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Research Article

Optimization of GMAW Process Parameters Using Particle Swarm Optimization

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To improve the corrosion-resistant properties of carbon steel cladding process is usually used. It is a process of depositing a thick layer of corrosion resistant material-over carbon steel plate. Most of the engineering applications require high strength and corrosion resistant materials for long-term reliability and performance. By cladding, these properties can be achieved with minimum cost. The main problem faced in cladding is the selection of optimum combinations of process parameters for achieving quality clad and hence good clad bead geometry. This paper highlights an experimental study to optimize various input process parameters (welding current, welding speed, gun angle, contact tip to work distance, and pinch) to get optimum dilution in stainless steel cladding of low-carbon structural steel plates using gas metal arc welding (GMAW). Experiments were conducted based on central composite rotatable design with full-replication technique and mathematical models were developed using multiple regression method. The developed models have been checked for adequacy and significance. Using particle swarm optimization (PSO) the parameters were optimized to get minimal dilution.

1. Introduction

Prevention of corrosion is a major problem in industries. Even though it cannot be eliminated completely, it can be reduced to some extent. A corrosion resistant protective layer is made over the less corrosion resistant substrate by a process called cladding. This technique is used to improve life of engineering components but also reduce their cost. This process is mainly used in industries such as chemical, textiles, nuclear, steam power plants, food processing, and petro-chemical industries [1].

Most accepted method of employed in weld cladding is GMAW. It has got the following advantages.

(i) High reliability;
(ii) all position capability;
(iii) ease to use;
(iv) low cost;
(v) high productivity;
(vi) suitable for both ferrous and non ferrous metals;
(vii) high deposition rate;
(viii) absences of fluxes;
(ix) cleanliness and ease of mechanization.

The mechanical strength of clad metal is highly influenced by the composition of metal but also by clad bead shape. This is an indication of bead geometry. Figure 1 shows the clad bead geometry. It mainly depends on wire feed rate, welding speed, arc voltage, and so forth. Therefore it is necessary to study the relationship between in process parameters and bead parameters to study clad bead geometry. Using mathematical models it can be achieved.

This paper highlights the study carried out to develop mathematical and PSO models to optimize clad bead geometry, in stainless steel cladding deposited by GAMAW. The experiments were conducted based on four factor five level central composite rotatable designs with full replication technique [2]. The developed models have been checked for

Table 1: Chemical composition of base metal and filler wire.

Materials	Elements wt%								
	C	SI	Mn	P	S	Al	Cr	Mo	Ni
IS 2062	0.150	0.160	0.870	0.015	0.016	0.031	—	—	—
ER 308L	0.03	0.57	1.76	0.021	0.008	—	19.52	0.75	10.02

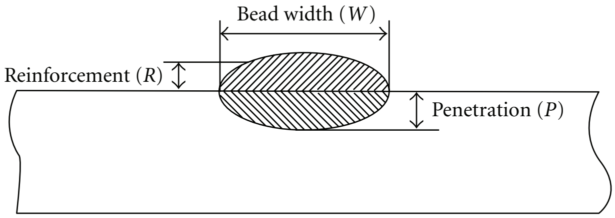

Figure 1: Clad bead geometry. Percentage dilution $(D) = [B/(A+B)] \times 100$.

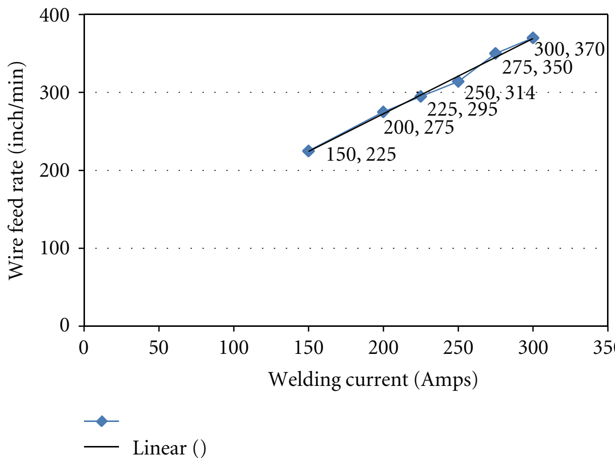

Figure 2: Relationship between current and wire feed rate.

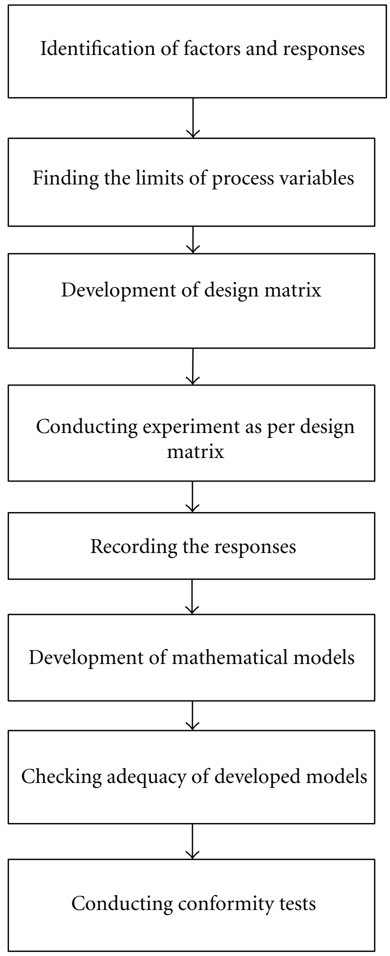

Figure 3: Experimental design procedures.

their adequacy and significance. Again using PSO, the bead parameters were optimized.

2. Experimental Procedure

The following machines and consumables were used for the purpose of conducting experiments.

(1) A constant current gas metal arc welding machine (Invrtee V 350-PRO advanced processer with 5–425 amps output range);

(2) welding manipulator;

(3) wire feeder (LF-74 Model);

(4) filler material Stainless Steel wire of 1.2 mm diameter (ER-308 L).;

(5) gas cylinder containing a mixture of 98% argon and 2% of oxygen;

(6) mild steel plate (grade IS-2062).

Test plates of size 300 × 200 × 20 mm were cut from mild steel plate of grade IS-2062 and one of the surfaces is cleaned to remove oxide and dirt before cladding. ER-308 L stainless steel wire of 1.2 mm diameter was used for depositing the clad beads through the feeder. Argon gas at a constant flow rate of 16 litres per minute was used for shielding. The properties of base metal and filler wire are shown in Table 1. The important and most difficult parameter found from trial run is wire feed rate. The wire feed rate is proportional to current [3].

Wire feed rate must be greater than critical wire feed rate to achieve pulsed metal transfer. The relationship found from trial run is shown in (1). The formula derived is shown in Figure 2:

$$\text{wire feed rate} = 0.96742857 * \text{current} + 79.1. \quad (1)$$

The selection of the welding electrode wire based on the matching the mechanical properties and physical characteristics of the base metal, weld size, and existing electrode

Table 2: Welding parameters and their levels.

Parameters	Unit	Notation	Factor levels				
			−2	−1	0	1	2
Welding current	A	*I*	200	225	250	275	300
Welding speed	mm/min	*S*	150	158	166	174	182
Contact tip to work distance	mm	*N*	10	14	18	22	26
Welding gun angle	Degree	*T*	70	80	90	100	110
Pinch	—	*Ac*	−10	−5	0	5	10

Table 3: Design matrix.

Trial number	Design matrix				
	I	*S*	*N*	*T*	*Ac*
1	−1	−1	−1	−1	1
2	1	−1	−1	−1	−1
3	−1	1	−1	−1	−1
4	1	1	−1	−1	1
5	−1	−1	1	−1	−1
6	1	−1	1	−1	1
7	−1	1	1	−1	1
8	1	1	1	−1	−1
9	−1	−1	−1	1	−1
10	1	−1	−1	1	1
11	−1	1	−1	1	1
12	1	1	−1	1	−1
13	−1	−1	1	1	1
14	1	−1	1	1	−1
15	−1	1	1	1	−1
16	1	1	1	1	1
17	−2	0	0	0	0
18	2	0	0	0	0
19	0	−2	0	0	0
20	0	2	0	0	0
21	0	0	−2	0	0
22	0	0	2	0	0
23	0	0	0	−2	0
24	0	0	0	2	0
25	0	0	0	0	−2
26	0	0	0	0	2
27	0	0	0	0	0
28	0	0	0	0	0
29	0	0	0	0	0
30	0	0	0	0	0
31	0	0	0	0	0
32	0	0	0	0	0

I: welding current; *S*: welding speed; *N*: contact tip to work distance; *T*: welding gun angle; *Ac*: pinch.

inventory. A candidate material for cladding which has excellent corrosion resistance and weldability is stainless steel. These have chloride stress corrosion cracking resistance and strength significantly greater than other materials. These have good surface appearance, good radiographic standard quality, and minimum electrode wastage. Experimental design procedure used for this study is shown in Figure 3 and important steps are briefly explained.

3. Plan of Investigation

The research work was planned to be carried out in the following steps.

(1) Identification of factors and responses.
(2) Finding limits of process variables.
(3) Development of design matrix.
(4) Conducting experiments as per design matrix.
(5) Recording the responses.
(6) Development of mathematical models.
(7) Checking the adequacy of developed models.
(8) Conducting conformity tests.

4. Prediction of Clad Bead Geometry Using Regression Equation

The following independently controllable process parameters were found to be affecting output parameters. These are wire feed rate (*W*), welding speed (*S*), welding gun angle (*T*), contact tip to work to distance (*N*) and pinch (*Ac*), the responses chosen were clad bead width (*W*), height of reinforcement (*R*), depth of Penetration (*P*), and percentage of dilution (*D*). The responses were chosen based on the impact of parameters on final composite model.

The basic difference between welding and cladding is the percentage of dilution. The properties of the cladding is the significantly influenced by dilution obtained. Hence control of dilution is important in cladding where a low dilution is highly desirable. When dilution is quite low, the final deposit composition will be closer to that of filler material and hence corrosion resistant properties of cladding will be greatly improved. The chosen factors have been selected on the basis to get minimal dilution and optimal clad bead geometry [4].

Few significant research works have been conducted in these areas using these process parameters and so these parameters were used for experimental study. Working ranges of all selected factors are fixed by conducting trial runs. This was carried out by varying one of the factors while keeping the rest of them as constant values. Working range of each process parameters was decided upon by inspecting the

Table 4: Design matrix and observed values of clad bead geometry.

Trial no.	Design matrix					Bead parameters			
	I	S	N	T	Ac	W (mm)	P (mm)	R (mm)	D (%)
1	−1	−1	−1	−1	1	6.9743	1.67345	6.0262	10.72091
2	1	−1	−1	−1	−1	7.6549	1.9715	5.88735	12.16746
3	−1	1	−1	−1	−1	6.3456	1.6986	5.4519	12.74552
4	1	1	−1	−1	1	7.7635	1.739615	6.0684	10.61078
5	−1	−1	1	−1	−1	7.2683	2.443	5.72055	16.67303
6	1	−1	1	−1	1	9.4383	2.4905	5.9169	15.96692
7	−1	1	1	−1	−1	6.0823	2.4672	5.49205	16.5894
8	1	1	1	−1	−1	8.4666	2.07365	5.9467	14.98494
9	−1	−1	−1	1	−1	6.3029	1.5809	5.9059	10.2749
10	1	−1	−1	1	1	7.0136	1.5662	5.9833	9.707297
11	−1	1	−1	1	1	6.2956	1.58605	5.5105	11.11693
12	1	1	−1	1	−1	7.741	1.8466	5.8752	11.4273
13	−1	−1	1	1	1	7.3231	2.16475	5.72095	15.29097
14	1	−1	1	1	−1	9.6171	2.69495	6.37445	18.54077
15	−1	1	1	1	−1	6.6335	2.3089	5.554	17.23138
16	1	1	1	1	1	10.514	2.7298	5.4645	20.8755
17	−2	0	0	0	0	6.5557	1.99045	5.80585	13.65762
18	2	0	0	0	0	7.4772	2.5737	6.65505	15.74121
19	0	−2	0	0	0	7.5886	2.50455	6.4069	15.77816
20	0	2	0	0	0	7.5014	2.1842	5.6782	16.82349
21	0	0	−2	0	0	6.1421	1.3752	6.0976	8.941799
22	0	0	2	0	0	8.5647	3.18536	5.63655	22.94721
23	0	0	0	−2	0	7.9575	2.2018	5.8281	15.74941
24	0	0	0	2	0	7.7085	1.85885	6.07515	13.27285
25	0	0	0	0	−2	7.8365	2.3577	5.74915	16.63287
26	0	0	0	0	2	8.2082	2.3658	5.99005	16.38043
27	0	0	0	0	0	7.9371	2.1362	6.0153	15.18374
28	0	0	0	0	0	8.4371	2.17145	5.69895	14.82758
29	0	0	0	0	0	9.323	3.1425	5.57595	22.8432
30	0	0	0	0	0	9.2205	3.2872	5.61485	23.6334
31	0	0	0	0	0	10.059	2.86605	5.62095	21.55264
32	0	0	0	0	0	8.9953	2.72068	5.7052	19.60811

W: width; P: penetration; R: reinforcement; D: dilution %.

bead for smooth appearance without any visible defects. The upper limit of given factor was coded as −2. The coded value of intermediate values were calculated using

$$X_i = \frac{2\left[2x - \left(x_{\max} + x_{\min}\right)\right]}{\left[\left(x_{\max} - x_{\min}\right)\right]}, \tag{2}$$

where X_i is the required coded value of parameter X is any value of parameter from $X_{\min} - X_{\max}$. $X_{\min}$ is the lower limit of parameters and $X_{\max}$ is the upper limit parameters. The chosen level of the parameters with their units and notation are given in Table 2.

Design matrix chosen to conduct the experiments was central composite rotatable design. The design matrix comprises of full replication of $2^5(= 32)$, Factorial designs. All welding parameters in the intermediate levels (o) constitute the central points and combination of each welding parameters at either is highest value (+2) or lowest value (−2) with other parameters of intermediate levels (0) constitute star points. 32 experimental trails were conducted that make the estimation of linear quadratic and two way interactive effects of process parameters on clad geometry [5].

The experiments were conducted at SVS College of Engineering, Coimbatore, India. In this work thirty-two experimental runs were allowed for the estimation of linear quadratic and two-way interactive effects of corresponding each treatment combination of parameters on bead geometry as shown Table 3 at random. At each run settings for all parameters were disturbed and reset for next deposit. This is very essential to introduce variability caused by errors in experimental set up.

In order to measure clad bead geometry of transverse section of each weld overlays were cut using band saw from mid length [6]. Position of the weld and end faces were machined and grinded. The specimen and faces were

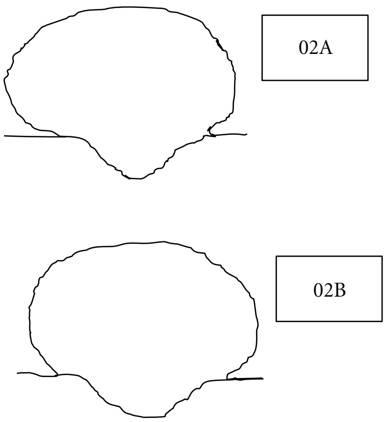

Figure 4: Traced Profiles (Specimen no. 2). 02A represents profile of the specimen (front side) and 02B represents profile of the specimen (rear side).

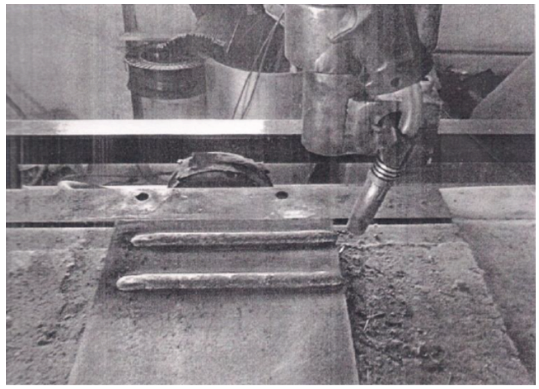

Figure 5: Clad deposited at optimal conditions.

polished and etched using a 5% nital solution to display bead dimensions. The clad bead profiles were traced using a reflective type optical profile projector at a magnification of ×10, in M/s Roots Industries Ltd. Coimbatore. Then the bead dimension such as depth of penetration height of reinforcement and clad bead width were measured. The traced bead profiles were scanned in order to find various clad parameters and the percentage of dilution with help of AUTO CAD software. This is shown in Figure 4 [7].

The measured clad bead dimension and percentage of dilution is shown in Table 4. Cladding deposited at optimal conditions is shown in Figure 5.

5. Development of Mathematical Models

The response function representing any of the clad bead geometry can be expressed as [8],

$$Y = f(A, B, C, D, E), \tag{3}$$

where Y = response variable, A = welding current (I) in amps, B = welding speed (S) in mm/min, C = contact tip to work distance (N) in mm, D = welding gun angle (T) in degrees, E = pinch (Ac).

The second order surface response model equals can be expressed as below [9].

$$\begin{aligned} Y = \beta_0 + {} & \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 D + \beta_5 E \\ & + \beta_{11} A^2 + \beta_{22} B^2 + \beta_{33} C^2 \\ & + \beta_{44} D^2 + \beta_{55} E^2 + \beta_{12} AB \\ & + \beta_{13} AC + \beta_{14} AD + \beta_{15} AE \\ & + \beta_{23} BC + \beta_{24} BD + \beta_{25} BE \\ & + \beta_{34} CD + \beta_{35} CE + \beta_{45} DE, \end{aligned} \tag{4}$$

where β_0 is the free term of the regression equation, the coefficients β_1, β_2, β_3, β_4 and β_5 are linear terms, the coefficients β_{11}, β_{22}, β_{33}, β_{44} and β_{55} quadratic terms, and the coefficients β_{12}, β_{13}, β_{14}, β_{15}, and so forth are the interaction terms. The coefficients were calculated using Quality America six sigma software (DOE-PC IV). After determining the coefficients, the mathematical models were developed. The developed mathematical models are given as follows.

$$\begin{aligned} & \text{Clad Bead Width } (W), \text{mm:} \\ & = 8.923 + 0.701A + 0.388B \\ & \quad + 0.587C + 0.040D + 0.088E \\ & \quad - 0.423A^2 - 0.291B^2 - 0.338C^2 \\ & \quad - 0.219D^2 - 0.171E^2 + 0.205AB \\ & \quad + 0.405AC + 0.105AD + 0.070AE \\ & \quad - 0.134BC + 0.225BD + 0.098BE \\ & \quad + 0.26CD + 0.086CE + 0.012DE. \end{aligned} \tag{5}$$

$$\begin{aligned} & \text{Depth of Penetration } (P), \text{mm:} \\ & = 2.735 + 0.098A - 0.032B \\ & \quad + 0.389C - 0.032D - 0.008E \\ & \quad - 0.124A^2 - 0.109B^2 - 0.125C^2 \\ & \quad - 0.187D^2 - 0.104E^2 - 0.33AB \\ & \quad + 0.001AC + 0.075AD + 0.005AE \\ & \quad - 0.018BC + 0.066BD + 0.087BE \\ & \quad + 0.058CD + 0.054CE - 0.036DE. \end{aligned} \tag{6}$$

Table 5: Analysis of variance for testing adequacy of the model.

Parameter	1st order terms		2nd order terms		Lack of fit		Error terms		F-ratio	R-ratio	Whether model is adequate
	SS	DF	SS	DF	SS	DF	SS	DF			
W	36.889	20	6.233	11	3.513	6	2.721	5	1.076	3.390	Adequate
P	7.810	20	0.404	11	0.142	6	0.261	5	0.454	7.472	Adequate
R	1.921	20	0.572	11	0.444	6	0.128	5	2.885	3.747	Adequate
D	506.074	20	21.739	11	6.289	6	15.45	5	0.339	8.189	Adequate

SS: sum of squares; DF: degree of freedom; F ratio (6, 5, 0.5) = 3.40451; R ratio (20, 5, 0.05) = 3.20665.

$$\begin{aligned}
&\text{Height of Reinforcement } (R)\text{, mm:}\\
&= 5.752 + 0.160A - 0.151B\\
&\quad - 0.060C + 0.016D - 0.002E\\
&\quad + 0.084A^2 + 0.037B^2 - 0.0006C^2\\
&\quad + 0.015D^2 - 0.006E^2\\
&\quad + 0.035AB + 0.018AC\\
&\quad - 0.008AD - 0.048AE\\
&\quad - 0.024BC - 0.062BD\\
&\quad - 0.003BE + 0.012CD - 0.092CE\\
&\quad - 0.095DE.
\end{aligned} \tag{7}$$

$$\begin{aligned}
&\text{Percentage Dilution } (D)\text{:}\\
&= 19.705 + 0.325A + 0.347B\\
&\quad + 3.141C - 0.039D - 0.153E\\
&\quad - 1.324A^2 - 0.923B^2 - 1.012C^2\\
&\quad - 1.371D^2 - 0.872E^2 - 0.200AB\\
&\quad + 0.346AC + 0.602AD + 0.203AE\\
&\quad + 0.011BC + 0.465BD + 0.548BE\\
&\quad + 0.715CD + 0.360CE\\
&\quad + 0.137DE.
\end{aligned} \tag{8}$$

6. Checking Adequacy of the Developed Models

The adequacy of the developed model was tested using the analysis of variance (ANOVA) technique. As per this technique, if the F-ratio values of the developed models do not exceed the standard tabulated values for a desired level of confidence (95%) and the calculated R-ratio values of the developed model exceed the standard values for a desired level of confidence (95%) then the models are said to be adequate within the confidence limit [10]. These conditions were satisfied for the developed models. The values are shown in Table 5.

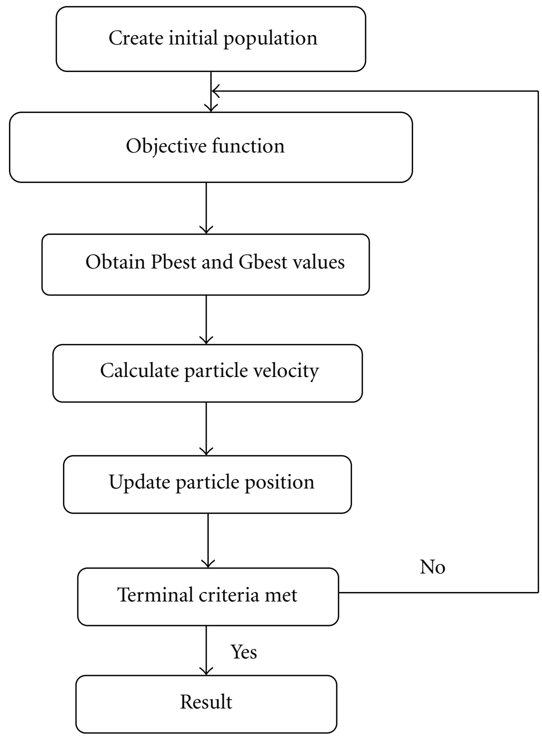

Figure 6: Procedure for proposed PSO to optimize GMAW process parameters.

7. Optimization of GMAW Process Parameters by PSO

Heuristic technique PSO is proposed to optimize clad bead geometry of stainless steel cladding deposited by GMAW. This is for achieving good cladding. The optimization procedure is shown in Figure 6. Initial populations is the possible number of solutions (particles) of the optimization problem and each possible solution is called an individual. In this study possible number of solutions is formed by the values of welding current, welding speed, contact tip to work distance, welding gun angle, and pinch. The objective of this study is to minimize percentage of dilution taken from (8).

Initial population is created using the cladding parameters (welding current, welding speed, contact tip to work distance, welding gun angle, and pinch) and for the current populations using objective function. The best fitness value is stored as Pbest from history. From all random solutions reobtained for percentage of dilution. Fitness function values

Table 6: Parameters for PSO optimization.

Population size	30
Dimension size	5
Inertia weight	0.4–0.9
Velocity factors $C1$, $C2$	1.4
Number of iteration allowed	100

for each individual (particles) are calculated particles choose the best fitness value called Gbest [11]. For each particle, calculate the velocity of the particle by

Velocity[] = wVelocity[] + C1rand1(Pbest[]− present[]) + C2xrand2(Gbest[]− present[]).

Particle position is updated by

Present[] = Present[] + velocity[].

rand1 and rand2 are two random functions in the range [0, 1] where C1 and C2 are two positive constants named learning factors taken as 2 and "w" is the inertial weight taken as 0.5.The parameters used for PSO optimization are shown in Table 6.

7.1. Method for Developing PSO Model

(i) Initiate each particle.

(ii) Calculate fitness value of each particle. If the fitness value is better than the best fitness value (Pbest) in history. Set the current value as new Pbest.

(iii) Calculate Gbest.

(iv) For each particle calculate the particle velocity.

7.2. Numerical Illustration for Developed PSO Model. The numerical illustration for the developed model to find optimal parameters for percentage of dilution as summarised in below.

ïĈů Welding current $I = I_{\min} + (I_{\max} - I_{\min}) - \text{rand}()$

ïĈů Welding speed $S = S_{\min} + (S_{\max} - S_{\min}) - \text{rand}()$

ïĈů Contact tip to work distance $N = N_{\min} + (N_{\max} - N_{\min}) - \text{rand}()$

ïĈů Welding gun angle $T = T_{\min} + (T_{\max} - T_{\min}) - \text{rand}()$

ïĈů Pinch $P = P_{\min} + (P_{\max} - P_{\min}) - \text{rand}()$

These values are substituted in (8) and dilution is obtained Consider.

ïĈů $X(1) = A$ = Welding current (I) in Amps,

ïĈů $X(2) = B$ = Welding Speed (S) in mm/min,

ïĈů $X(3) = C$ = Contact to work piece distance (N) in mm,

ïĈů $X(4) = D$ = Welding gun angle (T) in degree,

ïĈů $X(5) = E$ = Pinch (Ac).

Table 7: pbest value.

I	S	T	N	AC
0.6241	1.1490	−1.9241	−0.3936	−0.5707
0.6213	1.1414	−1.9139	−0.4406	−0.5562
−0.7617	1.2651	−1.8204	−0.3466	−0.5956
1.1993	0.4661	−1.4140	0.4173	−0.1746
0.6213	1.1368	−1.9224	−0.4496	−0.5725
1.2525	1.5234	−0.1270	−0.9208	0.6041
0.6188	1.1379	−1.9242	−0.4524	−0.5750
0.6196	1.1364	−1.9284	−0.4547	−0.5780
0.6230	1.1385	−1.9187	0.4487	−0.5717
0.6223	1.1368	−1.9227	−0.4507	−0.5761
0.6182	1.1378	−1.9227	−0.4507	−0.5761
0.6182	1.1378	−1.9221	−0.4511	−0.5754
0.6256	1.1393	−1.9129	−0.4459	−0.5675
0.6230	1.1385	−1.9187	−0.4487	−0.5717

Objective function for percentage of dilution which must be minimized was derived from 5–8. The constants of welding parameters are given Table 2 [12].

Subjected to bounds:

$$\begin{gathered} 200 \leq X(1) \leq 300, \\ 150 \leq X(2) \leq 182, \\ 10 \leq X(3) \leq 26, \\ 70 \leq X(4) \leq 110, \\ -10 \leq X(5) \leq 10. \end{gathered} \tag{9}$$

7.3. Objective Function

$$\begin{aligned} f(x) = {} & 19.75 + 0.325 * x(1) + 0.347 * x(2) \\ & + 3.141 * x(3) - 0.039 * x(4) - 0.153 * x(5) \\ & - 1.324 * x(1)^2 - 0.923 * x(2)^2 \\ & - 1.012 * x(3)^2 - 1.371 * x(4)^2 \\ & - 0.872 * x(5)^2 - 0.200 * x(1) * x(2) \\ & + 0.346 * x(1) * x(3) + 0.602 * x(1) * x(4) \\ & + 0.203 * x(1) * x(5) \\ & + 0.011 * x(2) * x(3) + 0.465 * x(2) * x(4) \\ & + 0.548 * x(2) * x(5) + 0.715 * x(3) * x(4) \\ & + 0.360 * x(3) * x(5) + 0.137 * x(4) \\ & * x(5). \end{aligned} \tag{10}$$

This is the percentage of dilution.

Table 8: Velocity of particles.

I	S	T	N	Ac
−0.0766	−0.0000	0.0000	0.0000	0.0000
−0.0737	−0.0000	0.0000	0.0000	0.0000
−0.0278	−0.0953	−0.0960	−0.3871	−0.3927
0.0369	−0.0000	−0.6304	−0.5643	−0.6966
−0.611	−0.1051	−0.1121	−0.4074	−0.4324
−0.0732	−0.0000	0.0000	0.0000	0.0000
−0.0000	−0.0000	0.0000	0.0000	0.0000
−0.0195	−0.0000	0.0000	0.0000	0.0000
−0.0517	−0.0940	−0.1307	−0.3794	−0.4224
−0.0296	−0.0000	0.0000	0.0000	0.0000
−0.0344	−0.0000	0.0000	0.0000	0.0000
−0.0766	−0.1135	−0.0974	−0.4006	−0.4197
−0.0211	−0.0000	0.0000	0.0000	0.0000

Table 9: Optimal process parameters.

Parameters	Range (coded value)	Actual
Welding current (I)	0.6196	265 A
Welding speed (S)	−1.1364	174 mm/min
Contact tip to work distance (N)	−1.9284	10 mm
Welding gun angle (T)	−0.4547	88 degree
Pinch (Ac)	−0.5780	−6

Dilution obtained is 8.5% and optimal process parameters shown in Table 9

7.4. Constraint Equations

$$\begin{aligned} W = {} & (8.923 + 0.701 * x(1) + 0.388 * x(2) \\ & + 0.587 * x(3) + 0.040 * x(4) + 0.088 * x(5) \\ & - 0.423 * x(1)^2 - 0.291 * x(2)^2 \\ & - 0.338 * x(3)^2 - 0.219 * x(4)^2 - 0.171 \\ & * x(5)^2 + 0.205 * x(1) * x(2) + 0.405 \\ & * x(1) * x(3) + 0.105 * x(1) * x(4) + 0.070 \\ & * x(1) * x(5) - 0.134 * x(2) * x(3) + 0.2225 \\ & * x(2) * x(4) + 0.098 * x(2) * x(5) + 0.26 \\ & * x(3) * x(4) + 0.086 * x(3) * x(5) \\ & + 0.12 * x(4) * x(5)) - 3. \end{aligned} \tag{11}$$

(Clad bead width (W) mm lower limit)

$$\begin{aligned} P = {} & (2.735 + 0.098 * x(1) - 0.032 * x(2) \\ & + 0.389 * x(3) - 0.032 * x(4) - 0.008 * x(5) \\ & - 0.124 * x(1)^2 - 0.109 * x(2)^2 \\ & - 0.125 * x(3)^2 \\ & - 0.187 * x(4)^2 - 0.104 * x(5)^2 \\ & - 0.33 * x(1) * x(2) + 0.001 * x(1) * x(3) \\ & + 0.075 * x(1) * x(4) \\ & + 0.005 * x(1) * x(5) \\ & - 0.018 * x(2) * x(3) \\ & + 0.066 * x(2) * x(4) + 0.087 * x(2) * x(5) \\ & + 0.058 * x(3) * x(4) \\ & + 0.054 * x(3) * x(5) \\ & - 0.036 * x(4) * x(5)) - 3. \end{aligned} \tag{12}$$

(Depth of penetration (P) upper limit),

$$\begin{aligned} P = {} & (2.735 + 0.098 * x(1) - 0.032 * x(2) \\ & + 0.389 * x(3) - 0.032 * x(4) - 0.008 * x(5) \\ & - 0.124 * x(1)^2 - 0.109 * x(2)^2 \\ & - 0.125 * x(3)^2 - 0.187 * x(4)^2 \\ & - 0.104 * x(5)^2 - 0.33 * x(1) * x(2) \\ & + 0.001 * x(1) * x(3) + 0.075 * x(1) * x(4) \\ & + 0.005 * x(1) * x(5) - 0.018 * x(2) * x(3) \\ & + 0.066 * x(2) * x(4) \\ & + 0.087 * x(2) * x(5) + 0.058 * x(3) * x(4) \\ & + 0.054 * x(3) * x(5) \\ & -0.036 * x(4) * x(5)) + 2. \end{aligned} \tag{13}$$

(Depth of penetration (P) lower limit),

$$\begin{aligned} W = {} & (8.923 + 0.701 * x(1) + 0.388 * x(2) + 0.587 * x(3) \\ & + 0.040 * x(4) + 0.088 * x(5) \\ & - 0.423 * x(1)^2 - 0.291 * x(2)^2 - 0.338 * x(3)^2 \\ & - 0.219 * x(4)^2 - 0.171 * x(5)^2 \\ & + 0.205 * x(1) * x(2) + 0.405 * x(1) * x(3) \\ & + 0.105 * x(1) * x(4) + 0.070 * x(1) * x(5) \\ & - 0.134 * x(2) * x(3) + 0.225 * x(2) * x(4) \\ & + 0.098 * x(2) * x(5) + 0.26 * x(3) * x(4) \\ & + 0.086 * x(3) * x(5) + 0.012 * x(4) * x(5)) - 10. \end{aligned} \tag{14}$$

(Clad bead width (W) upper limit),

$$\begin{aligned} R = {} & (5.752 + 0.160 * x(1) - 0.151 * x(2) - 0.060 * x(3) \\ & + 0.016 * x(4) - 0.002 * x(5) + 0.084 * x(1)^2 \\ & + 0.037 * x(2)^2 - 0.0006 * x(3)^2 + 0.015 * x(4)^2 \\ & - 0.006 * x(5)^2 + 0.035 * x(1) * x(2) \\ & + 0.018 * x(1) * x(3) - 0.008 * x(1) * x(4) \\ & - 0.048 * x(1) * x(5) - 0.024 * x(2) * x(3) \\ & - 0.062 * x(2) * x(4) - 0.003 * x(2) * x(5) \\ & + 0.012 * x(3) * x(4) - 0.092 * x(3) \\ & * x(5) - 0.095 * x(4) * x(5)) - 6. \end{aligned} \tag{15}$$

(Height of reinforcement (R) lower limit),

$$\begin{aligned} R = {} & (5.752 + 0.160 * x(1) - 0.151 * x(2) - 0.060 \\ & * x(3) + 0.016 * x(4) - 0.002 * x(5) + 0.084 \\ & * x(1)^2 + 0.037 * x(2)^2 - 0.0006 * x(3)^2 \\ & + 0.015 * x(4)^2 - 0.006 * x(5)^2 + 0.035 \\ & * x(1) * x(2) + 0.018 * x(1) * x(3) - 0.008 \\ & * x(1) * x(4) - 0.048 * x(1) * x(5) \\ & - 0.024 * x(2) * x(3) - 0.062 * x(2) * x(4) - 0.003 \\ & * x(2) * x(5) + 0.012 * x(3) * x(4) - 0.092 \\ & * x(3) * x(5) - 0.095 * x(4) * x(5)) + 6. \end{aligned} \tag{16}$$

(Heights of reinforcement (R) upper limit),

$$\begin{aligned} & f(x) - 23 \\ & -f(x) + 8. \end{aligned} \tag{17}$$

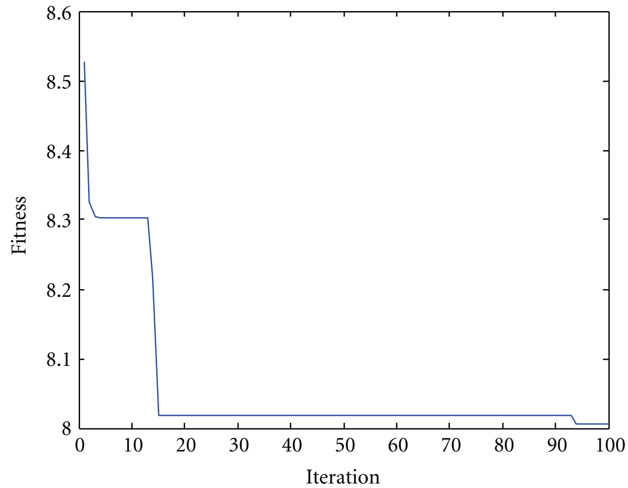

Figure 7: Convergence of PSO for optimal dilution.

(Dilution Upper and lower limit),

$$\begin{aligned} & x(1), x(2), x(3), x(4), x(5) \le 2, \\ & x(1), x(2), x(3), x(4), x(5) \ge -2. \end{aligned} \tag{18}$$

7.5. Calculation of Pbest Value. The minimum percentage of dilution for each individual solution is considered as Pbest value. This is the best value for the particular solution only [13, 14].

7.6. Calculation of Gbest Value. The minimum dilution for initial solution or the whole iteration is considered as Gbest value. Table 7 shows Pbest values and Table 8 shows velocity of particle. A program on MATLAB 7 is created and run to get optimal dilution. Figure 7 shows convergence of PSO for optimal dilution.

8. Results and Discussions

Experiments were conducted using GMAW to produce cladding of austenitic stainless steel material. From the experimental results a mathematical model was developed using regression model. Further to enhance scope of work PSO model was developed to optimize clad bead geometry.

In this study, a PSO model to optimize clad bead geometry was developed. To ensure accuracy of model developed evolutionary computing technique PSO invoked to optimize the parameters of GMAW, for optimal weld quality. Convergence of developed model for optimal dilution is shown in Figure 7. From the figure it is evident that dilution is increasing up to 15th iteration then it is constant up to 92 and iterations and decreasing and then constant.

PSO maintains internal memory to store the Gbest and Pbest solutions. Each individual in the population will try to emulate the Gbest and Pbest solutions in the memory through updating PSO equations. Hence effectiveness of finding the global solutions is s very effective.

It can be see that PSO models can be effectively used to model cladding parameters. These optimized values can be directly used in automatic cladding in the forms of programs and for real time quality control and for the entire cladding process control application to improve bead geometry.

9. Conclusions

(i) A PSO model has been developed from the experimental data to achieve desired clad bead geometry. PSO models are capable of making optimization of clad bead geometry with reasonable accuracy.

(ii) The developed models are able to optimize process parameters required to achieve the desired clad bead geometry of stainless steel cladding deposited by GMAW with reasonable accuracy.

(iii) In this study, the following steps were applied for prediction of stainless steel clad bead geometry using GMAW: (a) data collection using experimental studies, (b) analysing and processing of data, (c) prediction using regression equation, (d) development of PSO model, and (e) optimizing using PSO algorithm.

(iv) The results showed that PSO models can be used as an alternative tool according to the present conventional calculation methods.

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