Int J Interact Des Manuf (2008) 2:127–136
DOI 10.1007/s12008-008-0042-8

ORIGINAL PAPER

Modeling of fillet welded joint of GMAW process: integrated approach using DOE, ANN and GA

D. S. Nagesh · G. L. Datta

Received: 6 June 2007 / Revised: 10 April 2008 / Accepted: 22 April 2008 / Published online: 25 June 2008

Abstract An integrated approach based on the use of Design of Experiment (DOE), Artificial Neural Networks (ANN) and Genetic Algorithm (GA) for modeling of Gas Metal Arc Welding (GMAW) process has been explained in this paper. The effects on the five weld bead geometric descriptors by the five weld process variables has been initiated by means of 2^{n-1} fractional factorial experimental design technique. In this study, the 2^{n-1} fractional factorial experimental design method was applied on the data available from a published work (Wu in Weld J 43(4):179s–183s, 1964) to determine the main effects as well as 2-factor interaction effects. Using the results of 25-1 fractional factorial design experiments, multiple linear regression equations are postulated for both main as well as 2-factor interaction effects. It is observed that, main and 2-factor interaction linear equations have resulted in a small error between the estimated and experimental values while multiple linear regression equations have fitted the data very well. Back-propagation neural networks are used to associate the welding process variables with the features of the weld bead geometry. It is seen that neural network for estimating the weld bead geometric parameters can be effectively implemented, with little error percentage difference between the estimated and experimental results. In this study, Genetic Algorithms are used for optimizing the process parameters. The five process variables optimized by the GA are well within the vectors of minimum and maximum values of the controllable process variables of the experimental conditions in all the bead geometry descriptor cases. It can be concluded that genetic algorithms can able to optimize the process parameters for the desired weld bead geometric parameters.

Keywords Design of experiment (DOE) · Artificial neural network (ANN) · Genetic algorithm (GA) · GMAW · Weld bead geometric parameters · Fractional factorial design

1 Introduction

With the recent developments in the automated welding systems it has become very important that a high degree of confidence is ensured in predicting the weld bead geometry to achieve the desired mechanical and corrosion resistant properties of the weldment. The properties of the welded joint are affected by a large number of welding parameters. Weld modeling is important for predicting the quality of welds [1]. Several mathematical models have been established to describe the weld bead geometry mainly using multiple linear regression techniques [2,3]. However, most of the models were developed to investigate only the main effects of welding variables on weld bead geometry and the interaction effects had been ignored. But the interaction effects can also have significant effects on the weld quality. Therefore, in the present work multiple linear regression technique [4,5] was used to establish mathematical models for Gas Metal Arc Welding process (GMAW) considering the main effects as well as two factor interaction effects.

Artificial neural networks [6,7] and Genetic Algorithms [8,9] are being used in various engineering applications where prediction and optimization works are involved. In the present investigation attention is focused on modeling of fillet weld bead parameters for GMAW process using data based on fractional factorial design of experiments. Also optimization of process parameters had been tried using

D. S. Nagesh (✉)
Delhi College of Engineering, Delhi, India
e-mail: nageshds@yahoo.com

G. L. Datta
Indian Institute of Technology, Kharagpur, India

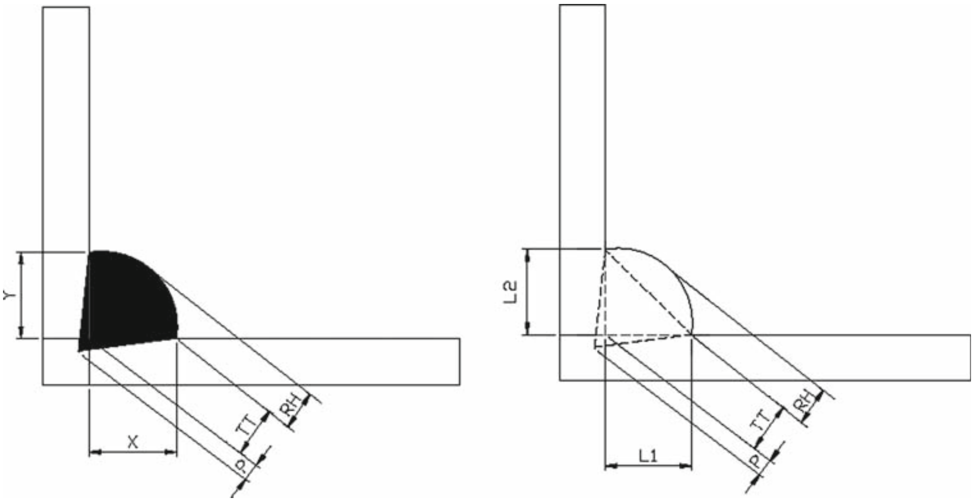


Fig. 1 Definition of weld bead shape (L1, L2 = Leg lengths; P = Penetration; TT = Throat Thickness; RH = Reinforcement Height)

Genetic Algorithm to obtain the desired bead geometry parameters.

2 Experimental data

The experimental data used in this investigation were obtained from the experimental database of Moon and Na [2] to study the effects of welding process variables (WPVs) on the geometric features of gas metal arc welding process. The base material used for the experiments was mild steel, the electrode material was solid wire AWSER70S-6 (1.2 mm) and shielding gas was Ar (80%) + CO_2(20).

The fillet welded joint shapes are characterised by leg length, penetration, throat thickness and reinforcement height as shown in Fig. 1. Schematic diagram of a fillet welded joint with the offset distance is shown in Fig. 2. A study on the relationship between weld bead geometry and welding conditions has been made to obtain a good fillet welded joint. In horizontal fillet welding, the WPVs include welding speed, welding current, arc voltage, gas flow rate and offset distance.

3 Analysis of effects of welding variables

2^{n-1} fractional factorial design method was adopted, where "n" means the number of WPVs. In this study "n" is 5 and 2^{n-1} can be represented by 2^{5-1}. By using 2^{5-1} fractional factorial design, the 5 individual effects and 10 two factor interaction effects can be determined with only 16 trials [3]. To evaluate the individual and interaction effects, the welding conditions for the electrode, shielding gas and base metal were set as shown in Fig. 3. The five main effects, each at lower and higher levels used for the study, are shown in Fig. 4. The low level of a variable is designated by –1 and high level by +1. The standardized variables are denoted by $X1$, $X2$,

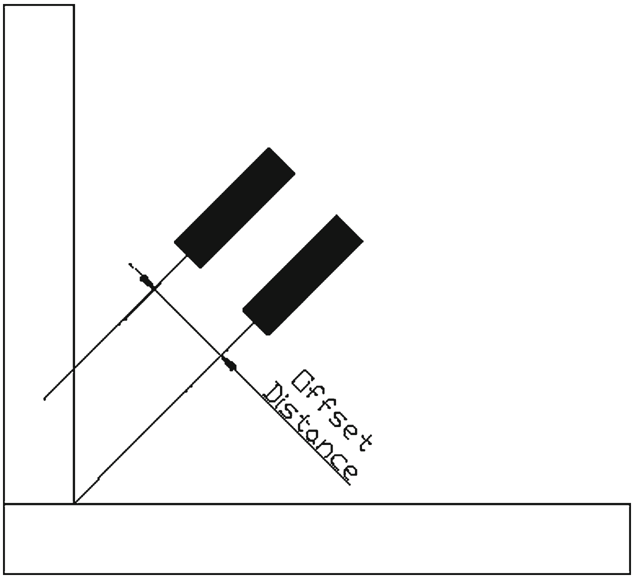


Fig. 2 Definition of offset distance

Experimental condition	Description
Electrode	Solid wire AWS ER70S-6 (1.2mm)
Shielding gas	Ar (80%) + CO_2 (20%)
Base metal	Mild steel (7 mm thickness)

Fig. 3 Electrode, shielding gas and base metal

	Experimental variables	Low level (-1)	High level (+1)
X1	Welding Speed (mm/sec)	4	8
X2	Arc voltage (V)	26	30
X3	Welding current (A)	250	280
X4	Gas flow rate (ltrs/min)	14	18
X5	Offset distance (mm)	0	2
	Experimental response factors		
H1	Leg length L1 (mm)		
H2	Leg length L2 (mm)		
H3	Penetration (mm)		
H4	Throat thickness (mm)		
H5	Reinforcement height (mm)		

Fig. 4 Experimental variable levels and response factors

Trial No.	Order No.	Welding Conditions					Standardized Variables														
		S	V	C	G	D	X1	X2	X3	X4	X5	X12	X13	X14	X15	X23	X24	X25	X34	X35	X45
1	3	4	26	250	14	2	-1	-1	-1	-1	1	1	1	1	-1	1	1	-1	1	-1	-1
2	5	8	26	250	14	0	1	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1
3	10	4	30	250	14	0	-1	1	-1	-1	-1	-1	1	1	1	-1	-1	-1	1	1	1
4	15	8	30	250	14	2	1	1	-1	-1	1	1	-1	-1	1	-1	-1	1	1	-1	-1
5	1	4	26	280	14	0	-1	-1	1	-1	-1	1	-1	1	1	-1	1	1	-1	-1	1
6	4	8	26	280	14	2	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	-1	1	-1
7	9	4	30	280	14	2	-1	1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1	-1
8	11	8	30	280	14	0	1	1	1	-1	-1	1	1	-1	-1	1	-1	-1	-1	-1	1
9	2	4	26	250	18	0	-1	-1	-1	1	-1	1	1	-1	1	1	-1	1	-1	1	-1
10	12	8	26	250	18	2	1	-1	-1	1	1	-1	-1	1	1	1	-1	-1	-1	-1	1
11	16	4	30	250	18	2	-1	1	-1	1	1	-1	1	-1	-1	-1	1	1	-1	-1	1
12	8	8	30	250	18	0	1	1	-1	1	-1	1	-1	1	-1	-1	1	-1	-1	1	-1
13	13	4	26	280	18	2	-1	-1	1	1	1	1	-1	-1	-1	-1	-1	-1	1	1	1
14	14	8	26	280	18	0	1	-1	1	1	-1	-1	1	1	-1	-1	-1	1	1	-1	-1
15	7	4	30	280	18	0	-1	1	1	1	-1	-1	-1	-1	1	1	1	-1	1	-1	-1
16	6	8	30	280	18	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Fig. 5 Welding conditions and standardized variables for trials 1-16

Trial No.	**S mm/sec**	**V volts**	**C amps**	**G ltrs/min**	**D mm**	**L_1 mm**	**L_2 mm**	**P mm**	**TT mm**	**RH mm**
1	4	26	250	14	2	8.0	8.3	1.1	4.9	0.9
2	8	26	250	14	0	5.5	5.4	1.5	3.6	1.0
3	4	30	250	14	0	9.5	9.5	0.7	5.5	0.9
4	8	30	250	14	2	5.1	6.4	1.5	3.6	0.9
5	4	26	280	14	0	9.0	10.5	2.0	5.5	1.5
6	8	26	280	14	2	5.3	6.0	2.3	3.5	1.7
7	4	30	280	14	2	10.2	10.5	2.1	6.0	1.0
8	8	30	280	14	0	8.5	8.5	1.8	5.5	0.9
9	4	26	250	18	0	7.5	7.5	1.7	5.0	0.8
10	8	26	250	18	2	4.3	5.9	1.6	3.5	1.6
11	4	30	250	18	2	8.5	9.5	0.9	5.4	1.4
12	8	30	250	18	0	6.0	5.3	0.8	4.1	1.2
13	4	26	280	18	2	9.5	9.5	1.8	5.7	2.4
14	8	26	280	18	0	5.9	6.3	2.2	4.5	1.0
15	4	30	280	18	0	11.0	10.0	2.0	5.7	1.3
16	8	30	280	18	1	5.5	7.0	1.9	4.3	1.0

Fig. 6 Experimental conditions and results

$X3$, $X4$ and $X5$. In the next step, the main task was to construct the uncoded and coded design matrices for the experiment as shown in Fig. 5. The experimental data are based on the design matrix and the response values are recorded on a data sheet for analysis. The variables affected by the standardized variables are denoted by $H1$, $H2$, $H3$, $H4$ and $H5$. The experimental conditions and results are shown in Fig. 6. The relationships between the standardized variables and the experimental variables are:

$$\begin{aligned} X1 &= (S - 6.0)/2.0 \\ X2 &= (V - 28.0)/2.0 \\ X3 &= (C - 265.0)/15.0 \\ X4 &= (G - 16.0)/2.0 \\ X5 &= (D - 2.0)/1.0 \end{aligned} \tag{1}$$

The individual and interaction effects have been calculated by multiplying the appropriate standardized variable by the experimental result for each trial and summing the resultant values. The dominant variables on the fillet welded joint shape were found to be welding speed, welding current and arc voltage [2].

3.1 Equations for weld bead geometric parameters

The geometrical features of the weld bead that were taken into account are leg length L1, leg length L2, penetration, reinforcement height and throat thickness. In the present study, for each feature, linear regression equations were obtained first considering only main variable effects and thereafter considering both main and two factor interaction effects. This is done with the help of measured values using the linear technique [4,5]. Weld geometric features were then computed from these linear regression equations and compared with actual experimental values.

3.1.1 Linear regression equations

Based upon the evaluation of the variable effects, ten linear regression equations were postulated first considering only main variable effects and then considering both main and two factor interaction effects. The postulated equations are:

Equations for leg length L1:

(a) Considering effects of main variables only:

$$\begin{aligned} Y11 = a01 + a11X1 + a21X2 + a31X3 \\ + a41X4 + a51X5 \end{aligned} \tag{2}$$

where,
$Y11 =$ estimated leg length L1
$a01, a11, a21, a31, a41, a51 =$ estimated coefficients determined by the least squares method.

(b) Considering main and 2-factor interaction effects:

$$\begin{aligned} Y1 = a0 + a1X1 + a2X2 + a3X3 + a4X4 \\ + a5X5 + a6X12 + a7X13 + a8X14 \\ + a9X15 + a10X23 + a11X24 + a12X25 \\ + a13X34 + a14X35 + a15X45 \end{aligned} \tag{3}$$

where,
$Y1$ = estimated leg length L1
$a0, a1, a2, a3, a4, a5, a6, a7, a8, a9, a10, a11, a12, a13, a14, a15$ = estimated coefficients determined by the least squares method.

Equations for leg length L2:

(a) Considering effects of main variables only:

$$Y21 = b01 + b11X1 + b21X2 + b31X3 + b41X4 + b51X5 \tag{4}$$

where,
$Y21$ = estimated leg length L2
$b01, b11, b21, b31, b41, b51$ = estimated coefficients determined by the least squares method.

(b) Considering main and 2-factor interaction effects:

$$\begin{aligned} Y2 = {} & b0 + b1X1 + b2X2 + b3X3 + b4X4 + b5X5 \\ & + b6X12 + b7X13 + b8X14 + b9X15 \\ & + b10X23 + b11X24 + b12X25 \\ & + b13X34 + b14X35 + b15X45 \end{aligned} \tag{5}$$

where,
$Y1$ = estimated leg length L2
$b0, b1, b2, b3, b4, b5, b6, b7, b8, b9, b10, b11, b12, b13, b14, b15$ = estimated coefficients determined by the least squares method.

Equations for penetration:

(a) Considering effects of main variables only:

$$Y31 = c01 + c11X1 + c21X2 + c31X3 + c41X4 + c51X5 \tag{6}$$

where,
$Y31$ = estimated penetration
$c01, c11, c21, c31, c41, c51$ = estimated coefficients determined by the least squares method.

(b) Considering main and 2-factor interaction effects:

$$\begin{aligned} Y3 = {} & c0 + c1X1 + c2X2 + c3X3 + c4X4 \\ & + c5X5 + c6X12 + c7X13 + c8X14 \\ & + c9X15 + c10X23 + c11X24 + c12X25 \\ & + c13X34 + c14X35 + c15X45 \end{aligned} \tag{7}$$

where,
$Y3$ = estimated penetration
$c0, c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15$ = estimated coefficients determined by the least squares method.

Equations for throat thickness:

(a) Considering only the effects of main variables:

$$Y41 = d01 + d11X1 + d21X2 + d31X3 + d41X4 + d51X5 \tag{8}$$

where,
$Y41$ = estimated throat thickness
$d01, d11, d21, d31, d41, d51$ = estimated coefficients determined by the least squares method.

(b) Considering main and 2-factor interaction effects:

$$\begin{aligned} Y4 = {} & d0 + d1X1 + d2X2 + d3X3 + d4X4 \\ & + d5X5 + d6X12 + d7X13 + d8X14 \\ & + d9X15 + d10X23 + d11X24 + d12X25 \\ & + d13X34 + d14X35 + d15X45 \end{aligned} \tag{9}$$

where,
$Y4$ = estimated throat thickness
$d0, d1, d2, d3, d4, d5, d6, d7, d8, d9, d10, d11, d12, d13, d14, d15$ = estimated coefficients determined by the least squares method.

Equations for reinforcement height:

(a) Considering effects of main variables only:

$$Y51 = e01 + e11X1 + e21X2 + e31X3 + e41X4 + e51X5 \tag{10}$$

where,
$Y51$ = 4 estimated reinforcement height
$e01, e11, e21, e31, e41, e51$ = estimated coefficients determined by the least squares method.

(b) Considering main and 2-factor interaction effects:

$$\begin{aligned} Y5 = {} & e0 + e1X1 + e2X2 + e3X3 + e4X4 + e5X5 \\ & + e6X12 + e7X13 + e8X14 + e9X15 \\ & + e10X23 + e11X24 + e12X25 + e13X34 \\ & + e14X35 + e15X45 \end{aligned} \tag{11}$$

where,
$Y5$ = estimated reinforcement height
$e0, e1, e2, e3, e4, e5, e6, e7, e8, e9, e10, e11, e12, e13, e14, e15$ = estimated coefficients determined by the least squares method.

Suffix	Leg length L1 a	Leg length L2 b	Penetration P c	Throat thickness TT d	Reinforcement height RH e
01	-5.6620	-3.1124	-3.437	-2.1372	0.2500
11	-0.8469	-0.7656	0.0406	-0.3469	-0.0281
21	0.2906	0.2281	-0.0781	0.1219	-0.0719
31	0.0444	0.0444	0.0263	0.0213	0.0087
41	-0.0906	-0.1281	-0.0031	0.0031	0.0591
51	-0.0812	-0.3441	0.0941	-0.1062	-0.1187

Fig. 7 Coefficients of effects of main variables in regression equations

The coefficients of main variables for the Eqs. (2), (4), (6), (8) and (10) are shown in Fig. 7. The coefficients of main and 2-factor interaction effects for the Eqs. (3), (5), (7), (9) and (11) are shown in Fig. 8. Experimental variable terms were also substituted in the equations by using the transforming Eq (1) to change the standardized variables to experimental variables.

Using Eqs. (2)–(11) the weld geometric parameters have been estimated. Figure 9 shows the results of error percentage between experimental and estimated data considering the effects of only main variables. Figure 10 presents the results of error percentage between experimental and estimated data considering the effects of main variables as well as 2-factor interactions. According to these results, the errors between experimental and estimated values are larger when estimated considering the effects of main variables only as shown in Figure 9. Therefore effects of main plus 2-factor interactions would lead to better estimates as compared to effects of main variables only.

Fig. 8 Coefficients of effects of main and 2-factor interaction variables in regression equations

Suffix	*Leg length L1* *a*	*Leg length L2* *b*	*Penetration* *c*	*Throat thickness* *d*	*Reinforcement height* *e*
0	1.1893	-30.8940	3.4029	-8.0383	-51.6383
1	1.4615	-0.3344	0.9615	-1.2156	1.7010
2	0.0333	0.7042	-0.6688	0.2417	1.2833
3	-0.0496	0.1121	-0.0346	-0.0037	0.2046
4	0.1113	1.1363	0.8577	1.2517	0.2475
5	0.6982	0.3065	-0.0820	0.1258	0.0841
6	-0.0172	-0.0016	-0.0109	0.0141	-0.0047
7	-0.0040	-0.0019	-0.0015	0.0019	-0.0048
8	-0.0391	0.0078	-0.0172	0.0047	-0.0203
9	-0.1531	-0.0156	0.0469	-0.0969	-0.0031
10	0.0035	0.0002	0.0031	0.0015	-0.0052
11	-0.0266	-0.0328	-0.0141	-0.0359	0.0078
12	-0.1531	0.0031	0.0531	-0.0156	-0.0719
13	0.0015	-0.0027	-0.0010	-0.0015	-0.0015
14	-0.0054	-0.0196	-0.0013	-0.0038	0.0021
15	0.3897	0.3251	-0.0879	0.1160	0.1014

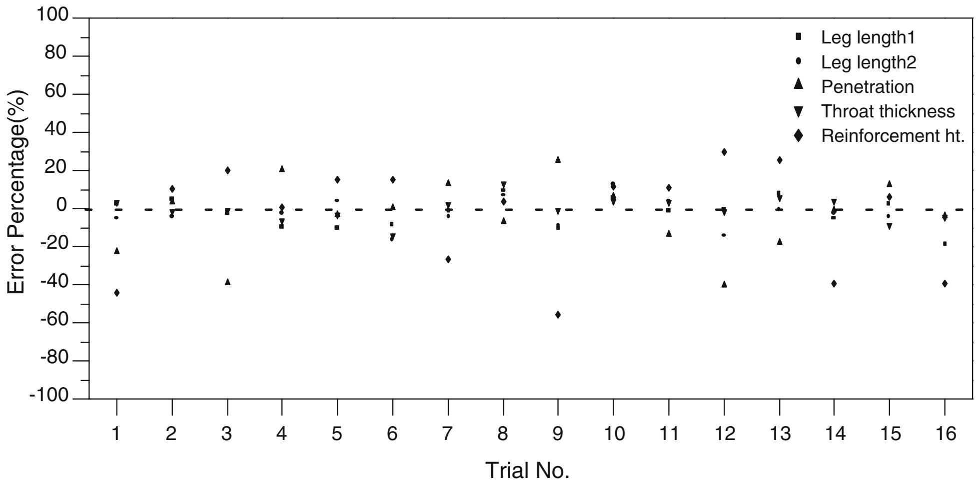


Fig. 9 Result of Error Percentage Between Experimental and Estimated Data Using Regression Eqns (Effects of Main Variables)

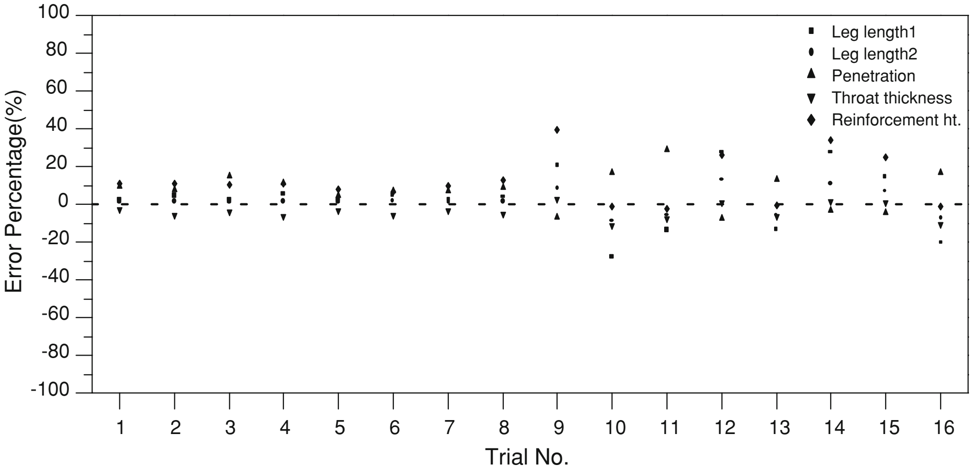


Fig. 10 Result of Error Percentage Between Experimental and Estimated Data Using Regression Eqns (Effects of Main and 2-Factor Interaction)

4 Prediction of weld bead geometric parameters by neural network

A multi layer back propagation neural network [6,10] consisting of 5 neurons at the input layer, 5 neurons at the output layer and 2 hidden layers each containing 8 neurons had been used for predicting the weld bead geometric parameters. The input parameters to the network were the welding speed, arc voltage, welding current, gas flow rate and offset distance. The model outputs were weld bead geometric parameters consisting of leg length L1, leg length L2, penetration, throat thickness and reinforcement height. The experimental data used to train the network were the same data, which were used in fractional factorial design of experiments, shown in Fig. 6. The network architecture of 5-8-8-4 neurones was trained for 10,984 iterations with learning rate 0.02 using neural network tool box on MATLAB platform. Further training did not improve the modeling performance of the network, and it turns out that with excessive training the network converges to "memorization" of the training data, rather than capturing the generalities of the process. The trend to memorize, rather than learn, when excessive training is applied is a well known characteristic of back propagation neural network [7].

The results of the test are summarized in Fig. 11. The testing data are bold faced in the table and these sets of data were not used for training the network. The results indicate that the neural networks having the architecture, as described earlier could yield moderately accurate results except in the case of penetration and reinforcement height, where, in few cases the predicted values were very large compared to actual experimental values. The results indicates that the network is considered to be able to predict with reasonable accuracy. The conclusion from this part of the work is that the neural networks appear to constitute a workable model for predicting the weld bead geometry under given set of welding conditions.

Trial No.	Actual (mm)					Network (mm)				
	L1	L2	P	TT	RH	L1	L2	P	TT	RH
1	8.0	8.3	1.1	4.9	0.9	8.0	8.1	1.0	4.9	1.0
2	**5.5**	**5.4**	**1.5**	**3.6**	**1.0**	**5.1**	**5.3**	**1.7**	**3.5**	**1.3**
3	9.5	9.5	0.7	5.5	0.9	9.3	9.6	0.7	5.5	0.9
4	5.1	6.4	1.5	3.6	0.9	5.2	6.2	1.3	3.5	1.0
5	9.0	10.5	2.0	5.5	1.5	9.0	10.2	1.7	5.7	1.7
6	5.3	6.0	2.3	3.5	1.7	5.3	5.9	2.3	3.5	1.5
7	**10.2**	**10.5**	**2.1**	**6.0**	**1.0**	**10.9**	**10.8**	**1.9**	**6.3**	**1.2**
8	8.5	8.5	1.8	5.5	0.9	8.4	8.4	1.7	5.4	0.8
9	7.5	7.5	1.7	5.0	0.8	7.4	7.8	1.5	4.8	1.0
10	4.3	5.9	1.6	3.5	1.6	4.3	5.5	1.3	3.6	1.4
11	8.5	9.5	0.9	5.4	1.4	8.8	9.1	0.8	5.3	1.2
12	6.0	5.3	0.8	4.1	1.2	5.6	5.8	1.0	3.9	1.0
13	9.5	9.5	1.8	5.7	2.4	9.3	10.0	1.9	5.3	2.1
14	**5.9**	**6.3**	**2.2**	**4.5**	**1.0**	**5.5**	**6.1**	**1.9**	**4.1**	**1.2**
15	11.0	10.0	2.0	5.7	1.3	10.9	9.9	1.8	5.6	1.2
16	5.5	7.0	1.9	4.3	1.0	5.7	6.9	1.8	4.0	1.2

Fig. 11 Comparison of experimental and network results of weld bead geometric parameters

5 Genetic algorithm approach for optimization of GMAW process variables for fillet welded joints

The process variables of gas metal arc welding process used for making fillet welded joints have been optimized by genetic algorithm approach.

5.1 Program formulation and execution of genetic algorithms

The genetic algorithm has been used to optimize the GMAW process variables. For the fillet welded joint the target values of bead shape are set for finding the optimum process variables. This task needs program formulation using various functions of the GA toolbox. Program formulation comprised of stating the objective function, the type of genetic algorithm to be used, the values for genetic algorithm parameters [8,9] etc. The program is executed after the program formulation is complete to get the optimized process variables for the case under study.

5.2 Optimization of process parameters using GA for output process variables

The objective of this investigation was to obtain the optimized process parameters for the desired experimental output process variables such as leg length L1, leg length L2, penetration, throat thickness and reinforcement height using GA. The experimental conditions and the output process variables used for this investigation are taken from Fig. 4.

5.2.1 Defining the objective function and GA parameters for genetic algorithm

The concept of regression analysis was used for designing the objective functions for obtaining the optimized GMAW process parameters for the desired shape configuration of fillet joint comprising of leg length L1, leg length L2, penetration, throat thickness and reinforcement height. Regression equations from Sect. 4 obtained from the experimental data presented in Fig. 6 are used for GA work. For realizing the desired leg length L1, leg length L2, penetration, throat thickness and reinforcement height, the objective functions were set at as shown below:

$$\mathrm{PI} = (Yd - Y)2$$

where,
PI = Objective function (Performance Index)
Yd = Desired value of leg length L1 or leg length L2 or penetration or throat thickness or reinforcement height depending on the bead parameter under study
Y = Estimated value of leg length L1 or leg length L2 or penetration or throat thickness or reinforcement height depending on the bead parameter under study using regression equations.

The equations obtained by using regression technique for the data shown in Fig. 4 are as under:

$$\begin{aligned} Y(\text{Leg Length L1}) = {} & -5.662 - 0.847^{*}X1 + 0.291^{*}X2 \\ & + 0.044^{*}X3 - 0.091^{*}X4 - 0.081^{*}X5 \end{aligned}$$

$$\begin{aligned} Y(\text{Leg Length L2}) = {} & -3.112 - 0.766^{*}X1 + 0.228^{*}X2 \\ & + 0.044^{*}X3 - 0.128^{*}X4 - 0.344^{*}X5 \end{aligned}$$

$$\begin{aligned} Y(\text{Penetration}) = {} & -3.437 + 0.041^{*}X1 - 0.078^{*}X2 \\ & + 0.026^{*}X3 - 0.003^{*}X4 + 0.094^{*}X5 \end{aligned}$$

$$\begin{aligned} Y(\text{Throat Thick ness}) = {} & -2.137 - 0.347^{*}X1 + 0.122^{*}X2 \\ & + 0.021^{*}X3 + 0.003^{*}X4 \\ & - 0.106^{*}X5 \end{aligned}$$

$$\begin{aligned} Y(\text{Reinforcement Height}) = {} & 0.250 - 0.028^{*}X1 - 0.072^{*}X2 \\ & + 0.009^{*}X3 + 0.059^{*}X4 \\ & - 0.119^{*}X5 \end{aligned}$$

X1	Welding Speed (mm/s)
X2	Arc voltage (V)
X3	Welding current (Amp)
X4	Gas flow rate (l/min)
X5	Offset distance (mm)

In GA program it is required to define the vector of minimum and maximum values of the controllable process variables and these values are taken from the experimental conditions presented in Fig. 5.

Vector of Minimum Values:

$$p_{\min} = [4 \quad 26 \quad 250 \quad 14 \quad 0]$$

Vector of Maximum Values:

$$p_{\max} = [8 \quad 30 \quad 280 \quad 18 \quad 2]$$

The low and high values of the independent input variables of GMAW process are presented to GA through vectors of minimum and maximum values which are the ranges used in the experimental work within which the genetic algorithm can choose the different process parameters to achieve the desired value of leg length L1, leg length L2, penetration, throat thickness and reinforcement height in the respective cases of GA computational work.

With the above defined objective functions, several computational experimentations were performed to arrive at the following list of GA parameters, which were able to optimize the GMAW process parameters to reach at the desired values of bead shape parameters of the fillet welded joint.

GA PARAMETERS
Type of GA: Micro GA
No. of generations for evolution: 30
Population size : 31
Type of selection: Tournament selection
Probability of cross over: 0.95

The GA programs were executed for each case of leg length L1, leg length L2, penetration, throat thickness and reinforcement height, after incorporating the above defined objective functions, vectors of minimum and maximum values of process variables and the GA parameters. The outputs

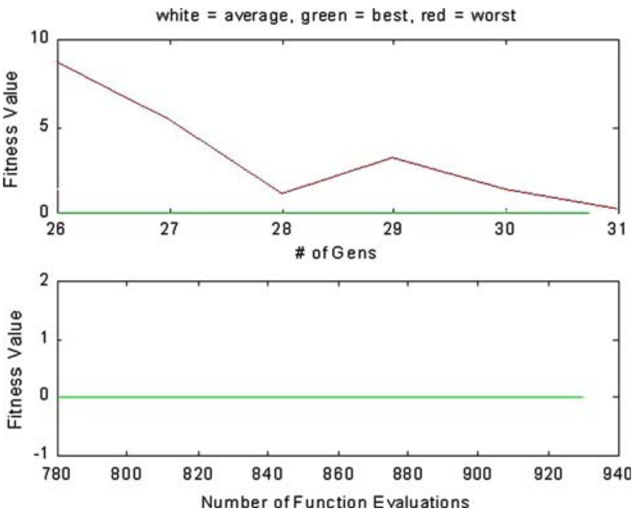


Fig. 12 Final phase plot of fitness value Vs number of generations for leg length L1

of GA programs executed separately for each of the bead geometric descriptors for obtaining the optimum process parameters in each of the cases are as follows and the plot between fitness values and number of generations were obtained similar to the one shown in Fig. 12 for leg length L1, for each of the bead geometry descriptors, when GA has performed the set number of generations to achieve the desired value of the parameter:

The final phase of the plot of fitness value v/s number of generations is shown in Fig. 12 for leg length L1. Figure 1 indicates that the genetic algorithm has searched the optimal parameters for GMAW process in 30 generation after arriving at the desired and the achieved values in the fitness function.

LEG LENGTH L1

Desired value of leg length L1 set for GA: 8.0 mm

Output of GA program for leg length L1

$$
\begin{aligned}
\sharp of\,Gens &= 2 Max = 2.5327 Min \\
&= 0.00026362 Avg = 0.4058 \\
\sharp of\,Gens &= 3 Max = 2.7294 Min \\
&= 0.00026362 Avg = 0.41257 \\
\sharp of\,Gens &= 4 Max = 4.5815 Min \\
&= 3.3105e - 005 Avg = 0.29203 \\
&\vdots \\
\sharp of\,Gens &= 30 Max = 1.4539 Min \\
&= 8.1637e - 007 Avg = 0.16132 \\
\sharp of\,Gens &= 31 Max = 0.24062 Min \\
&= 8.1637e - 007 Avg = 0.037194
\end{aligned}
$$

GA has optimized the welding parameters with respect to leg length L1 Best possible leg length L1 is 7.9991 mm

GA has also searched the five optimum input parameters which can yield the above best leg length L1 and the desired values in the remaining output parameters. Type “bp” and enter to obtain the above optimum input parameters. bp

$$
\begin{aligned}
&\mathrm{WS} = 5.7456 \quad \mathrm{V} = 29.1155 \quad \mathrm{C} = 258.5934 \\
&\quad \mathrm{G} = 14.2114 \quad \mathrm{D} = 0.3686
\end{aligned}
$$

LEG LENGTH L2

Desired value of leg length L2 set for GA: 8.0 mm

Output of GA program for leg length L2

$$
\begin{aligned}
\sharp of\,Gens &= 2 Max = 2.9822 Min \\
&= 3.0583e - 005 Avg = 0.33907 \\
\sharp of\,Gens &= 3 Max = 2.9597 Min \\
&= 3.0583e - 005 Avg = 0.41973 \\
\sharp of\,Gens &= 4 Max = 1.3631 Min \\
&= 3.0583e - 005 Avg = 0.19913 \\
&\vdots \\
&\vdots \\
\sharp of\,Gens &= 29 Max = 2.0776 Min \\
&= 1.3538e - 006 Avg = 0.41146 \\
\sharp of\,Gens &= 30 Max = 1.9238 Min \\
&= 1.3538e - 006 Avg = 0.21417 \\
\sharp of\,Gens &= 31 Max = 1.5895 Min \\
&= 1.3538e - 006 Avg = 0.2216
\end{aligned}
$$

GA has optimized the welding parameters with respect to leg Length L2

Best possible leg Length L2 is 8.0012 mm

GA has also searched the five optimum input parameters which can yield the above best leg length L2 and the desired values in the remaining output parameters. Type “bp” and enter to obtain the above optimum input parameters. bp

$$
\begin{aligned}
&\mathrm{WS} = 5.9022 \quad \mathrm{V} = 29.7260 \quad \mathrm{C} = 260.4542 \\
&\quad \mathrm{G} = 15.4481 \quad \mathrm{D} = 1.8196
\end{aligned}
$$

PENETRATION

Desired value of penetration set for GA: 2.0 mm

Output of GA program for penetration

$$
\begin{aligned}
\sharp of\,Gens &= 2 Max = 0.51791 Min \\
&= 5.8963e - 008 Avg = 0.091196 \\
\sharp of\,Gens &= 3 Max = 0.12615 Min \\
&= 5.8963e - 008 Avg = 0.024519 \\
\sharp of\,Gens &= 4 Max = 0.039625 Min \\
&= 5.8963e - 008 Avg = 0.0081369 \\
&\vdots
\end{aligned}
$$

$$\vdots$$

$$\begin{aligned}\sharp of Gens &= 29 Max = 0.056515 Min\\ &= 5.8963e - 008 Avg = 0.0091646\\ \sharp of Gens &= 30 Max = 0.11582 Min\\ &= 5.8963e - 008 Avg = 0.0091736\\ \sharp of Gens &= 31 Max = 0.026644 Min\\ &= 5.8963e - 008 Avg = 0.0027853\end{aligned}$$

GA has optimized the welding parameters with respect to penetration Best possible penetration is 2.0002 mm

GA has also searched the five optimum input parameters which can yield the above best penetration and the desired values in the remaining output parameters. Type “bp” and enter to obtain the above optimum input parameters. bp

WS = 6.8571 V = 26.7123 C = 278.3077
G = 16.4736 D = 0.5647

THROAT THICKNESS

Desired value of throat thickness set for GA: 4.5 mm
Output of GA program for throat thickness

$$\begin{aligned}\sharp of Gens &= 2 Max = 0.47236 Min\\ &= 1.5776e - 005 Avg = 0.107\\ \sharp of Gens &= 3 Max = 0.35217 Min\\ &= 1.5776e - 005 Avg = 0.08116\\ \sharp of Gens &= 4 Max = 0.46341 Min\\ &= 1.5776e - 005 Avg = 0.043656\end{aligned}$$

$$\vdots$$

$$\vdots$$

$$\begin{aligned}\sharp of Gens &= 29 Max = 0.52431 Min\\ &= 9.8451e - 008 Avg = 0.039423\\ \sharp of Gens &= 30 Max = 0.18137 Min\\ &= 9.8451e - 008 Avg = 0.022487\\ \sharp of Gens &= 31 Max = 0.092424 Min\\ &= 9.8451e - 008 Avg = 0.0079044\end{aligned}$$

GA has optimized the welding parameters with respect to throat thickness Best possible throat thickness is 4.5003 mm

GA has also searched the five optimum input parameters which can yield the above best throat thickness and the desired values in the remaining output parameters. Type “bp” and enter to obtain the above optimum input parameters. bp

WS = 6.5205 V = 26.0000 C = 273.7363
G = 15.3307 D = 0.6275

REINFORCEMENT HEIGHT

Desired value of reinforcement height set for GA: 1.2 mm
Output of GA program for reinforcement height

$$\begin{aligned}\sharp of Gens &= 3 Max = 0.057322 Min\\ &= 1.2364e - 008 Avg = 0.013464\\ \sharp of Gens &= 4 Max = 0.041134 Min\\ &= 1.2364e - 008 Avg = 0.0070488\end{aligned}$$

$$\vdots$$

$$\vdots$$

$$\begin{aligned}\sharp of Gens &= 29 Max = 0.019328 Min\\ &= 2.4699e - 010 Avg = 0.0037761\\ \sharp of Gens &= 30 Max = 0.057206 Min\\ &= 2.4699e - 010 Avg = 0.010316\\ \sharp of Gens &= 31 Max = 0.014614 Min\\ &= 2.4699e - 010 Avg = 0.0025598\end{aligned}$$

GA has optimized the eelding parameters with respect to reinforcement height Best possible reinforcement height is 1.2000 mm

GA has also searched the five optimum input parameters which can yield the above best reinforcement height and the desired values in the remaining output parameters. Type “bp” and enter to obtain the above optimum input parameters. bp

WS = 7.0528 V = 29.0137 C = 266.8278
G = 16.0039 D = 0.9176

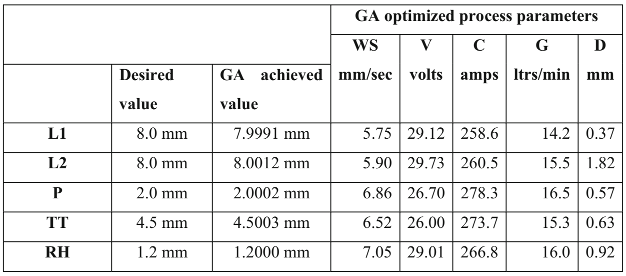
5.2.2 Results and discussions

The process parameters were optimized by GA separately for the bead shape parameters. GA has successfully searched the optimal process parameters to achieve the desired values of leg length L1, leg length L2, penetration, throat thickness and reinforcement height. Summarized results of GA are shown in Fig. 8.

The five process variables optimized by the GA are well within the vectors of minimum and maximum values of the controllable process variables of the experimental conditions in all the fillet weld bead shape descriptor cases. Since all the process variables are within the range, GAs can be effectively used for obtaining the input process parameters for achieving the desired leg length L1, leg length L2, penetration, throat thickness and reinforcement height (Fig. 13).

6 Conclusion

Mathematical models were developed for estimating the weld bead geometric descriptors like leg length L1, leg length L2,



			GA optimized process parameters				
			WS	V	C	G	D
	Desired value	GA achieved value	mm/sec	volts	amps	ltrs/min	mm
L1	8.0 mm	7.9991 mm	5.75	29.12	258.6	14.2	0.37
L2	8.0 mm	8.0012 mm	5.90	29.73	260.5	15.5	1.82
P	2.0 mm	2.0002 mm	6.86	26.70	278.3	16.5	0.57
TT	4.5 mm	4.5003 mm	6.52	26.00	273.7	15.3	0.63
RH	1.2 mm	1.2000 mm	7.05	29.01	266.8	16.0	0.92

Fig. 13 Results of GA work

penetration, throat thickness and reinforcement height of fillet welded joints by controlling five process variables such as welding speed, voltage, current, gas flow rate and offset distance of Gas Metal Arc Welding (GMAW) process using multiple linear regression equations. It has been observed that the predicted values match very closely the experimental values if both main and interaction effects are considered rather than only the main effects. A back-propagation neural network approach was also used for modeling the weld bead geometric descriptors of gas metal arc welding process. The results indicate that neural networks can yield moderately accurate results. Optimization of process parameters using GA for weld bead geometric descriptors like leg length L1, leg length L2, penetration, throat thickness and reinforcement height yielded satisfactory results and GA can be effectively used to determine input process parameters to get desired bead geometry. The mathematical modeling using regression analysis and artificial neural network, and optimization of process parameters using GA for the desired bead geometry descriptors could be effectively used in fillet welds made by GMAW process. Adaptive learning ability of ANN to learn how to do tasks based on the data given for training or initial experience and the capability of ANN of Real Time Operation i.e., ANN computations may be carried out in parallel, and special hardware devices are being designed and manufactured which take advantage of this capability is a great advantage for welding and other applications in industries. Genetic Algorithm as an optimization tool reduces the efforts required in industrial welding applications to arrive at machine settings to obtain desired weld bead geometric features.

References

1. Wu, S.M.: Analysis of rail steel bar welds by two-level factorial design. Weld. J. **43**(4), 179s–183s (1964)
2. Moon, H., Na, S.: Optimum design based on mathematical model and neural network to predict weld parameters for fillet joints. J. Manuf. Syst. **16**(1), 13–23 (1997)
3. Wu, S.M., Stegner, D.A.J., Braton, N.R.: Prediction of heat input for welding. Weld. J. **46**(3), 122–128 (1967)
4. Bartee, E.M.: Engineering Experimental Design Fundamentals. Prentice-Hall, Inc., Englewood Cliffs (1968)
5. Montgomery, D.C.: Design and Analysis of Experiments, 4th edn. Wiley, NY (1997)
6. Karsai, G., Cook, G.E., Andersen, K., Ramaswamy, K.: Artificial neural networks applied to arc welding process modeling and control. IEEE Trans. Ind. Applicat. **26**(5), 824–830 (1990)
7. Anderson, K.: Studies and implementation of stationary models of the gas tungsten arc welding process. Master's thesis, Vanderbilt University (1992)
8. Hsieah, C.C., Hunag, M.-W., Arora, J.S.: Genetic algorithm for sequence type problems in engineering design. Int. J. Numer. Methods Eng. **40**, 3105–3115 (1997)
9. Kim, D., Rhee, S.: Optimization of arc welding process parameters using genetic algorithm. Weld. J. **80**(7), 184–189 (2001)
10. Lippmann, R.P.: An introduction to computing with neural nets. IEEE ASSP Mag. 4–22 (1987)