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Modeling and prediction of HAZ using finite element and neural network modeling

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A B S T R A C T

With the increasing demands for product variety and quality level the need to eliminate human operator from the feedback path for welding process correction is evident. Of the several manufacturing methods welding alone has defined true automation. Success of automation depends on effective and efficient decision making tools. Neural network is applied to intelligent weld control. In Submerged Arc Welding (SAW), selecting appropriate values for process variables is essential to control heat affected zone (HAZ) dimensions and get the required bead size and quality. Also, conditions must be selected that will ensure a predictable and reproducible weld bead. This paper proposes the modeling and prediction of dimensions of Heat-Affected Zone for SAW process using Finite Element Analysis (FEA) and Artificial Neural Network (ANN). The dimensions of HAZ for SAW are modeled are simulated using FEA using the process variables such as welding current, arc voltage, arc efficiency and welding speed and the results are used as the learning file for ANN model. The developed ANN model is forwarded to predict the dimensions of HAZ and the results are compared with simulated FEA results. The developed method is found to be time consuming, competent and cost effective.

A R T I C L E I N F O

Keywords:
Heat-affected zone (HAZ)
Finite element analysis
Artificial neural network
Submerged arc welding

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1. Introduction

Saw is one of the most widely used metal joining process used in heavy fabrication industries, which involves heating, melting and solidification of metals. Geometry of the resulting weld bead and heat-affected zone is a good indicator of weld quality. However the geometrical parameters, such as bead width, bead height, depth of penetration etc., are closely coupled. Thus, independent adjustment of single parameter is difficult. Because of the unknown non-linear relationships between the desired weld geometry and the welding parameters (welding current, arc voltage, welding speed, etc.) it is difficult to adjust the parameters in the machine set up to get a good quality of weld. Many researchers used FEA to perform welding simulations and to predict weld HAZ and residual stresses in different types of joints and materials. Prediction of HAZ is very difficult due to the complex variations of temperature, thermal contraction and expansion, and variation of material properties with time and space. Furthermore, modeling of the weld process for the specialized effects of the moving weld arc, material deposit, and metallurgical transformations is a complex task. Effects of cooling rate and hardness [1] process variables [2] on HAZ in submerged arc welds have been observed. Monte Carlo simulation [3] and grey theory [4] have been employed to predict HAZ.

Finite Element procedures were developed for heat affected zone prediction [5-7] in weld joints. Finite Element Method (FEM) [6-8] was applied to calculate residual stress, to model drilling process [9] resistance spot welding process and to predict the hardness of HAZ. ADINAT [9, 10], ABAQUS [11] and ANSYS have been used to simulate the finite element HAZ weld models. Although finite element method has emerged as one of the most attractive tool to compute dimensions of HAZ, its application to practical analysis and design problems is hampered by computational difficulties. Gunaraj [12] used statistical techniques to predict the HAZ in submerged arc welding of structural steel pipes Analytical methods [13] and Taguchi method [14] employed to predict HAZ. Thermocouple [15] and Digital Image Processing [16] used for HAZ prediction. These methods require special equipment which is expensive. These techniques are limited in obtaining the entire picture of the HAZ distribution in weldment.

Artificial Neural Network is an efficient technique used to handle problems of nonlinearity. It has a wide scope in modeling the manufacturing process [17, 18]. ANN [19] is applied to predict the nugget size and hardness of HAZ of the weld. Results from FEA [20] were used to train ANN model to simulate the effects of welding process. This paper proposes the prediction of heat-affected zone in a SAW process, which is an important property in determining the good quality of weld to avoid unwanted residual stress, and distortion which leads to the failure of the weldment. Selection of appropriate process variables is essential in SAW to control the dimensions of HAZ to get the required weld quality. The main objective of this research was to explore applications for artificial neural networks in prediction of HAZ in welding. In this paper the following notation is used: I is welding current, A; V is arc voltage, V; S is welding speed, mm/min; E is electrode stickout, mm; FZ is fusion zone; A is weld bead area, mm^2; η_a is arc efficiency; q is heat flux, W/mm^2; Q is heat input, kJ.

2. Heat affected zone

Heat-affected zone is the portion of the parent material which has been heated above the critical temperature but has not melted. It is the area of base material, either a metal or a thermoplastic, which has had its microstructure and properties altered by welding. The heat from the welding process and subsequent re-cooling causes this change in the area surrounding the weld. The extent and magnitude of property change depends primarily on the base material, the weld filler metal, and the amount and concentration of heat input by the welding process. The thermal diffusivity of the base material plays a large role – if the diffusivity is high, the material cooling rate is high and the HAZ is relatively small. Alternatively, a low diffusivity leads to slower cooling and a larger HAZ. The amount of heat inputted by the welding process plays an important role as well, as processes like oxyfuel welding use high heat input and increase the size of the HAZ. The equation 1 is used to calculate the heat input for submerged arc welding process.

HAZ should be minimal to maximize the strength of the weld. The cracks caused in the HAZ are a major problem in the weld. The cracks are caused by low melting point phases present at the grain boundaries. Due to the thermal cycle of welding, the temperature may be so high that these phases melt.

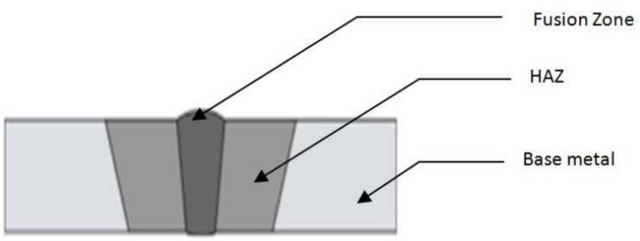

Fig 1: Cross-section of a butt weld joint

$$Q = \left(\frac{V \times I \times 60}{S \times 1000}\right) \times \text{Efficiency} \tag{1}$$

During the cooling phase the unmelted material shrinks, resulting in residual tensile stresses. A material deficiency at the grain boundary may then result in voids or intergranular, crack like defects. The presence of small HAZ-cracks does not necessarily affect the mechanical strength of a weld, however, it may reduce the fatigue lifetime and the fracture toughness. It is difficult to know how to avoid HAZ-cracks. Hence prediction of HAZ is necessary and essential. The cross-section of a welded butt joint, with the darkest gray representing the weld or fusion zone, the medium grey the heat affected zone, and the lightest grey the base material (Fig. 1).

Selection of appropriate process variables is essential in submerged arc welding, is necessary in order to control heat-affected zone dimensions to get the required bead size and quality. Also, conditions must be selected that will ensure a predictable and reproducible weld bead, which is critical for obtaining high quality. In this investigation, a finite element model was developed to study the effect of process variables and heat input to find dimensions of heat-affected zone.

3. Back propagation neural network model

The use of neural network models is vital in the modern manufacturing environment. Neural networks are dynamic systems that consist of processing units called neurons with weighted connections to each other. Neural networks can learn, remember and retrieve data. The significant functions of neural network are tackling non-linearity and mapping input-output information.

Back Propagation Neural Network [22] is a multiple layer ANN with input layer, output layer and some hidden layers between the input and output layers. Its learning procedure is based on gradient search with least mean squared optimality criteria. Once the input data is fed to the nodes in the input layer o_i; this will be fed to nodes j; in the hidden layer through weighting factors w_{ji}.

The net input to node j is:

$$net_j = \sum_i w_{ji}\, o_i - b_j \tag{2}$$

where b_j is the bias over node j.

The output of the node j is:

$$o_j = \frac{1}{1 + e^{net_j}} \tag{3}$$

Similarly the outputs from nodes in the hidden layer are fed into nodes in the output layer. This process is called the feed forward stage. After feed forward, calculation output, o_{pk} can be obtained from nodes in the output layer. In general, the output, o_{pk} will not be the same as the desired known target t_{pk}. Therefore the average system error is:

$$E = \frac{1}{2p} \sum_p \sum_k \left(t_{pk} - o_{pk}\right)^2 \tag{4}$$

$$\Delta_p w_{kj} = -\mu \frac{\partial E}{w_{kj}} = \mu \delta_k o_j \tag{5}$$

$$\delta_k = o_k (1 - o_k)(t_k - o_k) \tag{6}$$

$$\delta_j = o_j(1 - o_j)\sum w_{kj}\delta_k \tag{7}$$

$$\Delta w_{ij} = \sum_p w_{ij} \tag{8}$$

$$w_{ij}(n+1) = w_{ij}(n) + \Delta w_{ij} \tag{9}$$

The error is then back propagated from nodes in the output layer to nodes in the hidden layer using gradient search method (see equation 5), delta value for output layer is in equation 6, delta value for hidden value is defined in equation 7.

This process is called back propagation stage. After all examples are trained the system will collect adjusted weights according to equation 8. Updating of weights is done according to equation 9.

4. Proposed methodology

The stages of an ANN model are: a) data acquisition b) development of proposed ANN model c) comparison of results.

4.1 Data acquisition

Simulation of experiments to examine the dimensions of heat-affected zone is carried out using commercial ANSYS finite element analysis software. The process of forming a butt weld that joints two commercial plates of size 100 mm (length) by 6 mm (height) for HAZ is simulated with a moving heat source. A root gap of 3 mm was maintained for all samples. Welding was carried out using a direct current electrode positive with 3.25 mm mild steel welding wire. Appropriate constraint conditions were applied to the 2 dimensional finite element model to simulate the real process. The properties of the weld material are given in Table 1. The boundary condition applied is convection on all surfaces with a convective film coefficient of 10 W/m^2. The heat flux applied to the weld model is defined in Table 2. The whole plate is assumed initially at a temperature of 27 °C. The model of the heat source assumes a Gaussian heat flux distribution on the weld pool. The heat generated in the slag pool is the main source of the total heat input in SAW. Other sources of heat, such as chemical reaction between the metal and the slag, are insignificant and are ignored. The assumptions made in modeling are:

1. Identify the noise factor: the welding is considered as a single pass butt-welding.
2. The effect of edge preparation for welding is negligible.
3. The penetration and overfill of the weldment were not considered.
4. The wire diameter used for weld is considered as 3 mm.

Table 1 Properties of Mild Steel

No.	Properties	Values
1	Yield strength	248 N/mm^2
2	Tensile strength	400 N/mm^2
3	Young's modulus, E	200·10^3 N/mm^2
4	Shear modulus, G	79·10^3 N/mm^2
5	Poisson's ratio	0.26
6	Thermal expansion co-efficient	11.7·10^{-6}
7	Density, ρ	7861 kg/m^3
8	Thermal conductivity, k	53.604 W/(m·°C)
9	Specific heat, C	0.465 kJ/(kg·°C)
10	Melting point	1510 °C
11	Elongation	23 % in 50 mm
12	Tensile yield strain	30 %
13	Thermal expansion	10^{-6}/°C

4.1.1 Meshing

To analyze the heat transfer characteristics of the weld model 2-D Thermal solid element PLANE 55 is used which has thermal conduction capability. The element has four nodes with a single degree of freedom, temperature, at each node. The element can also compensate for mass transport heat flow from a constant velocity field. The mesh density is made very fine in fusion zone, fine in HAZ and course in other zones for accuracy.

4.1.2 Application of loads

The heat flux are calculated by equation 10 using the weld parameters such as welding current ranges which from 360–390 A, arc voltage which varies from 22–26 V with arc efficiency which varies from 0.8–0.85 %. The HAZ for the above welding parameters are 723–1495 °C [21].

Table 2 Properties of mild steel

Welding	Arc voltage (V)	Arc efficiency (%)	Heat flux (W/mm^2)
360	22	0.6	31680
360	22	0.65	34320
360	22	0.7	36960
360	22	0.75	39600
360	22	0.8	42240
360	23	0.6	33120
360	23	0.65	35880
360	23	0.7	38640
360	23	0.75	41400
360	23	0.8	44160
360	24	0.6	34560
360	24	0.65	37440
360	24	0.7	40320
360	24	0.75	43200
360	24	0.8	46080
360	25	0.6	36000
360	25	0.65	39000
360	25	0.7	42000
360	25	0.75	45000
360	25	0.8	48000
360	26	0.6	37440
360	26	0.65	40560
360	26	0.7	43680
360	26	0.8	49920
370	22	0.75	40700
370	23	0.8	45386.66
370	24	0.65	38480
370	24	0.8	47360
370	25	0.8	49333.33
370	26	0.7	44893.33
370	26	0.8	51306.66
380	22	0.7	39013.33
380	22	0.8	44586.66
380	23	0.8	46613.33
380	24	0.8	48640
380	25	0.75	47500
380	26	0.75	49400
380	26	0.8	52693.33
390	22	0.7	40040
390	22	0.8	45760
390	23	0.8	47840

Heat flux is:

$$q = \frac{\eta_a \cdot V \cdot I}{A} \tag{10}$$

Based on the requirement of the weld bead area the amount of heat flux supplied to the weld plate changes and is found by equation 11.

Weld bead area is:

$$A = \frac{I^{0.55}}{10^{3.95} \cdot S^{0.003}} \tag{11}$$

The use of appropriate welding speed for given welding current to avoid undercutting is found from equation 12.

$$S = 1.6 \cdot 10^{6} \cdot I^{-1.638} \tag{12}$$

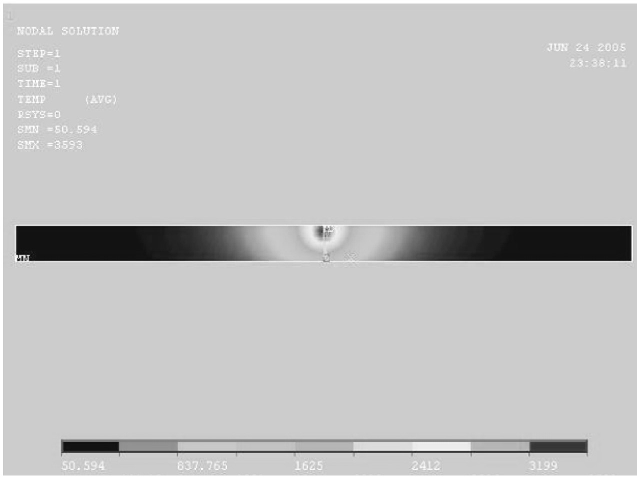

Fig. 2 Temperature distribution of welded plate

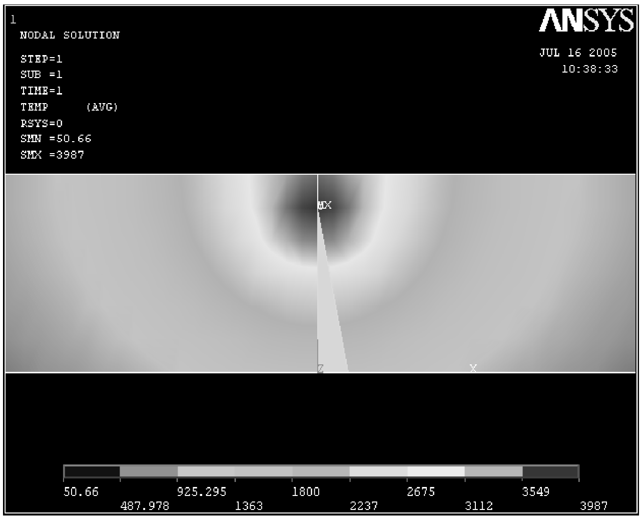

Fig. 3 Enlarged view of the HAZ

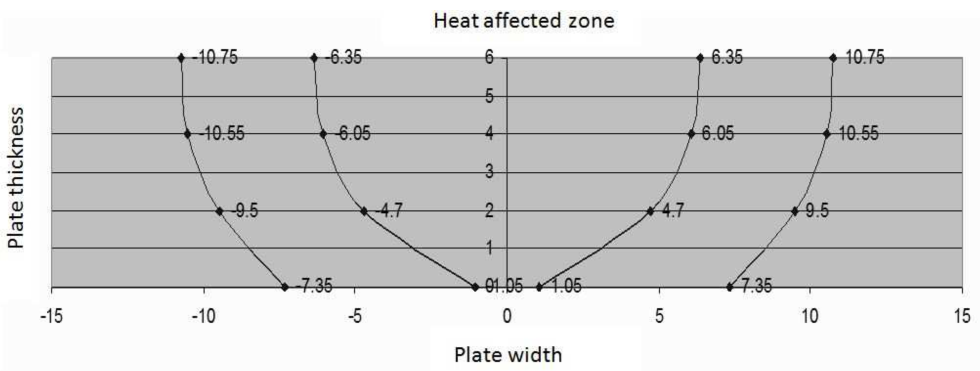

Fig. 4 Dimensions of HAZ

4.1.3 Simulation of results

The temperature T (t, x, y, z) as a function of time (t) and spatial coordinates (x, y, z) satisfies the diffusion equation 13 at every point within a finite domain.

4.1.4 Review of results

Result interpretation is the important phase in the analysis part, which needs significant attention to get the exact results for the available data. After the solution phase the simulated model results are reviewed in post processing phase. In this post-processing phase the results at each load step is taken and noted. Temperature distribution for the applied load is shown in Fig. 2. From the temperature distribution (Fig. 2) the heat-affected zone temperature nodes are selected. Then the distance of the nodes from the centerline is calculated manually (Fig. 3). HAZ dimensions measured for each input data are given in Tables 3 and 4. Dimensions of heat-affected zone are the region between two curves (Fig. 4). Results are used to train the artificial neural network in MATLAB.

Table 3 Heat-affected zone parameters at 723 ^{0}C. Distance measured from the center of the weld.

Top surface	2 mm below top surface	4 mm below top surface	Bottom surface
7.85	7.55	6.5	3.75
8.4	8	6.8	4.5
8.8	8.5	7.4	5
9.3	9	7.8	5.6
9.7	9.3	8.2	6
8.25	7.8	6.6	4.25
8.7	8.25	7.1	4.8
9.15	8.75	7.65	5.35
9.55	9.25	8.05	5.8
9.9	9.6	8.5	6.3
8.5	8.15	6.85	4.55
8.9	8.6	7.5	5.2
9.35	9.05	7.95	6.05
9.7	9.5	8.35	6.1
10.15	9.85	9.3	6.65
8.75	8.3	7.2	4.8
9.1	8.85	7.75	5.45
9.65	9.25	8.15	5.95
10.1	9.75	8.7	6.2
10.5	10.15	9.55	6.85
8.85	8.15	7.5	5.15
9.4	9.1	8	5.75
9.85	9.5	8.45	6.25
10.85	10.7	9.3	7.15
9.4	9.15	8	5.8
9.35	9.2	7.8	5.6
10.2	9.8	8.75	6.5
10.3	10.1	8.95	6.8
10.65	10.6	9.35	7.05
10.1	9.8	8.7	6.4
10.75	10.55	9.5	7.35
9.2	8.85	7.75	5.45
10.05	9.7	8.55	6.45
10.3	9.95	8.85	6.7
10.6	10.35	9.15	6.95
10.4	10.1	9	6.85
10.7	10.65	9.35	7.1
11.1	10.75	9.65	7.5
9.3	9	7.95	5.7
10.2	9.85	8.75	6.55
10.4	10.15	9.05	6.85
10.75	10.35	9.8	7.1
10.9	10.6	9.65	7.4
10.85	10.45	9.35	7.25

$$\frac{\partial T}{\partial} = \nabla\left(\frac{\lambda \nabla T}{\rho c}\right) + \frac{Q}{\rho c} \tag{13}$$

Table 4 Heat-affected zone parameters at 1500 ^{0}C. Distance measured from the center of the weld.

Top surface	2 mm below top surface	4 mm below top surface	Bottom surface
3.65	3.15	0	0
4.1	3.65	1.4	0
4.45	4.05	2.3	0
4.85	4.4	2.8	0
5.25	4.8	3.3	0
3.8	3.3	1	0
4.3	3.8	1.9	0
4.7	4.25	2.7	0
5.2	4.7	3.2	0
5.55	5.15	3.7	0
3.85	3.65	1.55	0
4.5	4.15	2.3	0
5.05	4.55	3.05	0
5.3	5	3.5	0
5.7	5.35	3.95	0
4.25	3.85	2	0
4.75	4.3	2.7	0
5.25	4.85	3.2	0
5.7	5.3	3.85	0
6	5.65	4.25	0
4.6	4.1	2.3	0
5.05	4.55	3.05	0
5.45	5.05	3.55	0
6.2	5.85	4.55	0
5.05	4.65	3.1	0
4.9	4.45	2.85	0
5.7	5.25	3.8	0
5.9	5.55	4.2	0
6.15	5.8	4.45	0
5.7	5.2	3.8	0
6.35	6.05	4.7	1.05
4.8	4.85	2.75	0
5.55	5.15	3.7	0
5.8	5.4	4.05	0
6.1	5.65	4.3	0
5.9	5.6	4.2	0
6.15	5.85	4.95	0
6.55	6.15	4.95	1.55
4.9	4.55	2.9	0
5.75	5.35	4	0
5.95	5.65	4.25	0
6.25	5.75	4.65	0
6.5	6.15	4.85	1.35
6.35	5.9	4.65	0.25

4.2 Development of proposed ANN model

The proposed neural network model built is a multilayered feed forward back propagation neural network. It has four welding parameters as input variables and the estimated HAZ dimension as an output variable.

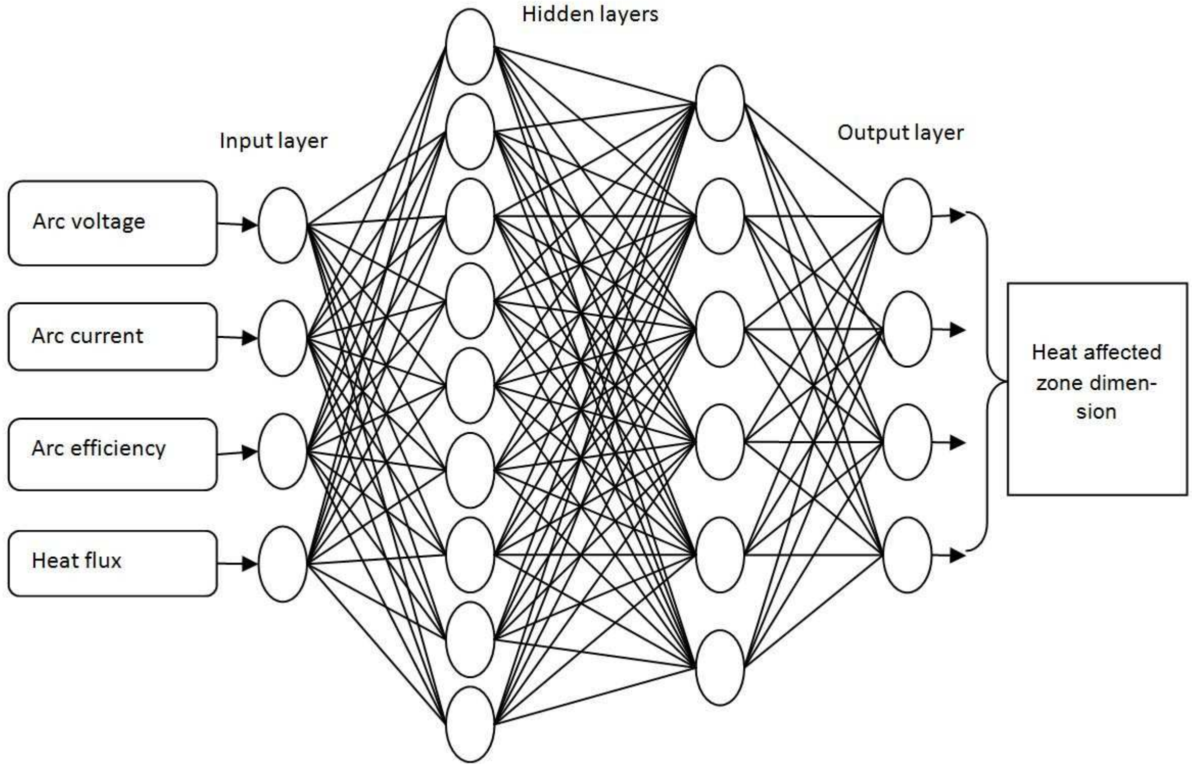

Fig. 5 Proposed neural network architecture

The learning function is gradient descent algorithm with momentum weight and bias learning function. The number of hidden layers and neurons are determined through a trial and error method, in order to accommodate the converged error. The structure of the proposed neural network is 4-9-14-1 (4 neurons in the input layer, 9 neurons in first hidden layer, 14 neurons in second hidden layer, and 1 neuron in the output layer (Fig. 5). The training function used in the proposed neural network is "TRAINLM" and the learning function is "LEARNGDM". With a learning rate of 0.55 and a momentum term of 0.9, the developed network is trained for 10000 iterations. The error between the desired and the actual outputs is less than 0.001 at the end of the training process.

4.3 Results and discussion

Results of modeling of HAZ in SAW process reveals that the heat input calculated using welding current, welding voltage and welding speed had a considerable positive effect on almost all HAZ dimensions. The neural network trained with the data from finite element simulation is tested with set of input parameters and the results are compared with the results obtained from FEA.

Table 5 Testing of input parameters used for comparison of FEA and ANN

Current *I*, A	Arc Voltage *V*, V	Arc efficiency	Heat flux, W/mm2
360	23	0.8	44160
360	25	0.6	36000
360	26	0.8	49920
370	25	0.8	49333.33
380	24	0.8	48640
390	22	0.7	40040

The input data set used for testing ANN is given in Table 5 and corresponding HAZ dimensions are given in Table 6. Comparison of results obtained from FEA and ANN (Fig. 6, 7, 8 and 9).

Table 6 Results of the test data for heat-affected zone parameters at 723 °C (Distance measured from the center of the weld)

Top surface	2 mm below top surface	4 mm below top surface	Bottom surface
9.9	9.6	8.5	6.3
8.7501	8.2999	7.2	4.8
10.85	10.7	9.3	7.15
10.6501	10.6	9.3499	7.05
10.6	10.35	9.15	6.95
9.3	9	7.95	5.7

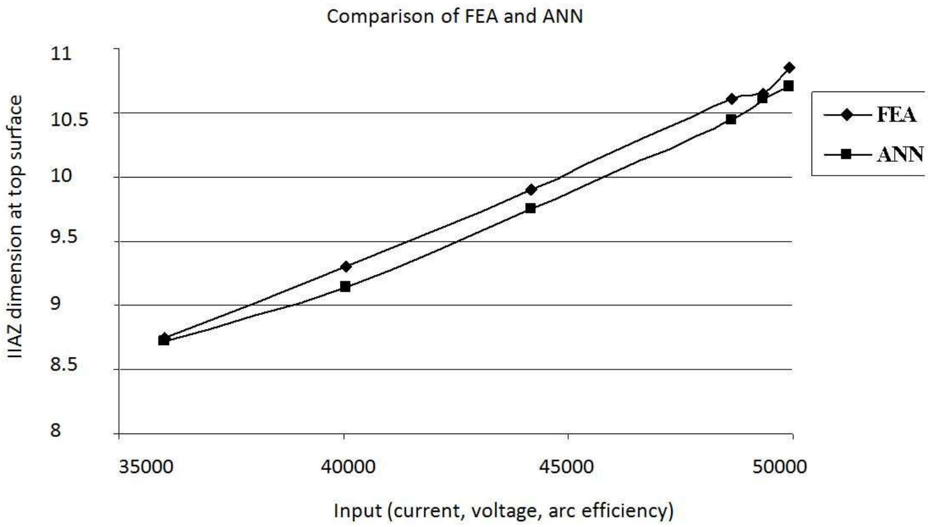

Fig. 6 Comparisons of HAZ dimension at top surface of plate

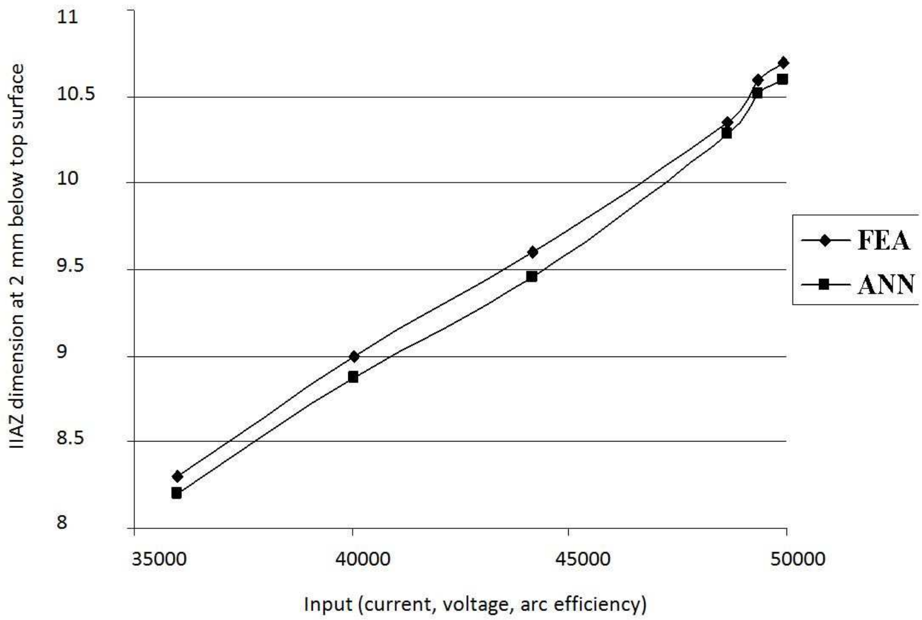

Fig. 7 Comparisons of HAZ dimension at 2 mm below top surface of plate

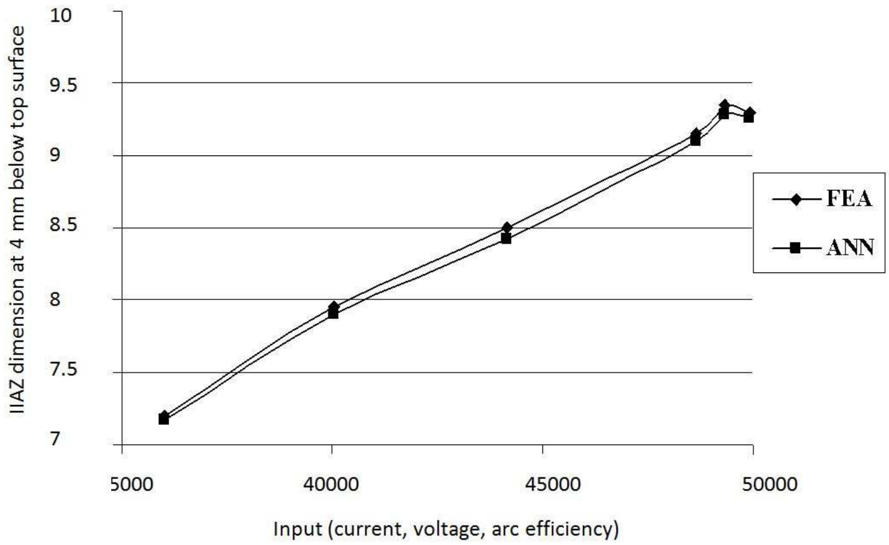

Fig. 8 Comparisons of HAZ dimension at 4 mm below top surface of plate

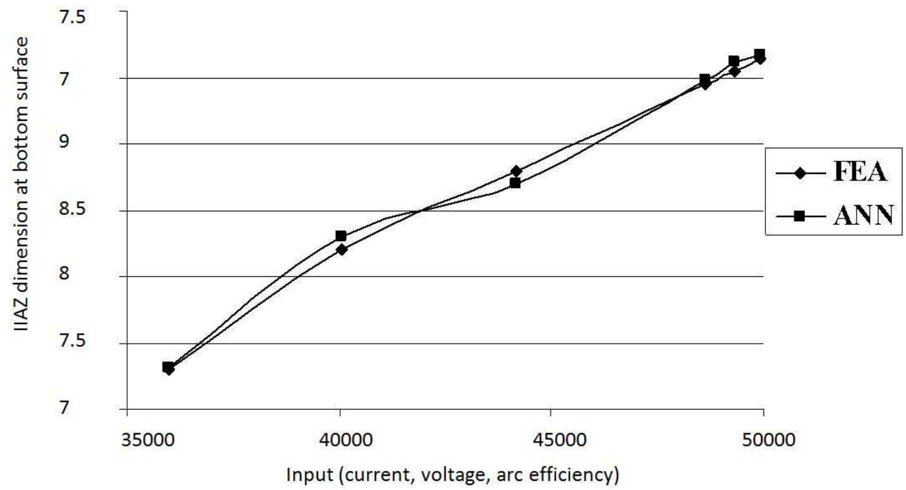

Fig. 9 Comparisons of HAZ dimension at bottom surface of plate

5. Conclusions

A substantial amount of work is done with a goal of developing an intelligent fully automatic system in welding. For this purpose neural network system has been investigated. The developed neural network system is able to control the behavioral characteristics of the welding process to improve quality, reliability and productivity in industrial areas. The welding process has been traditionally difficult to model analytically due to highly coupled nonlinear nature of complex parameters. The back propagation algorithm used in ANN can model traditionally difficult, nonlinear problems with a sufficient high degree of accuracy. In addition to neural networks' usefulness in solving complex nonlinear problems, they are attractive in view of their high execution speed with their modern computer hardware requirements. In this work the modeling of HAZ is done using FEA and prediction of HAZ in ANN to investigate the welding process. The results of this work show that the results of proposed ANN yields the similar results obtained by FEA simulation. Neural network systems are able to provide accurately off line quality control based on the observations of the dimensions of HAZ. Utilization of proposed ANN will reduce the time required to model the welding process in FEA simulation. It is an attempt to eliminate human operator to enact corrective actions on the system variables in real time.

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