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Optimization of Weld Bead Parameters of Nickel Based Overlay Deposited by Plasma Transferred Arc Surfacing with Adequacy Test

Bhaskarananda Dasgupta*, Pinaky Bhadury **
*(Department of Engineering Sciences & Humanities, Siliguri Institute of Technology, Siliguri, W.B)
** (Department of Engineering Sciences & Humanities, Siliguri Institute of Technology, Siliguri, W.B)

ABSTRACT
Plasma Transferred Arc surfacing is a kind of Plasma Transferred Arc Welding process. Plasma Transferred Arc surfacing (PTA) 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 this paper the analysis and optimization of weld bead parameters, during deposition of a Nickel based alloy Colmonoy on stainless steel plate by plasma transferred arc surfacing, are made and values of process parameters to produce optimal weld bead geometry are estimated. The experiments are conducted based on a five input process parameters and mathematical models are developed using multiple regression technique. The direct effects of input process parameters on weld bead geometry are discussed using graphs. Finally, optimization of the weld bead parameters, that is minimization of penetration and maximization of reinforcement and weld bead width, are made with a view to economize the input process parameters to achieve the desirable welding joint.
***Keywords* -** Adequacy test, Colmonoy; Optimization; Penetration; PTA welding; Reinforcement; Stainless steel 316L;

I. INTRODUCTION

Weld deposition of hard facing alloys is commonly employed to enhance the tribological life of Engineering components subjected to hostile environments. The clamation of worn-out metal parts is demanded worldwide and for this demand PTA hard facing 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 is extensively used in applications such as valve industries, Hydraulic machineries, Mining industries, Earthmoving 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. 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 feed stock by PTA welding process. Colmonoy5, 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 satellite alloys lead to induced activity which will harm the personnel involved in the maintenance of reactor components. Colmonoy5 is a good alternative to the Co based alloys used (9, 15) in nuclear applications, fabricated wearers instant bushes are made of hard facing alloys for high temperature applications. They report that there is 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 hard faced 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.

The shape of the weld bead geometry is affected by the values of PTA process parameters used in 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 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 deter mining the mechanical and corrosion properties of the weld. Therefore, process parameters for obtaining optimal weld-pool geometry. It is reported that five level factorial techniques can be employed for developing models to predict weld bead geometry(1,5,6,12,13).In this work, automatic PTA hard facing is carried out for depositing Colmonoy5 over Stainless steel 316L plates of size 150mm x 90mm x 30mm.The experiments are based on the central composite rotatable design matrix. Regression analysis was used to develop the model. Also, the main objective of this study is to optimize the weld bead parameters that is achieving minimum penetration, maximum reinforcement and maximum bead width which gives best weld joint and determining the corresponding process parameters. Penetration means the depth into substrate through which the filler metal penetrates. Reinforcement means height of filler metal on substrate. Weld width means the width of filler metal on substrate.

II. 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. Calculation of adequacy Test.
9. Presenting the relation of process variables on bead geometry in graphical form.
10. Results and discussions.
11. Optimization of weld bead parameter.

2.1. IDENTIFICATION OF PROCESS PARAMETERS-

The independently controllable process parameters identified based on their significant effect on weld bead geometry to carry out the experimental work are welding current(A),Oscillation width(O),Travel speed(S),Preheat temperature(T) and Powder feed rate(F) gas flow rate and Torch standoff distance. Welding current produce heat for fusion, Pre heat temperature and oscillation width (17) which may affect crack formation during hard facing, have to be properly controlled. Minimum torch travel speed gives better deposition of filler material on welding joints. In deposition of material the most effective process parameters are Welding current, Oscillation width, Travel speed, Preheat temperature and Powder feed rate, thus these process parameters are selected in the experiment and the Gas flow rate and Torch standoff distance are kept at constant levels.

2.2. LIMITS AND LEVELS OF PROCESS PARAMETERS-

It has been observed from different experiments that best deposition of nickel on steel plate occurs when the process parameters vary between the levels given in table 1.The working ranges of all selected parameters are fixed by conducting trial runs. This are carried out by varying one parameter while keeping the rest of them at constant values. The working range of each process parameter is decided upon by inspecting the bead for a smooth appearance without any visible defects. The upper limit of a factor is coded as +2, in between levels is -1, 0,1and the lower limit is coded as-2. The chosen levels of the process parameters and notations are given in Table 1.

Table 1: Levels of Process Variable

PARAMETER	UNITS	NOTATIONS	Factor Levels				
			-2	-1	0	1	2
Welding current	Amps	A	120	130	140	150	160
Oscillation width	mm	O	10	12	14	16	18
Travel speed	mm min-1	S	79	86	93	100	107
Preheat Temp.	°C	T	200	250	300	350	400
Powder Feed Rate	gm min-1	F	36	38	40	42	44

2.3. DEVELOPMENT OF DESIGN MATRIX-

The design matrix is developed according to the combinations normally taken in Genetic Algorithm process for five process parameters. The design matrix chosen to conduct the experiment is a central composite rotatable design. It consists of 32sets of coded conditions and comprising a half replication of 24=16 factorial design with 6centre 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. EXPERIMENTAL SETUP AND PROCEDURE-

The experiments are conducted by using a PTA welding machine, fabricated by National Automation Calcutta. Experiments are conducted by company and corresponding data are taken from their experiments. The PTA system has six modules namely traverse carriage unit, oscillator unit, powder feed unit, water-cooling unit, turntable unit and torch unit. All the units are supporting the effective functioning of the total PTA system. The experiments are conducted according to the design matrix at random to avoid systematic errors creeping into the system. Colmonoy 5 is deposited over stainless steel 316L plates 15cm x 9 cm.x3cm. Torch standoff distance, oscillating frequency, plasma/central gas flow rate, shielding gas flow rate and powder/carrier gas flow rate are kept constant respectively at 10mm, 72cycles per minute, 3.5 lpm, 12 lpm and 1.5 lpm while hard facing.

2.5. EXPERIMENTAL OBSERVATION-

The hard faced plates were cross sectioned at their midpoints to get the test samples. Those samples are 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 and the bead dimensions i.e. Penetration (P), reinforcement (R) and weld width (W) are measured. The observed values of P, R and W are given in Table: 2.

	Design matrix					weld bead dimensions		
SNo	A	O	S	T	F	Pmm	Rmm	Wmm
1	-1	-1	-1	-1	1	1.5	3.7	20
2	1	-1	-1	-1	-1	1.6	3.2	20.2
3	-1	1	-1	-1	-1	1.5	2.92	20.5
4	1	1	-1	-1	1	1.52	3.25	22.76
5	-1	-1	1	-1	-1	1.17	3.370	17.66
6	1	-1	1	-1	1	0.5	3.3	19
7	-1	1	1	-1	1	0.72	2.8	20.7
8	1	1	1	-1	-1	1.62	2.8	21.6
9	-1	-1	-1	1	-1	0.7	3.4	17.3
10	1	-1	-1	1	1	1.62	3.6	19.8
11	-1	1	-1	1	-1	0.52	3.1	19.9
12	1	1	-1	1	1	1	3.20	20.85
13	-1	-1	1	1	1	0.52	3.5	17
14	1	-1	1	1	-1	1.42	3.1	18
15	-1	1	1	1	-1	0.8	3.1	18.9
16	1	1	1	1	1	1.1	3.4	21.2
17	-2	0	0	0	0	0.275	3.475	18
18	2	0	0	0	0	1.65	3.3	21.3
19	0	-2	0	0	0	1.1	3.85	17.9
20	0	2	0	0	0	0.9	3.2	21.4
21	0	0	-2	0	0	0.75	3.65	20
22	0	0	2	0	0	0.75	3.15	19.5
23	0	0	0	-2	0	1.1	3.35	18.7
24	0	0	0	2	0	1.5	3.22	19.55
25	0	0	0	0	-2	0.87	3.52	19.5
26	0	0	0	0	2	0.7	3.55	19
27	0	0	0	0	0	0.95	3.55	19.4
28	0	0	0	0	0	0.95	3.5	18.5
29	0	0	0	0	0	1.2	3.55	19.2
30	0	0	0	0	0	0.9	3.4	18.6
31	0	0	0	0	0	0.9	3.6	19.4
32	0	0	0	0	0	1	3.35	18.6

Table 2: Design Matrix and Observed Values of Weld Bead Dimensions

III. 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) use to represent the response surface for k factors are given by:

$$Y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{\substack{i=1 \\ i \neq j}}^{k} b_{ii}\, x_i^{\,2} + \sum_{i,j=1}^{k} b_{ij}\, x_i x_j \quad (1)$$

3.1. THE SELECTED POLYNOMIAL FOR FIVE FACTORS CAN BE EXPRESSED:

$$Y = b_0 + b_1 A + b_2 O + b_3 S + b_4 T + b_5 F + b_{11} A^2 + b_{22} O^2 + b_{33} S^2 + b_{44} T^2 + b_{55} F^2 + b_{12} AO + b_{13} AS + b_{14} AT + b_{15} AF + b_{23} OS + b_{24} OT + b_{25} OF + b_{34} ST + b_{35} SF + b_{45} TF \quad (2)$$

where b_0 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.

3.2. DEVELOPMENT OF FINAL MATHEMATICAL MODEL:

The co-efficient of the polynomials has been found by using MATLAB. Software.

The final mathematical models determined by the regression analysis are as follows:

$$P = 0.95063 + 0.252A - 0.038O - 0.107S - 0.063T - 0.134F + 0.027A^2 + 0.0368\,O^2 - 0.025S^2 + 0.111T^2 - 0.016F^2 + 0.072AO - 0.028AS + 0.159AT - 0.027AF + 0.110OS - 0.091OT - 0.064OF + 0.122ST + 0.092SF + 0.023TF \quad (3)$$

$$R = 3.514 - 0.003A - 0.179O - 0.074S + 0.020T + 0.048F - 0.049A^2 - 0.014O^2 - 0.045S^2 - 0.074T^2 - 0.012F^2 + 0.089AO - 0.026AS + 0.036AT + 0.051AF + 0.053OS + 0.043OT - 0.059OF \quad (4)$$

$$W = 18.96 + 0.856A + 1.11O - 0.346S - 0.220T + 0.093F + 0.164A^2 + 0.164O^2 + 0.189S^2 + 0.033T^2 + 0.064F^2 + 0.253AO - 0.303AS + 0.284AT - 0.088AF + 0.212OS - 0.080OT - 0.171OF + 0.105ST + 0.1714SF - 0.165TF \quad (5)$$

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

Table: 3 Comparison of Square multiple R values and standard error for full and reduced models:

	Adjusted square multiple, R		Standard error of estimate	
	Full Model	Reduced Model	Full Model	Reduced Model
P	0.428	0.617	0.298	0.243
R	0.614	0.685	0.145	0.131
W	0.711	0.792	0.727	0.616

IV. CALCULATING ADEQUACY OF THE MODELS DEVELOPED:

The adequacies of the models were calculated using ANOVA Technique. If the calculated value of F ratio of the models exceeds the standard tabulated value of the F ratio for a desired level of confidence say (95%), the model can be considered adequate within the confidence limit. The calculated results of ANOVA are given in the Table 4.

Table: 4 Calculations for Adequacy test:

	Sum of Squares		Degrees of Freedom		Standard F ratio	F-ratio	Remarks
	Regression	Residual	Regression	Residual			
P	3.650	1.194	11	20	2.31	5.554	adequate
R	1.373	0.347	11	20	2.31	7.161	adequate
W	47.596	9.546	6	25	2.48	20.775	adequate

V. RESULTS AND DISCUSSION

The developed mathematical models can be used to predict the dimensions of the weld bead. Based on these models, the effects of process parameters on bead dimensions are computed and plotted by varying one parameter and keeping others at middle value.

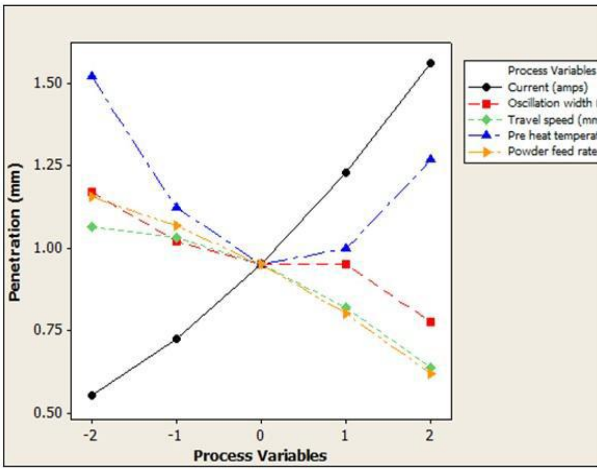

Figure 1: Direct effect of process variables on penetration

5.1. Direct effects of Process variables on Penetration:

Figure 1 shows that Penetration (P) increases significantly when welding current increases. This is attributed to the fact that heat input to the base metal increases when current is increased. Penetration decreases as Oscillation width increases. This is due to spreading of heat resulting from more melting of base metal. Penetration decreases steadily with the increase of Travel speed as less amount of powder is deposited per unit length of bead. Penetration decreases to a lower value when pre heat temperature increases but afterwards penetration increases with further increase of preheat temperature. This may be for the reasons that at lower preheat temperature the heat received from plasma arc will not spread in the stainless steel substrate due to lower thermal conductivity resulting in cushioning of arc. Penetration decreases with increase of Powder feed rate.

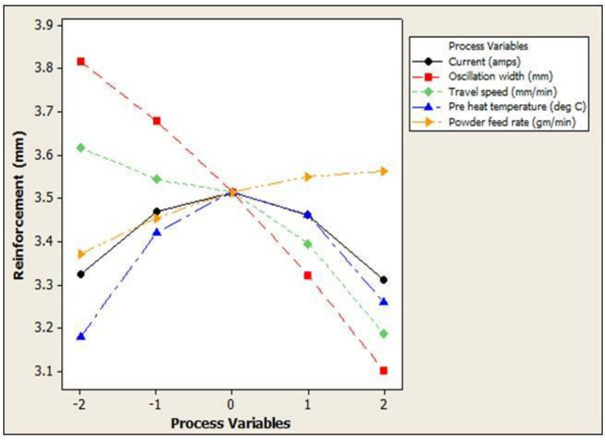

Figure 2: Direct effect of process variables on reinforcement

5.2. Direct effect of Process variables on Reinforcement:

It is evident from Fig 2 that Reinforcement (R) increases initially and then decreases with increase of welding current. Reinforcement decreases with increase in oscillation width. This could possibly due to the fact that the deposited metal gets distributed along the width resulting in decreasing in reinforcement. Reinforcement decreases steadily from highest value with the increase of travel speed. This is due to reduce amount of powder deposit per unit length of bead. Reinforcement increases with increase of preheat temperature to its peak value then decreases with further increase of preheat temperature. Reinforcement increases steadily with increase of powder feed rate as more powder is deposited per unit length of weld bead.

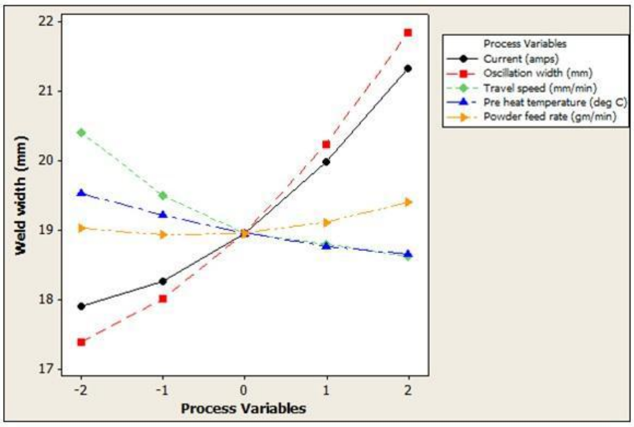

Figure 3: Direct effect of process variables on weld width

5.3. Direct effects of Process variables on Weld width:

Figure 3 shows that Weld width increases with increase of welding current .This is due to spreading of heat resulting of melting of more metal. Weld width increases steadily with increase in oscillation width due to decrease of Penetration. Weld bead decreases with increase of torch travel speed .This may be for reduced heat input per unit length of weld bead when travel speed is increased. Weld bead width reduces as the Preheat temperature increases. Weld width decreases initially but increases with increase of powder feed rate.

A better weld should have bead parameters as follows

1. Penetration should be minimum.
2. Reinforcement should be maximum.
3. Weld width should be maximum.

The bead parameters are found independently considering their equations obtain from mathematical modeling as objective function. The best weld bead parameters are found by analyzing the graph between weld bead parameters and process parameters .The best weld bead parameters and the corresponding process parameters are as follows:

a) Minimization of depth of penetration-
Optimum value of process parameters:

A (amps)	O (mm)	S(mm/min)	T(°C)	F
120 (-2)	18 (2)	107(2)	300(0)	

Predicted response for penetration P_{min}= 0.463mm

b) Maximization of height of reinforcement-

Optimum value of process parameters:

A (Amps)	O (mm)	S(mm/min)	T(°C)	F (gm/min)
140 (0)	10 (-2)	79 (-2)	300(0)	44(2)

Predicted response for reinforcement
$R_{maximum}$=4.29mm

c) Maximization of weld width-

Optimum value of process parameters:

A (Amps)	O (mm)	S(mm/min)	T(°C)	F (gm/min)
160 (2)	18 (2)	79 (-2)	250(-2)	44 (2)

Predicted response for weld width
$W_{maximum}$=26.58mm

Hence the best of bead parameters for different sets of process variable is as follows:

1. Penetration=0.463mm
2. Reinforcement = 4.29mm
3. Weld width = 26.58mm

VI. OPTIMIZATION

It is very difficult for an operator to perform the welding process to get best bead parameters using different sets of process variable. Hence it is necessary to find a single set of process variable which will provide the optimal bead parameters and are very close to the best bead parameters find with different sets of process variable. Here optimization of the bead parameters is done by considering the three sets of process variable obtained for best bead parameters as mentioned above. All possible combinations of process variables are carried by using MATLAB software and the corresponding bead parameters are recorded, neglecting negative ones. It can be seen that there are 24 sets of valid process variables giving as many sets of bead parameters. It is found from results that optimum set of bead parameter is as follows:

The process variables and corresponding optimum bead parameters are given below:

Table 5: Optimized values of bead parameters and corresponding process variables

A (amp)	O(mm)	S(mm/min)	T(°C)	F (gm./min)	P(mm)	R(mm)	W(mm)
160(2)	18(2)	79(-2)	300(0)	44(2)	0.640	3.1358	25.768

Condition for better welding joint:

1. Higher amperage produces higher welding temperature which interns produces better fusion of metal. Better fusion produces better weld
2. More oscillation width produces more weld width.
3. Less travel speed of torch produces better reinforcement.
4. Medium pre- heat temperature reduces the chance of cracking.
5. More powder feed rate produces more reinforcement.

According to the theory the best combination of process variables for optimum bead parameters should be as follows

Table 6: Combination of process variables for optimum bead parameters

A(amps)	O(mm)	S(mm/min)	T (°c)	F(gm/min)
160(2)	18(2)	79(-2)	300(0)	44(2)

VII. CONCLUSION

Accordingly the predicted bead parameters for this set are as follows Penetration is 0.640 mm, Reinforcement is 3.1358mm Weld bead is 25.768 mm. This is exactly the same set of bead parameters obtain by the optimization process. Hence it can be said that the optimization process is justifying the theory.

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