried out on such alloy hardfacings.

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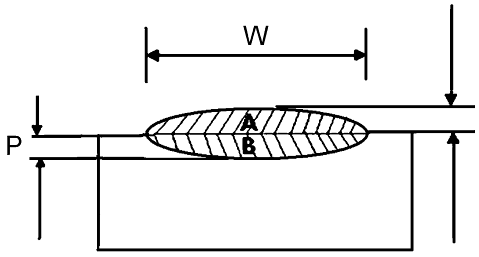
In hardfacing, dilution of powder by base metal from weld penetration is the most important aspect that can be calculated as shown in Fig. 1. Dilution critically affects the mechanical and metallurgical characteristics of overlays. Therefore, it has to be effectively controlled by properly selecting the process parameters to obtain the desired weld bead geometry. Marimuthu and Murugan reported that a successful hardfacing of these alloys required optimization of the process parameters to have low dilution and a crack-free overlay [8]. In order to carry out optimization, mathematical equations are needed for predicting the values of the bead geometry variables, penetration, reinforcement, and bead width. In this investigation, experiments conducted using the design of experiments concept were used for developing mathematical models to predict such variables. Many works were reported in the past for predicting bead geometry, heat-affected zone, bead volume, etc., using mathematical models for various welding processes [8–10]. Usually, the desired welding process parameters are determined based on the experience of skilled workers or from the data available in the handbook. This does not ensure the formation of optimal or near-optimal weld pool geometry [11]. It has been proven by several researchers that efficient use of statistical design of experiment techniques and other optimization tools can impart scientific approach in welding procedure [12–13]. These techniques can be used to achieve optimal or near-optimal bead geometry from the selected process parameters.

Kim et al. reviewed that optimization using regression modeling, neural network, and Taguchi methods could be effective only when the welding process was set near the optimal conditions or at a stable operating range [14], but, near-optimal conditions cannot be easily determined through full-factorial experiments when the number of experiments and levels of variables are increased. Also, the method of steepest ascent based upon derivatives can lead to an incorrect direction of search due to the non-linear characteristics of the welding process. Genetic algorithm, being a global algorithm, can overcome the above problems associated with full-factorial experiments and the objective function to be optimized using GA need not be differentiable [15]. In the present study, a sequential genetic algorithm has been used to optimize the process parameters and achieve minimum dilution and penetration, maximum reinforcement, and bead width [16]. This is imperative for reducing the cost of powder and imparting better surface property like resistance to wear and corrosion.



P - Penetration
R - Reinforcement
W - Width
% Dilution = [B/(A+B)] x 100

Fig. 1 Weld bead geometry

2 Experimental procedure

The independently controllable PTA process parameters identified based on their significant effect on weld bead geometry to carry out the experimental work were welding current (A), oscillation width (O), travel speed (S), preheat temperature (T) and powder feed rate (F). Preheat temperature and oscillation amplitude, which may affect crack formation during hardfacing, had to be properly controlled [17]. The gas flow rate and torch stand-off distance were kept constant.

The working ranges of all selected parameters were fixed by conducting trial runs, which were carried out by varying one of the parameters while keeping the rest of them at constant values. The working range of each process parameter was chosen by inspecting the bead for a smooth appearance without any visible defect. The upper limit of a factor was coded as +2 and the lower limit was coded as -2. The coded values for intermediate ranges were calculated using the following equation:

$$X_i = 2\{2X - (X_{max} - X_{min})\}/(X_{max} - X_{min}) \qquad (1)$$

where X_i is the required coded value of a variable X; X is any value of the variable from X_{max} to X_{min}; X_{min} is the lower level of the variable, and X_{max} is the upper level of the variable. The chosen levels of the process parameters with their units and notations are given in Table 1.

The experiments were conducted by using an automatic PTA welding machine fabricated by Primo Automation Systems, Chennai, India. The experiments were based on central composite rotatable full-factorial design matrix and conducted at random to avoid systematic errors creeping into the system. Colmonoy 5 was deposited over stainless-steel 316 L plates of size 150 mm × 90 mm × 30 mm. Torch stand-off distance, oscillating frequency, plasma/central gas flow rate, shielding gas flow rate and powder/carrier gas flow rate were kept constant, respectively, at 10 mm, 72 cycles per minute, 3.5 lpm, 12 lpm, and 1.5 lpm, during hardfacing.

The hardfaced plates were cross-sectioned at their midpoints to get the test samples (a typical weld cross

Table 1 Control parameters and its levels

Parameter	Units	Notation	Factor levels				
			-2	-1	0	+1	+2
Welding current	A	A	130	140	150	160	170
Oscillation width	mm	O	12	14	16	18	20
Travel speed	mm min^{-1}	S	89	96	103	110	117
Preheat temperature	°C	T	250	300	350	400	450
Powder feed rate	gm min^{-1}	F	38	40	42	44	46

section is shown in Fig. 2). These samples were prepared by the usual metallographic polishing methods and etched with aquaregia solution for carrying out weld bead geometry measurements. The profiles of the weld beads were traced using an optical profile projector and the bead dimensions penetration **P**, reinforcement **R**, bead width **W** were measured. Then the areas of weld above and below the interface were measured for the calculation of dilution using AutoCAD software. The observed values of P, R, and W and the calculated values of dilution are given in Table 2.

2.1 Development of mathematical models

The response function representing any of the weld bead dimensions like penetration, reinforcement, etc., can be expressed [18–20] as Y=f (A, O, S, T, F) where, Y is the response or yield. The second order polynomial (regression equation) used to represent the response surface for k factors is given by

$$Y = b_o + \sum_{i=1}^{k} b_i x_i + \sum_{\substack{i=1 \\ i \neq j}}^{k} b_{ii} x_i^2 + \sum_{i,j=1}^{k} b_{ij} x_i x_j \tag{2}$$

The selected polynomial for five factors can be expressed as

$$\begin{aligned} Y = {} & b_o + b_1A + b_2O + b_3S + b_4T + b_5F + b_{11}A^2 \\ & + b_{22}O^2 + b_{33}S^2 + b_{44}T^2 + b_{55}F^2 + b_{12}AO \\ & + b_{13}AS + b_{14}AT + b_{15}AF + b_{23}OS + b_{24}OT \\ & + b_{25}OF + b_{34}ST + b_{35}SF + b_{45}TF \end{aligned} \tag{3}$$

Where b_o is free term of the regression equation, the coefficients b_1, b_2, b_3, b_4, and b_5 are linear terms, the coefficients b_{11}, b_{22}, b_{33}, b_{44}, and b_{55} are quadratic terms, and the coefficients b_{12}, b_{13}, b_{14}, b_{15}, b_{23}, b_{24}, b_{25}, b_{34}, b_{35} and b_{45} are interaction terms [18–20].

The less significant coefficients were eliminated without affecting the accuracy of the developed model by using student *t*-test. Using Systat software (version 11) back-elimination technique was used to determine significant coefficients. The final mathematical model was constructed using the significant coefficients.

The final mathematical models with parameters in coded form as determined by the above regression analysis are as follows:

$$\begin{aligned} \text{Penetration, } P = {} & 0.970 + 0.240A - 0.043O - 0.099S \\ & - 0.068T - 0.111F + 0.135AT \\ & + 0.117OS + 0.098OT + 0.130ST \\ & - 0.126SF + 0.107T^2 \end{aligned} \tag{4}$$

$$\begin{aligned} \text{Reinforcement, } R = {} & 3.49 - 0.022A - 0.179O - 0.075S \\ & + 0.021T + 0.067F + 0.061AO \\ & + 0.049AF + 0.053OS - 0.047A^2 \\ & - 0.044S^2 - 0.073T^2 \end{aligned} \tag{5}$$

$$\begin{aligned} \text{Bead width, } W = {} & 19.413 + 0.745A + 1.098O - 0.331S \\ & - 0.235T + 0.065F + 0.234OS \end{aligned} \tag{6}$$

$$\begin{aligned} \text{Dilution, } D = {} & 18.544 + 3.566A + 1.018O - 0.715S \\ & - 1.004T - 1.723F - 1.816OT \\ & + 1.780ST - 2.155SF + 1.762T^2 \end{aligned} \tag{7}$$

It was found that the reduced models were better than the full models because the adjusted R square values and

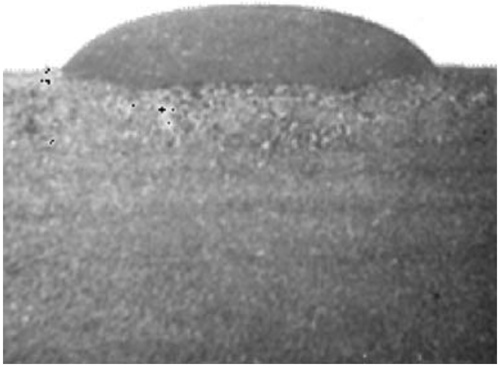


Fig. 2 Typical weld cross section

Table 2 Design matrix and observed values of weld bead dimensions

	Design matrix					Weld bead dimensions *			
S NO	A	O	S	T	F	P mm	R mm	W mm	%D
1	-1	-1	-1	-1	1	1.6	3.8	19	24.513
2	1	-1	-1	-1	-1	1.7	3.3	20.1	28.119
3	-1	1	-1	-1	-1	1.4	2.95	20.4	26.416
4	1	1	-1	-1	1	1.55	3.27	22.75	28.760
5	-1	-1	1	-1	-1	1.175	3.375	17.65	20.194
6	1	-1	1	-1	1	0.4	3.4	18	10.803
7	-1	1	1	-1	1	0.75	2.9	20.6	16.791
8	1	1	1	-1	-1	1.65	2.9	21.5	33.353
9	-1	-1	-1	1	-1	0.8	3.5	17.2	15.845
10	1	-1	-1	1	1	1.65	3.7	19.7	24.844
11	-1	1	-1	1	-1	0.55	3.1	19.8	14.480
12	1	1	-1	1	1	1	3.25	20.85	19.420
13	-1	-1	1	1	1	0.55	3.5	17	12.246
14	1	-1	1	1	-1	1.45	3.2	18	26.240
15	-1	1	1	1	-1	0.7	3.2	18.9	17.020
16	1	1	1	1	1	1.1	3.4	21.2	20.893
17	-2	0	0	0	0	0.275	3.475	18	7.278
18	2	0	0	0	0	1.65	3.3	21.3	28.475
19	0	-2	0	0	0	1.1	3.85	17.9	17.334
20	0	2	0	0	0	0.9	3.2	21.4	22.391
21	0	0	-2	0	0	0.75	3.65	20	13.132
22	0	0	2	0	0	0.75	3.15	19.5	16.977
23	0	0	0	-2	0	1.1	3.35	18.7	20.244
24	0	0	0	2	0	1.5	3.22	19.55	27.18
25	0	0	0	0	-2	0.87	3.52	19.5	15.320
26	0	0	0	0	2	0.7	3.55	19	13.477
27	0	0	0	0	0	0.95	3.55	19.4	18.617
28	0	0	0	0	0	0.95	3.5	18.5	17.490
29	0	0	0	0	0	1.2	3.55	19.2	20.140
30	0	0	0	0	0	0.9	3.4	18.6	17.890
31	0	0	0	0	0	0.9	3.6	19.4	18.620
32	0	0	0	0	0	1	3.35	18.6	21.200

* *P* penetration, *R* reinforcement, *W* width and *D* dilution.

standard error of estimates of reduced models were found to be higher and lower, respectively, than that of full models.

3 Implementation of GA

The genetic algorithm (GA), a computerized search procedure, inspired by Darwin's theory of biological evolution, has been recognized as a general optimization method to produce global and robust solutions to optimization problems. A random population with ten chromosomes was initially generated. The chromosomes generated were selected by using the Roulette wheel selection scheme and then the selected chromosomes were subjected to genetic operations, crossover, and mutation. We have employed single-point crossover in this work [21]. The chromosomes were tested for acceptability of solutions. The generation was stopped when the end condition was satisfied. The procedure was repeated until the termination criterion was reached [22]. In the present study, the termination criterion is the number of generations.

3.1 Evaluation of fitness function values

The optimization of bead parameters was carried out by considering their respective mathematical equations as their objective functions. The program was developed using Turbo C. It is desirable to minimize penetration and dilution and to maximize reinforcement and bead width. The fitness function was taken as the inverse of objective function for minimizing problems and the objective function itself was taken as the fitness function for maximizing problems.

Table 3 Results of generations for minimizing penetration

Generations	A	O	S	T	F	Penetration, mm
1	150	16	117	400	46	0.345
2	150	16	117	400	46	0.345
3	150	16	117	400	46	0.345
4	150	16	117	400	46	0.345
13	150	16	117	400	46	0.345
14	130	12	103	400	46	0.319
15	130	12	103	400	46	0.319
52	130	12	103	400	46	0.319
53	140	18	110	450	46	0.317
54	140	18	110	450	46	0.317
24	140	18	110	450	46	0.317
99	140	18	110	450	46	0.317
100	140	18	110	450	46	0.317

3.2 Bounds

The bounds or constraints were set to the weld Parameters as follows:

Penetration	$0.3\ \text{mm} < P < 1.7\ \text{mm}$
Reinforcement	$2.5\ \text{mm} < R < 4.5\ \text{mm}$
Bead width	$15\ \text{mm} < W < 25\ \text{mm}$
Dilution	$6 < \%D < 29$

For dilution, the constraints were applied based on the bounds of penetration, reinforcement, and bead width as mentioned above. Similarly, the constraints of other objective functions were based on the bounds of remaining weld parameters. Chromosomes not found within the bounds were not considered or eliminated.

4 Results and discussion

In order to select the genetic algorithm parameters such as crossover probability, mutation probability, population size, chromosome length, and maximum number of generations, a parametric study was carried out. The values of population size, chromosome length, and number of generations were taken as 10, 5, and 100, respectively, for all the bead geometry variables. Based on several test runs, the GA parameters were selected and optimization was carried out until the termination criterion was satisfied. The obtained results were also compared with the results obtained using Microsoft Excel Solver which used Generalized Reduced Gradient (GRG2) non-linear optimization code developed by Leon Lasdon, University of Texas at Austin, and Allan Waren, Cleveland State University [16].

4.1 Minimization of penetration

The cross over and mutation probability values were selected as 0.85 and 0.3, respectively, for the attempt on minimization of penetration. The results of generations for minimizing penetration using GA are shown in Table 3. The minimum penetration that can be obtained from Fig. 3 is 0.317 mm and the corresponding optimum process parameters are A=140 A, O=16 mm, S=103 mm/min, T=450°C, F=46 g/min. The minimum penetration attained from optimization using Solver was 0.36 mm and the corresponding process parameters were A=140 A, O=18 mm, S=117 mm/min, T=350°C, F=44 g/min for the same bounds and number of iterations. The selected values of other Solver parameters were tolerance=5%, precision=0.000001 and convergence=0.0001.

4.2 Maximization of reinforcement

The cross over and mutation probability values were selected as 0.85 and 0.28, respectively, for the study on maximization of reinforcement. The maximum reinforcement obtained from GA is 4.165 mm and the predicted

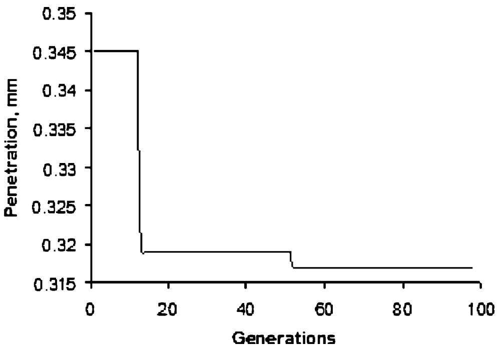


Fig. 3 Generations against penetration

Table 4 Results of generations for minimizing dilution

Generations	A	O	S	T	F	% dilution
1	140	16	89	350	40	13.821
2	140	16	89	350	40	13.821
3	140	16	89	350	40	13.821
4	130	16	96	350	40	11.695
8	130	16	96	350	40	11.695
9	130	16	89	350	40	10.255
27	130	16	89	350	40	10.255
28	130	14	103	350	44	8.671
31	130	14	103	350	44	8.671
32	130	12	103	350	44	7.653
35	130	12	103	350	44	7.653
36	130	12	103	300	44	6.787
82	130	12	103	300	44	6.787
83	130	14	89	350	38	6.65
84	130	14	89	350	38	6.65
85	130	12	89	350	38	5.632
99	130	12	89	350	38	5.632
100	130	12	89	350	38	5.632

process parameters are A=130 A, O=12 mm, S=89 mm/min, T=350°C, F=40 g/min. The maximum reinforcement attained using Solver is 4.115 mm and the corresponding process variables are A=140 A, O=12 mm, S=89 mm/min, T=250°C, F=46 g/min.

4.3 Maximization of bead width

For the maximization of bead width, cross over and mutation probability values were selected as 0.89 and 0.23, respectively. The maximum bead width that can be obtained using GA is 23.973 mm and the corresponding process variables are A=170 A, O=20 mm, S=117 mm/min, T=250°C, F=46 g/min. The maximum bead width that can be attained from optimization using Solver is also 23.973 mm with the same predicted values of process parameters.

4.4 Minimization of dilution

The cross over and mutation probability values were selected as 0.82 and 0.25, respectively, for the attempt on minimization of dilution. GA results for dilution with generations are tabulated in Table 4. The minimum % dilution that can be obtained is 5.632 and the corresponding process parameters are A=130 A, O=12 mm, S=89 mm/min, T=350°C, F=38 g/min. Figure 4 depicts the convergence of dilution with corresponding changes in generations. The minimum % dilution that can be optimized using solver is 6.356 and the corresponding process parameters are A=140 A, O=20 mm, S=117 mm/min, T=300°C, F=46 g/min. Low dilution being the most important criteria in a hardfaced component, the optimized results of process parameter values for minimization of dilution could be useful for any hardfacing application. Hence, the results of GA are better than the results of Solver, which indicates GA is more effective.

5 Conclusions

Genetic algorithm was used to achieve optimal weld bead dimensions in an effective manner. In the case of any surfacing like hardfacing, bead geometry plays an important role in determining the properties of the surface exposed to the hostile environments and in reducing the cost of manufacturing. In this computational approach, the objective functions are aimed at minimizing penetration and dilution, and maximizing reinforcement and weld width. The results obtained from GA are better than the results obtained using Excel Solver.

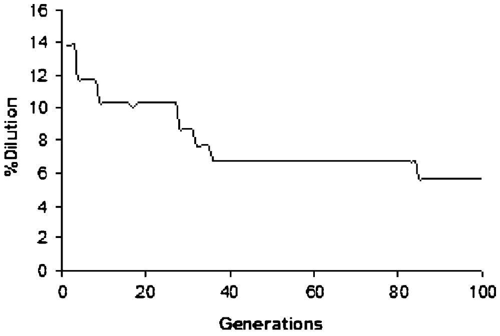


Fig. 4 Generations against % dilution

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