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Modelling, analysis and optimisation of weld bead parameters of nickel based overlay deposited by plasma transferred arc surfacing

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ABSTRACT

Purpose: Plasma Transferred Arc surfacing is increasingly used in applications where enhancement of wear, corrosion and heat resistance of materials surface is required. The shape of weld bead geometry affected by the PTA Welding process parameters is an indication of the quality of the weld. In the paper the modelling, analysis and optimization of weld bead parameters of nickel based overlay deposited by plasma transferred arc surfacing are made.

Design/methodology/approach: The experiments were conducted based on a five factor, five level central composite rotatable design and a mathematical model was developed using multiple regression technique. The direct and interaction effects of input process parameters of PTA Hardfacing on weld bead geometry are discussed. Finally, Microsoft Excel Solver has been used to optimize the process parameter with a view to economize the powder and achieve the desirable bead dimensions.

Findings: Penetration, dilution and total area are increased when the welding current is increased but reinforcement marginally increases and then decreases. Penetration, weld width, dilution and total area decrease when travel speed is increased. Reinforcement increases slightly and then decreases.

Practical implications: The developed mathematical models can be used to predict the dimensions of the weld bead and dilution.

Originality/value: This paper highlights the development of a mathematical model correlating various process parameters to weld bead geometry in PTA hardfacing of Colmonoy 5, a Nickel based alloy over Stainless steel 316 L plates.

Keywords: PTA welding; Overlay; Stainless steel 316L; Colmonoy; Dilution; Penetration; Reinforcement; Regression analysis; Mathematical model; Validation; Optimization

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METHODS OF ANALYSIS AND MODELLING

1. Introduction

Weld deposition of hardfacing alloys is commonly employed to enhance the tribological life of Engineering components subjected to hostile environments. The reclamation of worn out metal parts is demanded worldwide and for this demand PTA hardfacing of hard, wear resistant thin surface layer of metals and alloys on suitable substrates is one of the proven surfacing techniques [7]. In the recent years, PTA Surfacing finds extensive use in applications such as valve industries, Hydraulic machineries, Mining industries, Earth moving equipment, Chemical, Nuclear and Thermal power plants etc. PTA process can be considered as an advanced Gas Tungsten Arc welding process more widely used for overlay applications. Eschnauer [4] reviewed various hard material and alloy powders for plasma surface coating. The metal and alloy powder is carried from the powder feeder to the central electrode holder in the arc-gas stream. From the electrode holder the powder is directed to the constricted arc zone, where it is melted and fusion bonded to the base metal. Thus, smooth, thin deposits of overlays can be made through this way of precise control of feedstock by PTA welding process. Colmonoy 5, a Nickel based alloy (Ni-Cr-B-Si-C) provides excellent resistance to abrasive and adhesive wear with resistance to corrosion and high temperature oxidation. It is widely applied in Thermal power plants, Chemical industries, Nuclear reactors, food processing industries etc.

In nuclear reactors, use of Co based stellite alloys lead to induced activity which will harm the personnel involved in the maintenance of reactor components. Colmonoy 5 is a good alternative to the Co based alloys used [9,15] in nuclear applications. Das *et al.* [3] fabricated wear resistant bushes made of hardfacing alloys for high temperature applications. They reported that there was a growing tendency to replace Co based alloys by Nickel based alloys, due to the high cost and scarcity of cobalt based alloys. The problem of cracking susceptibility of nickel based Colmonoy alloy hardfaced deposits can be controlled by using preheating and slow cooling during deposition. Compared to other welding processes PTA surfacing requires less quantity of material to be deposited with improved mechanical and metallurgical properties. All these desirable properties of coatings are degraded if dilution which is an interalloying of hard surfacing alloy with base metal increases. Dilution is very much based on the weld bead geometry as shown in Fig. 1.

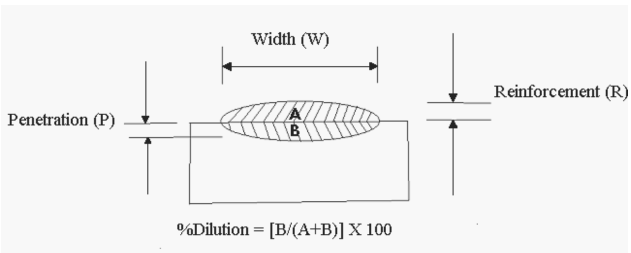

Fig. 1. Weld bead geometry

The shape of the weld bead geometry is affected by the values of PTA process parameters kept during deposition. These process parameters should be well established and categorized to enable automation and robotisation of PTA surfacing. Therefore it is imperative to develop mathematical models to predict the bead geometry and study the direct and interaction effects of various PTA process parameters on the weld bead shapes. The selection of welding procedure must be more specific to ensure that adequate bead quality is obtained [8]. Further, a complete control over the process parameters is essential to produce quality welds with required bead geometry based on which the integrity of the weldment is known. It has been reported by researchers that in PTA surfacing, process quality can be represented by bead shape [11]. Thus the weld pool geometry plays an important role in determining the mechanical and corrosion properties of the weld. Therefore, it is very important to select and control the welding process parameters for obtaining optimal weld pool geometry. Marimuthu and Murugan [11] studied the effect of process parameters on weld bead geometry for stellite 6 PTA hard facing. It was reported that five level factorial technique can be employed for developing models to predict weld bead geometry [1,5,6,12,13]. In this work, automatic PTA hardfacing was carried out for depositing Colmonoy 5 over Stainless steel 316L plates of size 150 mm x 90 mm x 30 mm. The experiments were based on the central composite rotatable design matrix. Regression analysis was used to develop the model and the analysis of variance method was used to test their adequacy. Also, the main objective of this study is to optimize the process parameters achieving minimum penetration, maximum reinforcement, maximum bead width and minimum dilution using Microsoft Excel Solver [16]. As the amount of data generated in the iterative process for optimization was enormous and each design cycle required number of calculations, software like solver has been used.

2. Plan of investigations

The work to be carried out was planned in the following order:

1. Identification of important process parameters
2. Finding the upper and lower limits with different levels of the identified process parameters
3. Development of Design matrix
4. Conducting experiments as per the design matrix
5. Recording the responses
6. Calculation of regression coefficients and development of mathematical model
7. Development of final mathematical model
8. Checking adequacy of the developed model
9. Presenting the main and significant interaction effects of process parameters on bead geometry in graphical form.
10. Optimization of weld bead parameters using Microsoft Excel Solver

2.1. Identification of important process parameters

The independently controllable process parameters identified based on their significant effect on weld bead geometry to carry out the experimental work were welding current (A), Oscillation

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	^{o}C	T	250	300	350	400	450
Powder feed rate	gm min^{-1}	F	38	40	42	44	46

width (O), Travel speed (S), Preheat temperature (T) and Powder feed rate (F). Preheat temperature and oscillation amplitude [17] which may affect crack formation during hardfacing, have to be properly controlled. The gas flow rate and Torch stand off distance were kept at constant levels.

2.2. Finding the limits and levels of the identified process parameters

The working ranges of all selected parameters were fixed by conducting trial runs. This was 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 decided upon by inspecting the bead for a smooth appearance without any visible defects. 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

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

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.

2.3. Development of design matrix

The design matrix chosen to conduct the experiment was a central composite rotatable design. It consists of 32 sets of coded conditions and comprising a half replication of $2^4 = 16$ factorial design with 6 centre points and 10 star points. All the welding parameters at the middle level (0) constitute centre points whereas the combination of each welding parameter at its lower value (-2) or higher value (2) with the other four parameters at the middle levels constitute the star points [2,10,14]. Thus the 32 experimental runs allowed the estimation of linear, quadratic and two-way interactive effects of the process parameters on the weld bead geometry.

2.4. Conducting experiments as per design matrix

The experiments were conducted by using an automatic PTA welding machine fabricated by Primo Automation systems as shown in Fig. 2. The PTA system shown in the figure has six modules namely traverse carriage unit, oscillator unit, powder feed unit, water cooling unit, turn table unit and torch unit. All the units are supporting the effective functioning of the total PTA system.

Fig. 2. Plasma transferred arc welding equipment

The experiments were conducted according to the design matrix at random to avoid systematic errors creeping into the system. Colmonoy 5 was deposited over stainless steel 316 L plates. 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 while hardfacing.

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	TA mm^2	%D
1	-1	-1	-1	-1	1	1.6	3.8	19	70.357	24.513
2	1	-1	-1	-1	-1	1.7	3.3	20.1	71.102	28.119
3	-1	1	-1	-1	-1	1.4	2.95	20.4	62.173	26.416
4	1	1	-1	-1	1	1.55	3.27	22.75	78.668	28.760
5	-1	-1	1	-1	-1	1.175	3.375	17.65	55.019	20.194
6	1	-1	1	-1	1	0.4	3.4	18	50.750	10.803
7	-1	1	1	-1	1	0.75	2.9	20.6	51.405	16.791
8	1	1	1	-1	-1	1.65	2.9	21.5	66.022	33.353
9	-1	-1	-1	1	-1	0.8	3.5	17.2	54.225	15.845
10	1	-1	-1	1	1	1.65	3.7	19.7	72.438	24.844
11	-1	1	-1	1	-1	0.55	3.1	19.8	53.404	14.480
12	1	1	-1	1	1	1	3.25	20.85	58.403	19.420
13	-1	-1	1	1	1	0.55	3.5	17	51.222	12.246
14	1	-1	1	1	-1	1.45	3.2	18	58.413	26.240
15	-1	1	1	1	-1	0.7	3.2	18.9	53.199	17.020
16	1	1	1	1	1	1.1	3.4	21.2	67.921	20.893
17	-2	0	0	0	0	0.275	3.475	18	50.858	7.278
18	2	0	0	0	0	1.65	3.3	21.3	72.312	28.475
19	0	-2	0	0	0	1.1	3.85	17.9	62.965	17.334
20	0	2	0	0	0	0.9	3.2	21.4	64.389	22.391
21	0	0	-2	0	0	0.75	3.65	20	62.969	13.132
22	0	0	2	0	0	0.75	3.15	19.5	54.486	16.977
23	0	0	0	-2	0	1.1	3.35	18.7	56.980	20.244
24	0	0	0	2	0	1.5	3.22	19.55	64.18	27.18
25	0	0	0	0	-2	0.87	3.52	19.5	60.219	15.320
26	0	0	0	0	2	0.7	3.55	19	58.383	13.477
27	0	0	0	0	0	0.95	3.55	19.4	60.809	18.617
28	0	0	0	0	0	0.95	3.5	18.5	57.552	17.490
29	0	0	0	0	0	1.2	3.55	19.2	62.483	20.140
30	0	0	0	0	0	0.9	3.4	18.6	57.372	17.890
31	0	0	0	0	0	0.9	3.6	19.4	60.913	18.620
32	0	0	0	0	0	1	3.35	18.6	58.830	21.200

* P - penetration, R - reinforcement, W - width, TA - total area & D - dilution

2.5. Recording the responses

The hardfaced plates were cross sectioned at their midpoints to get the test samples. A typical hardfaced plate and a typical weld cross section are shown in Fig. 3 & Fig. 4 respectively. Those 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**, weld 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 and Total area are given in Table 2.

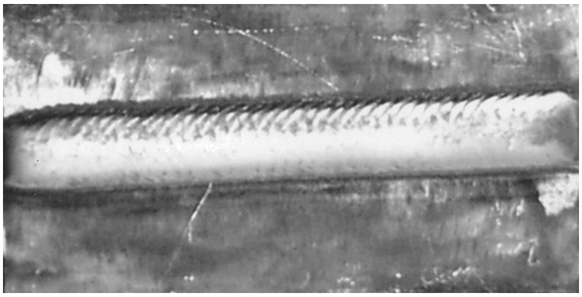

Fig. 3. Typical hard faced plate

Table. 3.
Comparison of square multiple R values and standard error of estimates for full and reduced models

	Adjusted square multiple, R		Standard error of estimate	
	Full model	Reduced model	Full Model	Reduced model
P	0.429	0.618	0.299	0.244
R	0.615	0.686	0.146	0.132
W	0.712	0.793	0.729	0.618
TA	0.535	0.681	4.851	4.015
%D	0.342	0.521	4.813	4.106

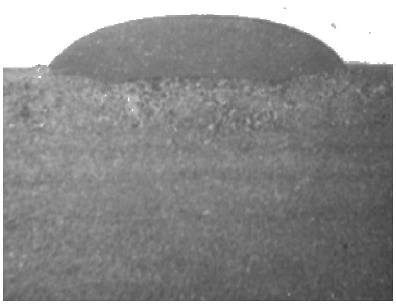

Fig. 4. Typical weld cross section

2.6. Calculation of regression coefficients and development of mathematical models

The response function representing any of the weld bead dimensions like penetration, reinforcement etc, can be expressed 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

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

The selected polynomial for five factors can be expressed as

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

were 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 [2,10,14].

2.7. Development of final mathematical model

From the calculated coefficients of the polynomial less significant coefficients were eliminated without affecting the accuracy of the developed model by using 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 determined by the regression analysis are as follows:

$$\text{Penetration, } P = 0.970 + 0.240A - 0.043O - 0.099S - 0.068T - 0.111F + 0.135AT + 0.117OS - 0.098OT + 0.130ST - 0.126SF + 0.107T^2 \quad (1)$$

$$\text{Reinforcement, } R = 3.49 - 0.022A - 0.179O - 0.075S + 0.021T + 0.067F + 0.061AO + 0.049AF + 0.053OS - 0.047A^2 - 0.044S^2 - 0.073T^2 \quad (2)$$

$$\text{Dilution, } D = 18.544 + 3.566A + 1.018O - 0.715S - 1.004T - 1.723F - 1.816OT + 1.780ST - 2.155SF + 1.762T^2 \quad (3)$$

$$\text{Width, } W = 19.413 + 0.745A + 1.098O - 0.331S - 0.235T + 0.065F + 0.234OS \quad (4)$$

$$\text{Total Area, } TA = 60.638 + 4.435A + 0.438O - 3.491S - 0.911T + 0.258F + 2.414OS + 3.212ST - 2.036SF \quad (5)$$

It was found that the reduced models were better than the full models, because the adjusted R square values and standard error of estimates of reduced models were higher and lower respectively than that of full models. The values of adjusted R square and standard error of estimates are given in Table. 3.

2.8. Assessing adequacy of developed models

The adequacies of the models were tested using the analysis of variance technique (ANOVA). According to this technique, if the calculated value of the F ratio of the model exceeds the standard tabulated value of the F ratio for a desired level of confidence (say 95%), then the model can be considered adequate within the confidence limit. The results of ANOVA are presented in Table. 4.

Table.4.
Analysis of variance for testing adequacy of models

	Sum of squares		Degrees of freedom		Standard F ratio	F- ratio	Remarks
	regression	residual	regression	Residual			
P	3.651	1.195	11	20	2.31	5.555	Adequate
R	1.374	0.349	11	20	2.31	7.162	Adequate
W	47.598	9.547	6	25	2.49	20.774	Adequate
TA	1196.718	370.792	8	23	2.38	9.279	Adequate
%D	721.065	370.944	9	22	2.35	4.752	Adequate

Table.5.
Comparison of predicted and actual values of bead parameters

S. No	Process parameters in coded form					Bead dimensions				Error %	
						Predicted		Actual			
	A	O	S	T	F	P	%D	P	%D	P	%D
1	-1.5	0.4	0.5	1.2	1	0.253	11.973	0.268	11.422	5.9	-4.6
2	2	0.03	-1	1.5	-0.5	1.881	25.912	1.850	24.020	-1.65	-7.3
3	1	-1	1.1	0.8	1.3	1.006	18.327	1.047	19.866	4.07	8.4

Error % = {(actual value – predicted value)/predicted value} X 100

3. Results and discussion

The developed mathematical models can be used to predict the dimensions of the weld bead and dilution. Also, accuracy of the models was determined by conducting conformity test runs six months after the development of the models using the same welding machine. In this procedure, the process variables were assigned intermediate values in order to carry out the conformity test runs and the responses were measured and recorded as shown in Table 5. The results show that models are accurate. Based on these models, the main and interaction effects of process parameters on bead dimensions were computed and plotted. It is also possible to substitute the values for bead dimensions and get the corresponding values of PTA process parameters in coded form.

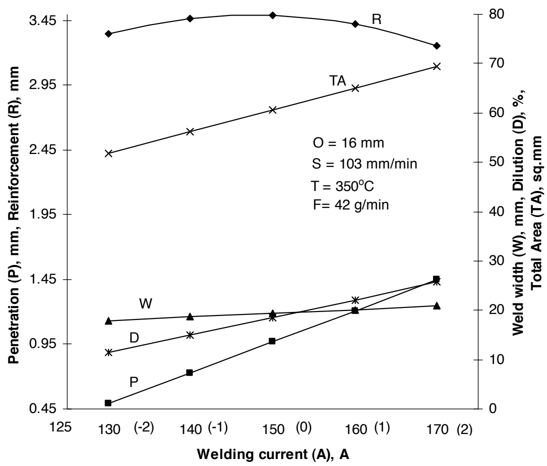

Fig. 5. Direct effects of welding parameters on welding current

3.1. Direct effects of welding parameters

Effect of Welding current on bead dimensions

Figure 5 shows that penetration P increases significantly when welding current A increases. This is attributed to the fact that heat input to the base metal increases when A is increased. Weld width W, dilution D and total area TA gradually increase as A increases. This is due to spreading of heat and increase in P resulting from more melting of base metal. Reinforcement R increases marginally and then decreases when A increases.

Effect of Oscillation width on bead dimensions

It is evident from Fig. 6 that R decreases with increase in oscillation width O. This could possibly due to the fact that the deposited metal got distributed along the width resulting in decrease in R. P decreases slightly when O increases which may be due to the increase of weld width. D increases with increase in O which could be due to the significant effect of decrease in R. TA is slightly increased due to more area covered from increase in O.

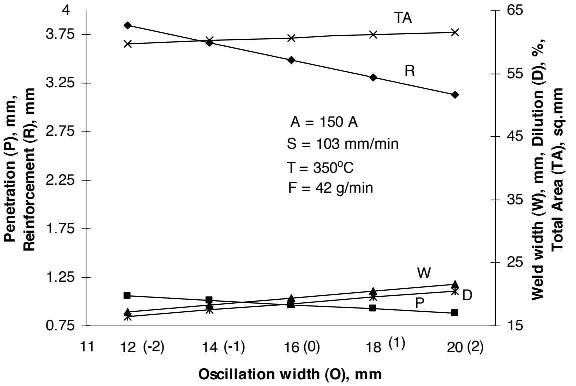

Fig. 6. Direct effects of welding parameters on oscillation width

Effect of Travel speed on welding variables

It is evident from Fig. 7 that P and D decrease steadily with increase in S. This could be attributed to the reduced heat input per unit length of weld bead when S is increased. R increases to an optimal value and then decreases with further increase in S due to the reduced amount of powder deposited per unit length of bead. W is not significantly affected.

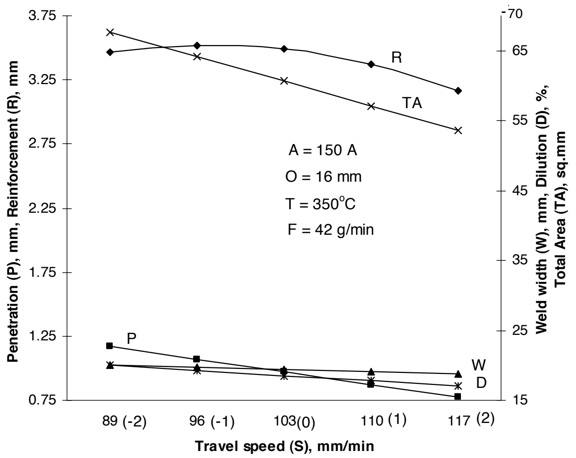

Fig. 7. Direct effects of welding parameters on travel speed

Effect of Preheat temperature on welding variables

It is evident from Fig. 8 that P and D decrease to a lower value when Preheat temperature T increases and increase with the further increase in T. This could be attributed to the following: At lower preheat temperature, the heat received from plasma arc will not spread in the stainless steel substrate due to its lower thermal conductivity resulting in cushioning of arc. At higher preheat temperature, the spreading of heat may occur resulting in arc penetration. R increases to a maximum value when T increases and then R decreases with the further increase in T. This again can be attributed to the same fact. W is not affected significantly by T.

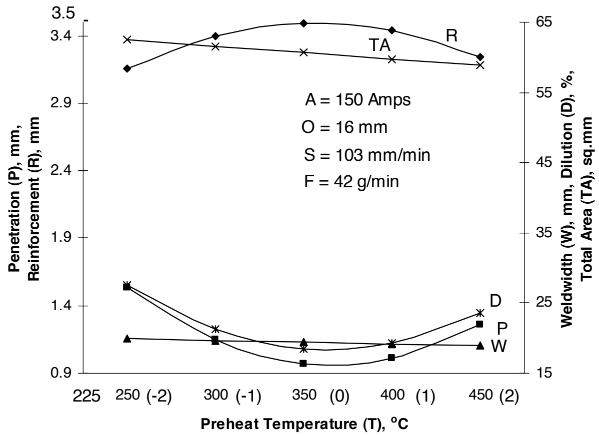

Fig. 8. Direct effects of welding parameters on preheat temperature

Effect of Powder feed rate on welding variables

It is obvious from Fig. 9 that R increases slightly with increase in Powder feed rate F due to increase in deposition of powder per unit length of bead. D and P decrease when F is increased. D decreases due to the combined effect of increase in R and decrease in P. W is not affected. TA also increases with the increase in F.

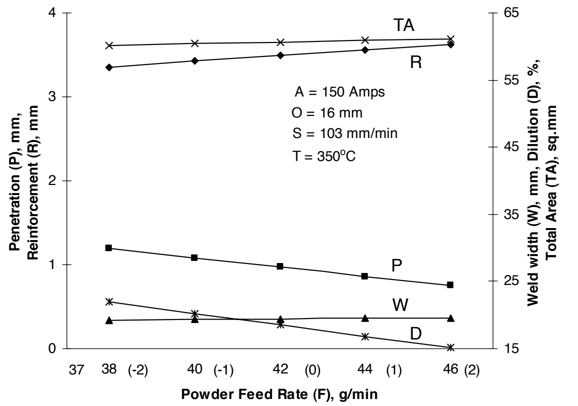

Fig. 9. Direct effects of welding parameters on powder feed rate

3.2. Interaction effects

The difference in effect of one variable when a second variable is changed from one level to another is known as interaction effect and study of interaction effects of process variables on bead dimensions is interesting and very useful for understanding the process behavior. In this study, to avoid complexity two way interactive effects of the variables are selected.

Interaction effects of welding current and Preheat temperature on Penetration

It is clear from Fig. 10 that P increases with increase in A for all values of T except at T = 250° C. This is due to the increase in heat input to the base metal from both factors A and T. Steep increase in P is found with increase in A at higher levels of T. It is because more heat input is given at higher levels of T.

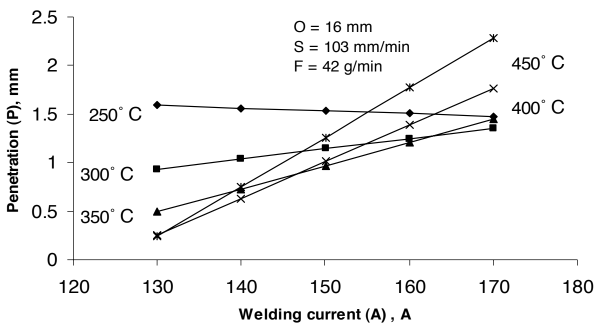

Fig. 10. Interaction effects of welding current and preheat temperature on penetration

Interaction effects of Travel speed and Powder feed rate on Dilution

It is seen from Fig. 11 that when F is at a lower value, D increases with increase in S. When F is at a higher value, D decreases with increase in S. It is because increase in F reduces the heat input to the base metal.

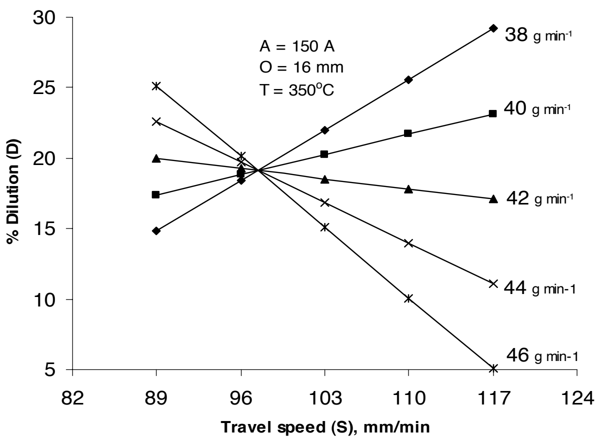

Fig. 11. Interaction effects of travel speed and powder feed rate on dilution

4. Optimization procedure

The main bead parameters penetration, reinforcement, weld width and dilution were optimized independently by considering their equations obtained from mathematical modeling as objective functions [16]. The formulated objective functions are available in the coded form. The optimization was carried out using Microsoft Excel Solver software. Solver is part of a suite of commands with what-if analysis tools. Solver works with a group of cells that are related, either directly or indirectly, to the objective function equation in the target cell. Solver adjusts the values in the changing cells, called the adjustable cells to produce the result. Constraints are applied to restrict the range of values of the variables used in the objective function. Microsoft Excel Solver tool uses the Generalized Reduced Gradient (GRG2) non-linear optimization code developed by Leon Lasdon, University of Texas at Austin, and Allan Waren, Clevel and State University. The results of optimization are given below:

Minimization of depth of penetration

Optimum values of process parameters:
A = -1 (140 A), O = 1 (18 mm), S = 2 (117 mm/min), T = 0 (350° C), F = 1 (44 gm/min).
Predicted response for penetration: P = 0.36 mm.

Maximization of height of reinforcement

Optimum values of process parameters:
A = -1 (140 A), O = -2 (12 mm), S = -2 (89 mm/min), T = 1 (400° C), F = 2 (46 gm/min).
Predicted response for reinforcement: R = 4.115 mm.

Maximization of weld width

Optimum values of process parameters:
A = 2 (170 A), O = 2 (20 mm), S = 2 (117 mm/min), T = -2 (250° C), F = 2 (46 gm/min).
Predicted response for weld width: W = 23.973 mm.

Minimization of dilution

Optimum values of process parameters:
A = -1 (140 A), O = 2 (20 mm), S = 2 (117 mm/min), T = -1 (300° C), F = 2 (46 gm/min).
Predicted response for dilution: D = 6.356 %

5. Conclusions

- A five level factorial technique can be employed easily for developing mathematical models for predicting weld bead geometry within the limits of the process parameters applied for hardfacing of Colmonoy 5.
- Penetration, dilution and total area are increased when the welding current is increased but reinforcement marginally increases and then decreases.
- Penetration, weld width, dilution and total area decrease when travel speed is increased. Reinforcement increases slightly and then decreases.
- When the powder feed rate is increased, reinforcement is increased and subsequently dilution is decreased. When preheat temperature is increased penetration and dilution finally increase, whereas reinforcement and total area decrease.
- Reinforcement and penetration are decreased slightly with increase in oscillation width but dilution and total area are increased.

- Two way interactive effects of welding variables are significant.
- The process parameters were optimized using Excel Solver to achieve the desired weld bead geometry.

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