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Prediction and Control of Weld Bead Geometry in Gas Metal Arc Welding Process Using Simulated Annealing Algorithm

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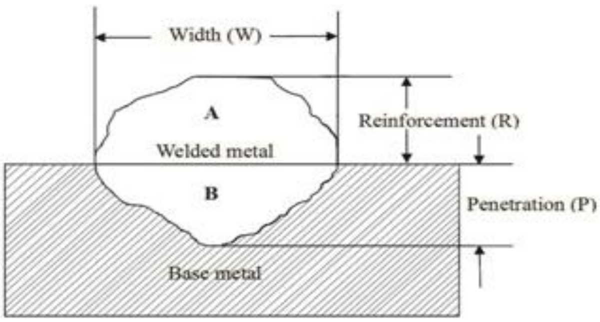
Abstract
In order to automate a welding process, which is a present trend in fabrication industry, it is necessary to have a mathematical model that is to relate the process parameters. Because of high reliability, easiness in operation, high penetration good surface finish and high productivity gas metal arc welding (GMAW) became a natural choice for fabrication industries. This paper presents five level factorial techniques to predict four critical dimensions of bead geometry. The developed models have been checked for adequacy and significance. The bead geometry is predicted again using Simulated annealing Algorithm (SA).

Key Words: GMAW, Weld bead geometry, Multiple Regression, Mathematical models,

1. Introduction
Quality is a vital factor in today's manufacturing world. Quality can be defined as the degree of customer satisfaction. Quality of a product depends on how it performs in desired circumstances. Quality is a very vital factor in the field of welding. The quality of a weld depends on mechanical properties of the weld metal which in turn depends on metallurgical characteristics and chemical composition of the weld [1]. The mechanical and metallurgical feature of weld depends on bead geometry which is directly related to welding process parameters. In other words quality of weld depends on in process parameters.GMA welding is a multi objective and multifactor metal fabrication technique. The process parameters have a direct influence on bead geometry [2]. Fig 1 shows the clad bead geometry. 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. It mainly depends on wire feed rate, welding speed, arc voltage etc. Therefore it is necessary to study the relationship between in process parameters and bead parameters to study clad bead geometry. This paper highlights the study carried out to develop mathematical and GA models to predict clad bead geometry, in stainless steel cladding deposited by GMAW [3].



Percentage dilution (D) = [B/ (A+B)] X 100

Figure 1: Clad bead geometry

2. Experimentation
The following machines and consumables were used for the purpose of conducting experiment.

1) A constant current gas metal arc welding machine (Invrtee V 350 – PRO advanced processor with 5 – 425 amps output range)
2) Welding manipulator
3) Wire feeder (LF – 74 Model)
4) Filler material Stainless Steel wire of 1.2mm 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 x 200 x 20mm 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 1.2mm 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. 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 equation (1). The formula derived is shown in Fig 2.

Wire feed rate = 0.96742857 *current + 79.1 -------------------- (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 inventory [4]. A candidate material for cladding which has excellent corrosion resistance and weld ability 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 used for this study is shown in Fig 3 and importance steps are briefly explained.

Table 1: Chemical Composition of Base Metal and Filler Wire

Elements, Weight %									
Materials	C	SI	Mn	P	S	Al	Cr	Mo	Ni
IS 2062	0.150	0.160	0.870	0.015	0.016	0.031	-	-	-
ER308L	0.03	0.57	1.76	0.021	1.008	-	19.52	0.75	10.02

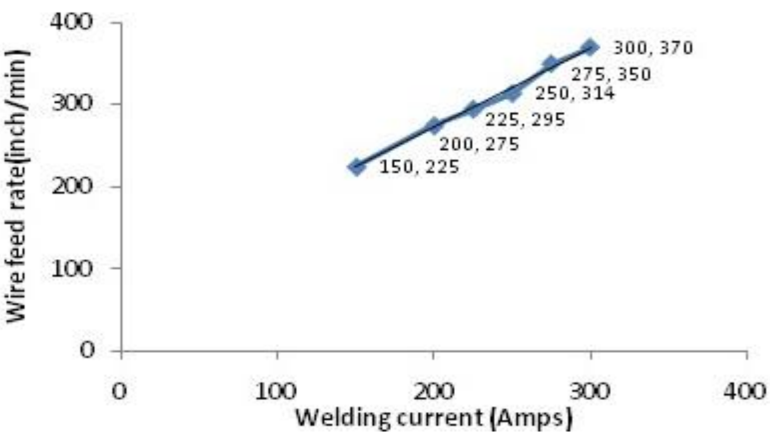


Figure 2: Relationship between Current and Wire Feed Rate

3. Plan of Investigation

The research work is carried out in the following steps [5] .Identification of factors, finding the limit of process variables, development of design matrix, conducting experiments as per design matrix, recording responses, development of mathematical models, checking adequacy of developed models, and predicting the parameters.

3.1 Identification of Factors and Responses

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 [1]. These are wire feed rate (W), welding speed (S), welding gun angle (T), contact tip to work to The following independently controllable process parameters were found to be affecting output parameters 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.

3.2 Finding the limits of process variables

Working ranges of all selected factors are fixed by conducting trial run. This was carried out by varying one of factors while keeping the rest of them as constant values. Working range of each process parameters was decided upon by inspecting the 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 the equation (2)

$$X_i = \frac{2[2X-(X_{max}+X_{min})]}{(X_{max}-X_{min})} \quad \text{---------------- (2)}$$

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 [4].
The chosen level of the parameters with their units and notation are given in Table 2.

Table 2: Welding Parameters and their Levels

Parameters	Factor Levels						
	Unit	**Notation**	**-2**	**-1**	**0**	**1**	**2**
Welding Current	A	1	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

3.3 Development of design matrix

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 (-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].

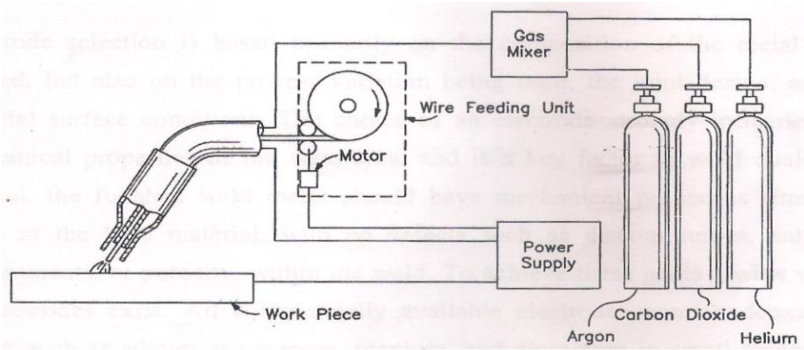


Figure 3: GMAW Circuit Diagram

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

3.4 Conducting experiments as per design matrix

In this work Thirty two experimental run were allowed for the estimation of linear quadratic and two-way interactive effects of correspond 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. The experiments were conducted at SVS College of Engineering, Coimbatore, 642109, India.

3.5 Recording of Responses

For measuring the clad bead geometry, the transverse section of each weld overlays was cut using band saw from mid length. Position of the weld and end faces were machined and grinded. The specimen and faces were 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 X10, 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 [6]. The profiles traced using AUTO CAD software. This is shown in Fig 4. This represents profile of the specimen (front side).The cladded specimen is shown in Fig. 5. The measured clad bead dimensions and percentage of dilution is shown in Table 4.

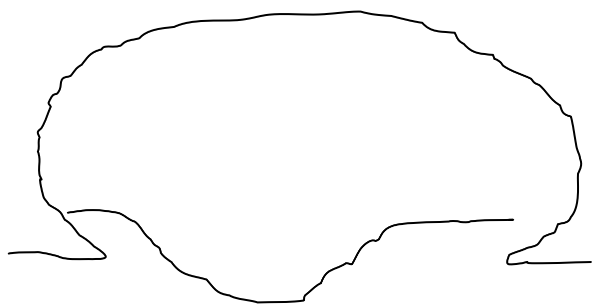


Figure 4: Traced Profile of bead geometry

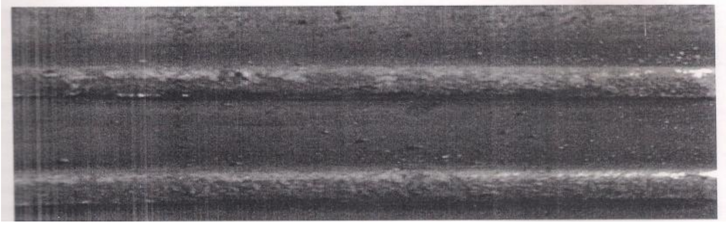


Figure 5: cladded specimen

Table 4: Design Matrix and Observed Values of Clad Bead Geometry

W-

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

Width; R - Reinforcement W - Width; P - Penetration; D - Dilution %

3.6 Development of Mathematical Models

The response function representing any of the clad bead geometry can be expressed as [7, 8, and 9],

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

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

$$Y = \beta_0 + \sum_{i=0}^{5} \beta_i X_i + \sum_{i=0}^{5} \beta_{ii} X_i^2 + \sum_{i=0}^{5} \beta_{ij} X_i X_j$$

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

Where, β_0 is the free term of the regression equation, the coefficient $\beta_1, \beta_2, \beta_3, \beta_4$ and β_5 is are linear terms, the coefficients $\beta_{11}, \beta_{22}, \beta_{33}, \beta_{44}$ and β_{55} quadratic terms, and the coefficients $\beta_{12}, \beta_{13}, \beta_{14}, \beta_{15}$, etc are the interaction terms. The coefficients were calculated by 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.

$\beta_o = 0.166338((\sum X_0 Y) + 0.05679(\sum\sum X_{ii} Y))$ --- (5)

$\beta_i = 0.166338(\sum X_i Y)$ --- (6)

$\beta_{ii} = 0.0625((\sum X_{ii} Y) + 0.06889(\sum\sum X_{ii} Y) - 0.056791(\sum\sum X_0 Y))$ ---------------------------------- (7)

$\beta_{ij} = 0.125(\sum X_{ij} Y)$ --- (8)

Clad Bead Width (W), mm = 8.923 + 0.701A + 0.388B + 0.587C + 0.040D + 0.088E – 0.423A^2 – 0.291B^2 – 0.338C^2 – 0.219D^2 – 0.171E^2 + 0.205AB + 0.405AC + 0.105AD + 0.070AE– 0.134BC+0.225BD+0.098BE+0.26CD+0.086CE+0.012DE ---------------------- (9)

Depth of Penetration (P), mm = 2.735 + 0.098A – 0.032B + 0.389C – 0.032D – 0.008E – 0.124A^2– 0.109B^2 – 0.125C^2 – 0.187D^2 – 0.104E^2 – 0.33AB + 0.001 AC + 0.075AD + 0.005 AE–0.018BC+0.066BD+0.087BE+0.058CD+0.054CE–0.036DE ---------------------- (10)

Height of Reinforcement (R), mm = 5.752 + 0.160A – 0.151B – 0.060C + 0.016D – 0.002E + 0.084A^2 + 0.037B^2 – 0.0006C^2 + 0.015D^2 – 0.006E^2 + 0.035AB + 0.018AC – 0.008AD – 0.048AE–0.024BC–0.062BD–0.003BE+0.012CD–0.092CE–0.095DE.-----------------------(11)

Percentage Dilution (D), % = 19.705 + 0.325A + 0.347B + 3.141C – 0.039D – 0.153E – 1.324A^2 – 0.923B^2 – 1.012C^2 – 1.371D^2 – 0.872E^2 – 0.200AB + 0.346 AC + 0.602 AD + 0.203AE+0.011BC+0.465BD+0.548BE+0.715CD+0.360CE+0.137DE ---------------------- (12)

Co-efficient of the above polynomial equation where calculated by regression as given by equations (5) to (8)

3.7 Checking the adequacy of the developed models

Analysis of variance (ANOVA) technique was used to test the adequacy of the model. 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.

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	3.51 3	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

4. The Prediction Function

The mathematical models furnished above provide one to one relationships between process parameters and weld bead geometry. They can be used in two ways;

1) Predicting weld bead geometry based on input parameters and
2) Predicting process parameters for a desired weld bead specification.

The later one is more practical since the welding parameters are usually set based on desired bead geometry. For this purpose, the set of non-linear equations must be solved simultaneously for all the process parameters. Evolutionary algorithms are powerful optimization techniques widely used for solving combinatorial problems. Nevertheless, other capabilities of these techniques have rarely been explored. As a new and promising approach, one of these algorithms, called SA, is implemented for prediction purposes in this research.

To predict the process parameters based on a desired bead quality, we first define the prediction function as follow(13):

$$E=\propto_1 \frac{(P_t-P_{Equ})^2}{P_t}+\propto_2 \frac{(R_t-R_{Equ})^2}{R_t}+\propto_3 \frac{(W_t-W_{Equ})^2}{W_t}+\propto_4 \frac{(D_t-Dp_{Equ})^2}{Ap_t}+ \quad (13)$$

Where:

$P_{Equ}, R_{Equ}, W_{Equ} D_{Equ}$ are bead specifications namely penetration, reinforcement, width of weld bead and percentage of dilution respectively which are given by Equations 9 to 12. In the same manner, we define $P_t, R_t, W_t D_t,$ as the target values for the desired weld bead geometry.

The coefficients $\propto_i$ represent weighing importance of different parameters in the objective function. In the prediction process, the purpose is to minimize this objective function. By doing so, the process parameters are calculated in such way that the bead geometry parameters approach their desired values. A SA method is employed to find the best welding variables with respect to process specifications.

5. Simulated Annealing Algorithm

Simulated annealing was originally inspired by formation of a crystal in solids during cooling. As discovered by long ago by Iron Age black smiths the slower cooling, the most perfect crystal is formed. By cooling complex physical systems naturally converge towards state of minimal energy. The systems move randomly, but probability to stay in a particular configuration depends directly on the energy of the system and on its temperature. Gibbs law stated as equation (14).

$$P = e^{\frac{E}{kT}} \quad \text{---------- (14)}$$

Where E stands for energy k is the Boltzmann constant and T is the temperature. The iteration of the simulated annealing consists of randomly choosing a new solution in the neighbourhood of actual solution. If the fitness function of the new solution is better than the fitness function of the current one the new solution is accepted as the new current solution. If the fitness function is not improved the new solution will be retained with probability shown in equation (15).

$$P = e^{\frac{-(f(y)-f(x))}{kT}} \quad \text{-------- (15)}$$

Where f(y)-f(x), being the difference between new and old solutions.

In this study Simulated Annealing (SA) which utilizes stochastic optimization is used for the optimization of clad bead geometry deposited by GMAW. The main advantage of using this stochastic algorithm is that global optimization point can be reached regardless of the initial starting point. Since the algorithm incorporates. The major advantage of SA is an ability to avoid being trapped at a local optimum point during optimization. The algorithm employs a random search accepting not only the changes that improve the objective function but also the changes that deteriorate it.Fig.6 shows simulated annealing algorithm. [11]

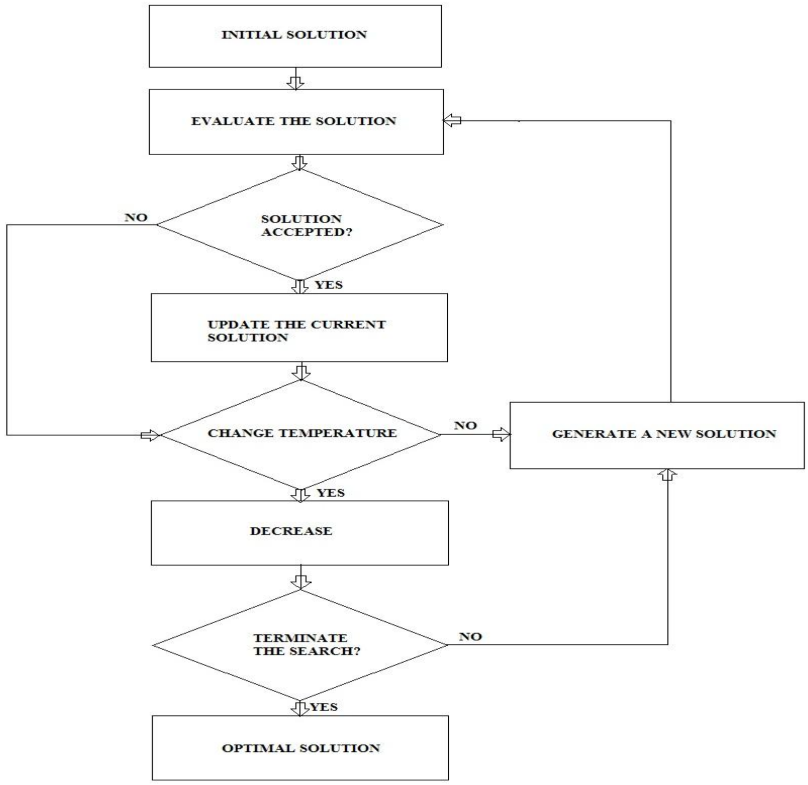


Figure. 6 Traditional Simulated Annealing Algorithms

6 An Illustrative Example

In this section a numerical example is presented to illustrate the performance of proposed procedure and solution technique [12]. The target values for desired weld bead geometry are given in Table 6.

Table 6 Target values for weld bead geometry.

Weld Bead Geometry	**Target Value**
P_t , *(mm)*	2.49
R_t (mm)	5.83
W_t (mm)	7.99
D_t (%)	12.59

Without lose of generality, all elements of the bead geometry are assumed to be of the same importance and therefore constants a_1 to a_7 are set to unity [13].

The prediction function given in Equation 13 along with weld bead modeling equations 9 to 12 are embedded into SA algorithm. The parameters for the algorithm are set as follows and shown in Table 7:

Table 7. SA process parameters

Annealing Function	Boltzmann Annealing
Population size	30
Re annealing temperature	100
Initial Temperature	100
Data Type	Double

The objective is to minimize the perdition function which is used as the fitness criterion in evaluation each generation of solutions. The best values found by proposed SA for process parameters are presented in Table 8. By setting these parameters in GMAW, the target weld bead geometry specifications may be achieved.

Table 8 Predicted values for process parameters.

Process parameters	Predicted value by SA
Welding current (I)	242
Welding Speed (S) (mm/min)	161
Contact tip to work distance (N) mm (m/min)	16
Welding Gun Angle (T) Degree	88
Pinch(Ac)	-10

The performance of the solution procedure was tested by substituting parameters values obtained by GA into the weld bead models and comparing the results with the desired values of bead geometry. The comparison of the calculated and desired values is shown in Table 9. The largest error is around 0.3 while most parameters deviate much less than 1% from their desired values. The computational results show that GA can be used efficiently and with good accuracy as a prediction technique.

Table 9 Comparison between desired and predicted weld bead geometry values

Weld Bead Geometry	Targets	SAResults	Error
Penetration	2.29	2.493	.203
Reinforcement	5.83	6.213	.383
Clad Bead Width	7.9	8.35	.45
Clad Bead Width	7.9	8.35	.45

7. Results and Discussions

1. A five level five factor full factorial design matrix based on central composite rotatable design technique was used for the mathematical development of model to predict clad bead geometry of austenitic stainless steel deposited by GMAW.
2. SA tool available in MATLAB 7 software was efficiently employed for prediction of clad bead geometry.
3. In cladding by a welding process clad bead geometry is very important for economising the material. This study effectively used SA models to predict weld bead geometry.
4. In this study two models regression and SA system for prediction of bead geometry in GMAW welding process. In this study it is proved that SA model prediction is efficient and error is approximately equal to five percent.

8. Conclusions

Based on the above study it can be observed that the developed model can be used to predict clad bead geometry within the applied limits of process parameters. This method of predicting process parameters can be used to get minimum percentage of dilution. In this study regression and SA was used for achieving optimal clad bead dimensions. In the case of any cladding process bead geometry plays an important role in determining the properties of the surface exposed to hostile environments and reducing cost of manufacturing. In this approach the objective function aimed for predicting weld bead geometry within the constrained limits.

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