J. Marine Sci. Appl. (2012) 11: 387-391
DOI: 10.1007/s11804-012-1147-9

Development of Fuzzy Logic System to Predict the SAW Weldment Shape Profiles

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Abstract: A fuzzy model was presented to predict the weldment shape profile of submerged arc welds (SAW) including the shape of heat affected zone (HAZ). The SAW bead-on-plates were welded by following a full factorial design matrix. The design matrix consisted of three levels of input welding process parameters. The welds were cross-sectioned and etched, and the zones were measured. A mapping technique was used to measure the various segments of the weld zones. These mapped zones were used to build a fuzzy logic model. The membership functions of the fuzzy model were chosen for the accurate prediction of the weld zone. The fuzzy model was further tested for a set of test case data. The weld zone predicted by the fuzzy logic model was compared with the experimentally obtained shape profiles and close agreement between the two was noted. The mapping technique developed for the weld zones and the fuzzy logic model can be used for on-line control of the SAW process. From the SAW fuzzy logic model an estimation of the fusion and HAZ can also be developed.
Keywords: submerged arc welding (SAW); fuzzy-logic controller; bead height; weldment cross-sectional-area; heat affected zone (HAZ); fuzzy model; fuzzy logic system
Article ID: 1671-9433(2012)03-0387-05

1 Introduction

The weldment characteristics of submerged arc welding (SAW) such as weld reinforcement, weld penetration depth, and heat affected zones (HAZ) are important considerations which affect the overall weld integrity. The SAW process is a multivariable, nonlinear, fast reactive, and high-order sensible welding system. The weldment characteristics not only depend on the welding process but also on the process parameters and determine the quality of the weld (Datta *et al.*, 3003; Lee *et al.*, 2010). In the conventional arc welding process, most of the optimization theories are solved by mathematical modelling. But in a true sense, there are many complex welding process parameters which are difficult to formulate accurately using mathematical models. Differing from conventional approaches, the fuzzy control technique can provide a satisfactory resolution for these problems by introducing linguistic information. The most difficult feature in the design of a fuzzy model is the construction of the rule base. The construction of fuzzy rules is mainly based on the experience of operators or actions. Also, selecting the fuzzy rule membership function is an important task in the design of a fuzzy model system.

Researchers have tried to predict SAW and other fusion welding characteristics using statistical and soft computing methods. Most of the research work related to arc weldment characteristics involves prediction of the maximum reinforcement height, width, and penetration. Rarely a complete prediction of weldment shape profile including that of HAZ has been observed in contemporary research literature (Chan *et al*., 1994; Chandel and Bala, 1998; Kim *et al*., 1996). Investigators have also resorted to experimentation and prediction of weldment characteristics based on experimental results using statistical modelling such as regression analysis and response surface methods (Mahapatra *et al*., 2005; Lee and Um, 2000; Nagesh and Datta, 2002; Kim *et al*., 2002). Sensitivity analysis has been used to predict the variation in the objective function due to small changes in the optimum values of constraints. The bead width of SAW using adaptive neural fuzzy inference systems (Dhas and Kumanan, 2007) was designed. The fuzzy logic controller based on a non-linear model (Tanaka and Sugeno, 1992). The applications of fuzzy algorithms and fuzzy relationships to engineering applications have been well established (Zadeh, 1968; Bandler and Kohout, 1988). In fusion weldment the HAZ is situated adjacent to the weld metal. It is the portion of the parent metal that is affected by welding heat with a temperature so high that the grain structures have been altered. The HAZ is subjected to a complex thermal cycle ranging from a melting temperature to a much lower temperature and hence consists of a series of varying microstructures. The quality of the welded joint depends on the nature of the HAZ as most of the welding failures originate from it. In this investigation the SAW weldment characteristics and shape profile (complete weldment profile including bead width, bead height, depth of HAZ, width of HAZ, and weld bead cross-sectional area) have been predicted with respect to the input process

Received date: 2011-08-02.
Foundation item: Supported by the IIT Roorkee Project under Grant No. FIG-A Scheme-A
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parameters by constructing a fuzzy model based on the experimental data. The prediction capability of the fuzzy model was also validated with a number of test cases.

2 Experimental details

In the present investigation a constant current SAW power source was used for the experiments. The setup for the experiment is shown in Fig. 1. A copper coated electrode AWS (EH-14), of 4 mm diameter, with basic-fluoride-type granular flux, was used. The composition of flux, electrode, and mild steel are given in Tables 1 to 3, respectively.

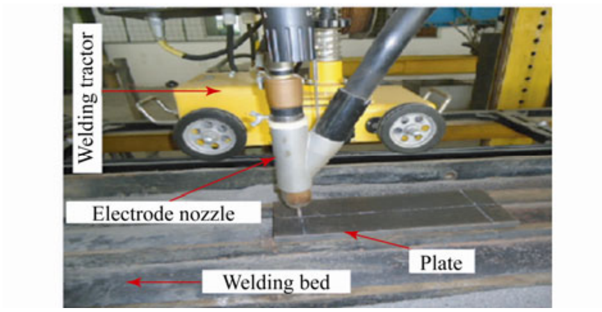


Fig. 1 The SAW setup for experiment

Table 1 Composition of flux

CaF_2/%	CaO+ MgO/%	$Al2O_3$+ MnO/%	SiO_2+ TiO_2/%	Fe
25	40	20	15	Balance

Table 2 Chemical composition of SAW wire

C/%	Mn/%	Si/%	S/%	P/%	Cu/%	Fe
0.10	0.30-0.62	0.03	0.03	0.03	0.15	Balance

Table 3 Chemical composition of the mild steel %

C	Si	Mn	P	S	Ni	Cr	Fe
0.16	0.178	0.45	0.18	0.07	0.13	0.016	98.8

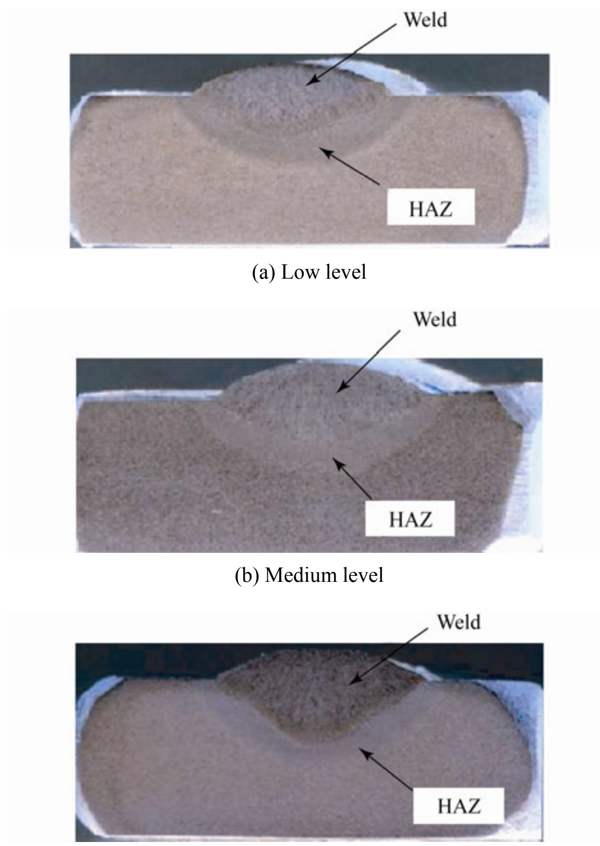
The experiments were conducted to select the range of welding input parameters so that no observable defect such as slag inclusion, undercutting, and porosity occurred. The welding process parameters for the full factorial design matrix used for the experiments are given in Table 4. The welding current, voltage, and traverse speed were used as the input parameters. Each input parameter (factor) has three levels as indicated in Table 4. Twenty-seven experiments were conducted based on the design experiment matrix. The length, width, and thickness of mild steel plates used in the experiments were 300, 100, and 12 mm, respectively. The electrode was set perpendicular to the plate. Weld samples were cut from the test pieces and polished by silicon carbide paper with different grades and etched by a nital solution (5%–10%, Nitric Acid with water), and then bead geometries were measured as shown in Figs. 2 and 3, including the bead width, bead height, depth of penetration, width of HAZ, depth of HAZ, and weld bead cross-sectional area.

Table 4 Design matrix of input parameters

Parameters	High	Medium	Low
Current/A	525	475	450
Voltage/V	29	32	36
Traverse speed /($mm \cdot s^{-1}$)	8.33	6.94	5.55

Table 5 Outputs parameters for SAW

Sl.No	Outputs
1	Bead height (H1)
2	Bead width (BW)
3	Depth of penetration (P1)
4	Depth of HAZ (DH1)
5	HAZ width (HW)
6	Weld cross-sectional area (CSA)/mm^2



(a) Low level

(b) Medium level

(c) High level

Fig. 2 Three polished and etched SAW beads showing weld zone and HAZ of input process parameters as indicated in Table 4

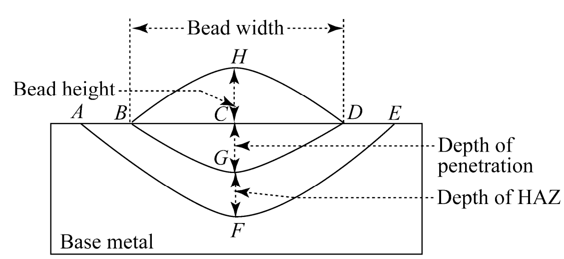


Fig. 3 Schematic of SAW weldment shape

3 Bead profiles mapping

The SAW experiments indicate the repeatability of the process which facilitates modelling the bead characteristics. The SAW beads were cross-sectioned as shown schematically in Fig. 3 and various zones were measured. From Fig. 3 it can be observed that the HAZ width (HW) is the distance *AB*. Similarly *BD*, *HC*, *CG*, and *GF* can be measured for representing bead width (BW), reinforcement height (H), penetration depth (P), and depth of HAZ (DH) by curve fitting of the points *A*, *B*, *H*, *D*,*G*, *E* and *F*, respectively. These dimensions of various zones can be utilised in graphical software for representing the complete weldment shape profile. In the present investigation the bead cross sections were measured. The fuzzy model was derived to study the suitability of the relationships for predicting the bead characteristics of test cases. These dimensions of various zones can be utilised in graphical software for representation.

4 Fuzzy logic based modeling of saw shape profiles

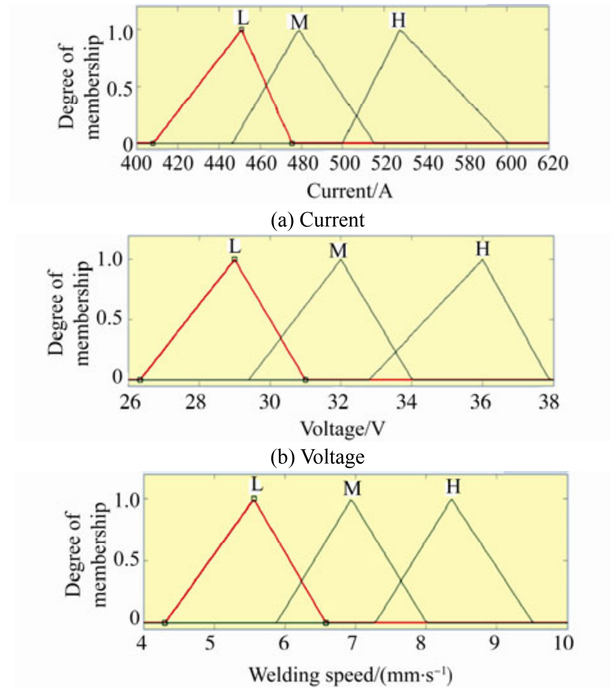
Fuzzy logic is one of the most successful applications of fuzzy set theory (Zadeh, 1968; Bandler and Kohout, 1988). Its major feature is the use of linguistic variables rather than numerical variables. Linguistic variables, defined as variables whose values are sentences in natural language (such as low, medium, and high) may be represented by fuzzy sets. Fuzzy sets are characterised by fuzzification, membership functions, a fuzzy rule, an inference system, and a defuzzification inference. A fuzzy logic controller consists of four major components: 1) a fuzzifier, which converts input (current, voltage, and speed) data into suitable linguistic values; 2) the knowledge based linguistic definitions and control rule set; 3) decision-making logic, which infers the fuzzy control action from the knowledge of the control rules and the linguistic variable definitions; 4) a defuzzification control action deduced from an inferred fuzzy controlled action. The fuzzy rules are expressed in the form of fuzzy conditional statements R_i of the type

R_i: if x is small, y is large, and z is large

'x' and 'y' are fuzzy variables, and 'small' and 'large' are labels of the fuzzy set. If there are i= 1 to n rules, the rule set is represented by a union of these rules.

$$R = R_1 \text{ else } R_2 \text{ else } \ldots R_n$$

A fuzzy logic controller is based on a collection of R control rules. The execution of these rules is governed by a compositional rule. In this paper modelling of SAW parameters based on three input parameters was constructed using fuzzy logic. The proposed fuzzy logic simulation was intended to establish the relationship of weldment characteristics of input process parameters. Fig. 4 describes the membership function of input process parameters and Fig. 5 the membership functions of output process parameters. The fuzzy logic controller is the Mamdani type and contains a rule base (Bandler *et al*., 1988).



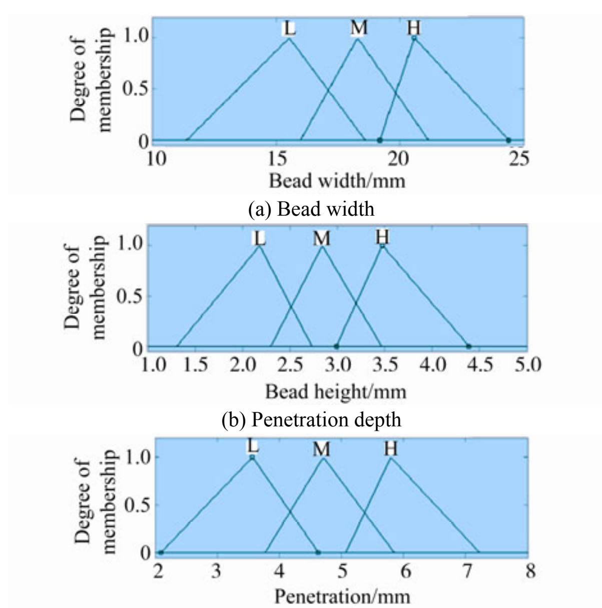
(a) Current

(b) Voltage

(c) Welding speed

Fig. 4 Membership functions of input process parameters

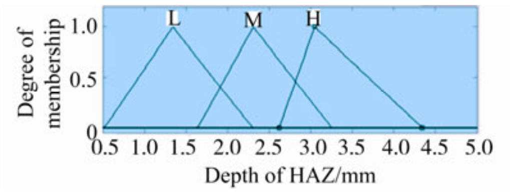
This base is comprised of groups of rules, each of which contains 27 rules. Base rules (162) are derived from heuristic knowledge of the behaviour and theoretical criteria. The fuzzy input and output are linguistically divided into three levels of membership: low (L), medium (M), and high (H). Various degrees of membership of the fuzzy sets calculated based on the values of x, y, and z of SAW weldment are shown in Figs. 4 and 5.



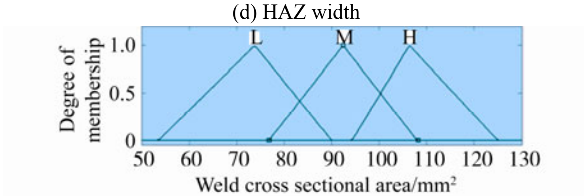
(a) Bead width

(b) Penetration depth

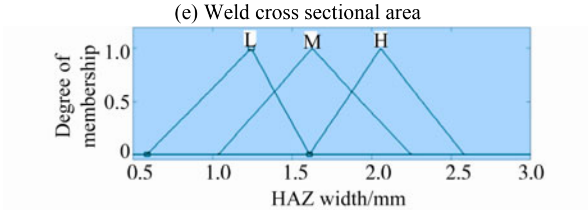
(c) Depth of HAZ



(d) HAZ width



(e) Weld cross sectional area



(f) HAZ width

Fig. 5 Membership function of output process parameters

5 Fuzzy logic simulation results

In this paper, a fuzzy model was developed for 27 SAW butt bead-on-plate experiments. The experiments were performed using the three values of process parameters: current, voltage, and welding speed (as shown in Table 4), and the simulation purpose is to predict the output for test case experiments with minimum error. A MATLAB SIMULINK model, shown in Fig. 6, was developed to predict the nonlinear output of SAW weldment characteristics. To verify the fuzzy logic model, test case experiments were conducted. The process parameters used in the test case experiments were not used in the fuzzy logic model building process. The percentage of errors for test cases from the fuzzy logic model for the input (current (I), voltage (V), traverse speed (S)) and output (bead width (BW), penetration depth (P), bead height (H), HAZ depth (DH), HAZ width (HW)) are presented in Table 6. The maximum percentage of error for prediction (for depth of penetration) is found to be 14.73.

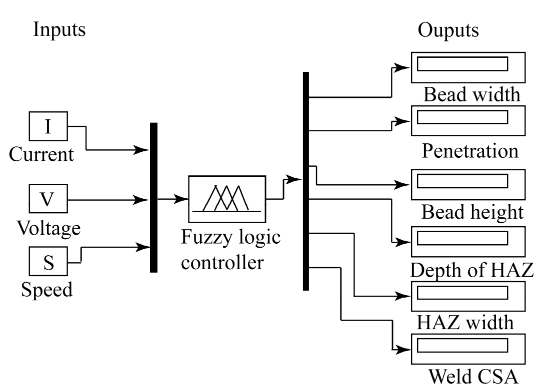


Fig. 6 Simulation block of fuzzy logic model

The experimentally observed and fuzzy logic model-predicted weldment shape profiles have been compared graphically and presented for test cases No. 3, 7, and 9, shown in Table 6 by Figs. 7, 8, and 9, respectively. It can be observed that there is a good agreement between the experimental and predicted values of shape profile characteristics.

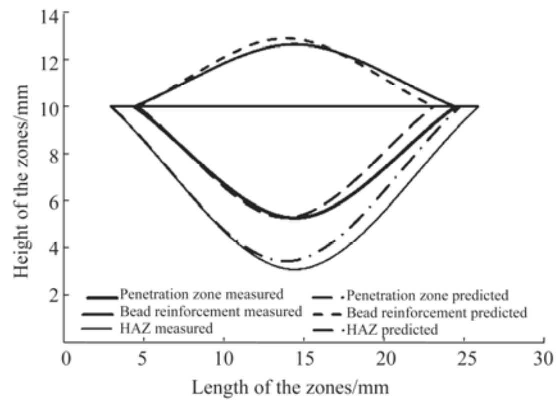


Fig. 7 SAW weldment shape profile of test case No.3 (Table 6)

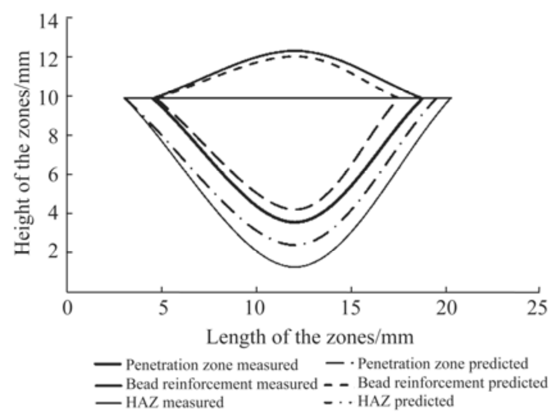


Fig. 8 SAW weldment shape profile of test case No.7 (Table 6)

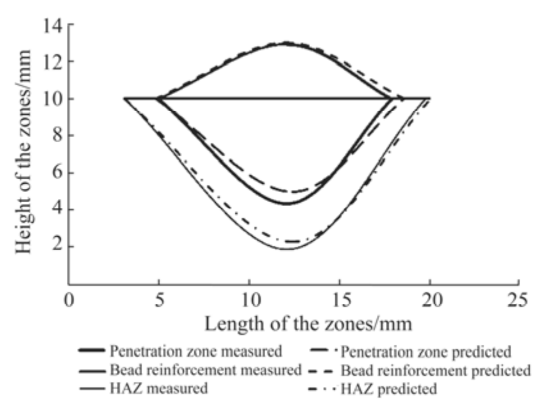


Fig. 9 SAW weldment shape profile of test case No.9 (Table 6)

6 Conclusions

A nonlinear fuzzy logic model of an SAW weld was developed. The following conclusions can be made from the fuzzy logic modelling of SAW weldment shape profiles.

- The SAW deposits' width can be divided into a number of equal segments; they correspond to the weld deposit heights, penetration depths, and depths of HAZ, and can be used for the effective graphical representation of the weldment shape profile.
- The fuzzy model prediction is within an accuracy limit of 15% for the test case experiments.
- The mapping technique developed in the present work can be utilized for online monitoring of SAW weldment shape profiles.
- An estimation of the SAW fusion zone and HAZ can also be made by the fuzzy model developed in the present work.

Table 6 Percentage of error for test cases from fuzzy logic model

SN	I	V	S	Pred. BW	Exp. BW	Er of BW /%	Pred. P	Exp. P	Er of P/%	Pred. H	Exp. H	Er of H/%	Pred. DH	Exp. DH	Er of DH /%	Pred. HW	Exp. HW	Er of HW /%
1	430	31	5.56	18.46	17.45	−5.80	4.16	3.67	−13.45	3.40	2.98	−14.06	2.25	2.61	−10.35	1.13	1.32	−14.16
2	470	28	7.50	15.33	15.88	3.48	3.36	4.84	11.72	2.51	2.93	14.30	1.90	2.23	13.80	1.50	1.66	−9.60
3	550	34	8.33	15.18	17.50	13.23	5.80	4.40	−14.40	2.13	2.15	0.89	1.33	1.54	9.87	1.64	1.44	8.47
4	500	34	6.94	18.33	20.38	10.05	4.68	5.52	14.73	2.90	2.69	−7.74	2.23	2.60	13.34	1.63	1.66	−1.71
5	500	35	8.06	15.31	17.84	14.17	4.68	4.10	−13.92	2.89	2.55	−13.31	1.31	1.50	14.53	1.13	1.27	−11.25
6	520	29	7.22	15.39	17.24	10.72	4.67	6.35	14.44	2.16	2.43	11.41	2.25	2.49	12.77	1.52	1.41	7.31
7	490	36	7.22	18.43	19.94	7.57	4.67	4.69	0.53	2.88	2.64	−8.98	2.25	2.59	14.62	1.64	1.51	13.45
8	575	36	9.72	17.5	18.23	4.00	5.00	5.18	3.49	3.00	2.69	−11.57	2.75	2.47	−11.41	1.64	1.57	4.36
9	600	30	8.33	17.5	15.98	−9.51	5.00	5.67	11.81	3.00	2.93	−2.27	2.75	1.27	−116.6	1.64	1.74	−5.61

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