Neuro-Fuzzy System for Predicting Optimal Weld Parameters of Horizontal Fillet Welds

H. S. Moon and S. J. Na

Abstract

To get the appropriate welding process variables, mathematical modeling in conjunction with many experiments is necessary to predict the magnitude of weld bead shape. Even though the experimental results are reliable, it has a difficulty in accurately predicting welding process variables for the desired weld bead shape because of nonlinear and complex characteristics of welding processes. The welding condition determined for the desired weld bead shape may cause the weld defect if the welding current/voltage/speed combination is improperly selected. In this study, the 2^{n-1} fractional factorial design method and correlation parameter were used to investigate the effect of the welding process variables on the fillet joint shape, and the multiple non-linear regression analysis was used for modeling the gas metal arc welding(GMAW) parameters of the fillet joint. Finally, a fuzzy rule-based method and a neural network method were proposed so that the complexity and non-linearity of arc welding phenomena could be effectively overcome. The performance of the proposed neuro-fuzzy system was evaluated through various experiments. The experimental results showed that the proposed neuro-fuzzy system could effectively check the welding conditions as to whether or not weld defects would occur, and also adjust the welding conditions to avoid these weld defects.

Key Words: 2^{n-1} fractional factorial design method, Weld quality, Sound bead shape, Weld defects, Neural network, Fuzzy rule

1. Introduction

Welding is an operation in which two or more parts are united by means of heat or pressure or both in such a way that there is a continuity in the nature of the metal between these parts. Especially for the GMAW process, heat and mass inputs are coupled, while the heat is transferred from the welding arc to the molten weld pool and the molten metal from the wire to the molten pool. Because of the melting and metal transfer phenomena, GMAW processes are non-linear and complex to analyze.

Welding process variables(WPV) such as the welding current, arc voltage, welding speed, gas flow rate and offset distance are highly coupled, and thus it is essentially difficult to derive a mathematical relationship between them. The approach to the mathematical modeling is to deepen the understanding of the basic phenomena involved in the process. Therefore, many attempts were implemented to model the weld bead geometry, but generally restricted to the computational approaches[1,2)] or controls[3,4)] for a single input and output parameter. Thus there are many drawbacks to estimating the WPV for various weld bead shapes at the same time.

In general, the fillet welded joint shapes are classified into four parts; leg length, penetration, throat thickness and reinforcement height as shown in Fig. 1, and the weld defects in horizontal fillet welding are classified into six parts; undercut, overlap, insufficient throat, insufficient leg, excess concavity and excess convexity as shown in Fig. 2. The welding conditions to obtain the desired fillet welded joint shape are highly coupled, thus a series of preliminary experiments are required to achieve the desired fillet welded joint shape. Therefore, it is difficult to determine the unique relationship between the weld bead geometry and the combination of various welding conditions. However, even if once the combination of welding conditions is appropriately selected, it may still cause weld defects due to the lack of information on the condition for the weld defect origination. Although many works pertaining to the selection of welding conditions have been carried out, there is scarcely any information found on means to avoid weld defects when determining the appropriate welding parameters. Thus, a new approach is required to achieve the appropriate welding conditions and at the

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same time to avoid the weld defects by choosing an adequate combination of welding conditions.

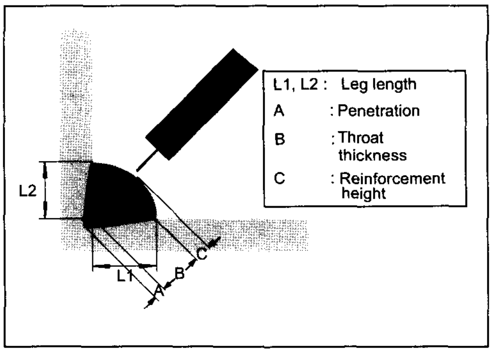


Fig.1 Definition of weld bead shape

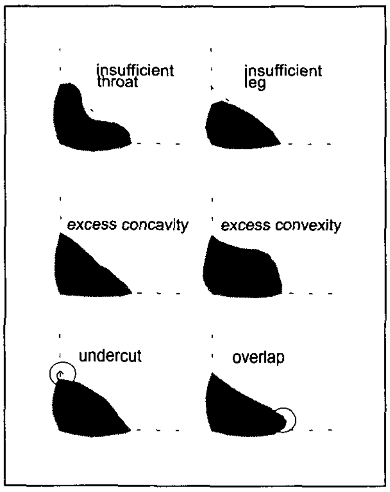


Fig.2 Definition of various weld defects in horizontal fillet welding

To overcome the previous difficulties, the neural network method and the fuzzy rule-based method on the basis of the 2^{n-1} fractional factorial design method were used in this study. The neural network method based on the back propagation algorithm was used to predict the appropriate welding conditions for the desired weld bead geometry. The fuzzy rule-based method was used to choose the appropriate welding conditions which could avoid weld defects in horizontal fillet welding. The fuzzy rule-based method was divided into two parts. The first part was to check the welding conditions for the weld defects, while the second part to adjust the welding conditions to avoid weld defects, keeping the pre-specified weld bead geometry resulting from the neural network. Finally, to evaluate the proposed algorithm, experiments were performed under various welding conditions by using the experimental apparatus as shown in Fig. 3.

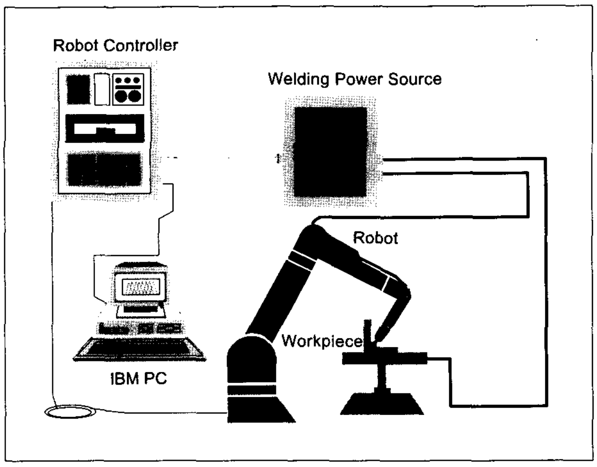


Fig.3 Schematic diagram of experimental apparatus

2. Analysis of variable effects

Generally, fillet welded joint shapes are classified into four parts such as the leg length, penetration, throat thickness and reinforcement height. To achieve a satisfactory fillet welded joint geometry, it is necessary to study the relationship between the weld bead shape and welding conditions, which can be represented by a mathematical model based on the experimental results. In this study, the WPV included the welding current, arc voltage, welding speed, gas flow rate and offset distance for horizontal fillet welding. All other parameters except these parameters under consideration were kept constant.

Before the experiments for the fillet welded joint shape were conducted, the effect of five variables on the leg length, penetration, throat thickness and reinforcement height were determined by the 2^{n-1} fractional factorial design, where n means the number of the WPV. In this case, n is 5, and 2^{n-1} can be represented by 2^{5-1}. The 2^{5-1} fractional factorial design has the unique efficient property that five main effects and 10 two-factor interaction effects can be determined with only 16 trails $(2^{5-1}=2^4=16)$[5)] by neglecting the higher level interaction effects. The individual effect of a variable is the independent effect on the fillet welded joint shape. An interaction effect is the dependent effect that two or more variables together have on the fillet joint shape. To evaluate the individual and interaction effects, the welding conditions for the electrode, shielding gas and base metal were set as shown in Table 1, and a higher and lower level of each variable were chosen as shown in Table 2. The difference between the high level and low level of a variable was defined as the range of the variable. The ranges for the welding speed and welding current were limited due to the possibility that the values below or above the values listed in Table 2 would cause weld defects such as the undercut and overlap. Table 3 shows the values of the individual effects and the two-factor interact ional effects for each experimental result obtained from the 2^{5-1} fractional factorial design. According to the data in Table 4, E1, E2, E3 show larger values than the other effects in the leg length1, length2, penetration and throat thickness, where E1, E2 and E3 mean the effectiveness of X1(welding speed), X2(arc voltage) and X3(welding current) on the weld surface profile respectively. The larger the absolute value of these effect(E), the more dominant the effect on the weld surface profile.

Table 1 Electrode, shielding gas and base metal

Experimental condition	Description
electrode	Solid wire AWS ER70S-6(1.2mm)
shielding gas	AR(80%)+CO_2(20%)
base metal	Mild steel

Table 2 Experimental variable levels and result variables

	Thickness	7mm	
	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(l/min)	14	18
X5	Offset distance(mm)	0	2
	Experimental results		
H1	Leg length 1(mm)		
H2	Leg length 2(mm)		
H3	Penetration(mm)		
H4	Throat thickness(mm)		
H5	Reinforcement height(mm)		

Table 3 Variable effects for trial 1-16

	Parameters for fillet weld surface profile				
	LEG LENGTH1 (RANK)	LEG LENGTH2 (RANK)	PENETRATION (RANK)	THROAT THICKNESS (RANK)	REINFOEC EMENT HEIGHT (RANK)
E1	-27.1(1)	-24.5(1)	1.3(4)	-11.1(1)	-0.9(10)
E2	9.3(3)	7.3(3)	-2.5(2)	3.9(3)	-2.3(2)
E3	10.5(2)	10.5(2)	6.3(1)	5.1(2)	2.1(6)
E4	-2.9(7)	-4.1(6)	-0.1(15)	0.1(15)	1.9(7)
E5	-6.5(4)	0.1(14)	0.5(12)	-2.5(5)	2.3(2)
E12	-1.1(14)	-0.1(14)	-0.7(10)	0.9(8)	-0.3(14)
E13	-1.9(9)	-0.9(9)	-0.7(10)	0.9(8)	-2.3(2)
E14	-2.5(8)	0.5(10)	-1.1(8)	0.3(14)	-1.3(9)
E15	-4.9(5)	-0.5(10)	1.5(6)	-3.1(4)	-0.1(15)
E23	1.7(10)	0.1(12)	1.5(6)	0.7(11)	-2.5(1)
E24	-1.7(10)	-2.1(7)	-0.9(9)	-2.3(6)	0.5(12)
E25	-4.9(5)	0.1(12)	1.7(5)	-0.5(13)	-2.3(2)
E34	0.7(15)	-1.3(8)	-0.5(13)	-0.7(12)	-0.7(11)
E35	-1.3(12)	-4.7(5)	-0.3(14)	-0.9(8)	0.5(12)
E45	1.3(12)	5.5(4)	-1.5(3)	1.7(7)	1.9(7)

To verify this result, a correlation parameter was adopted. The correlation parameter R, which stood for the correlation between the variable x and y, was represented by the following equation.

$$R = \frac{\text{covariance of x and y}}{\text{square root of product of variance x and y}}$$

$$= \frac{\text{covariance }(x,y)}{(\text{variance x, variance y})^{1/2}} \qquad (1)$$

$$= \frac{n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{[(n\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2)(n\sum_{i=1}^{n} y_i^2 - (\sum_{i=1}^{n} y_i)^2)]^{1/2}}$$

where,

$$\text{variance x} = \sigma_x^2 = \sum_i^n (x_i - \bar{x})^2/(n-1)$$

$$\text{variance y} = \sigma_y^2 = \sum_i^n (y_i - \bar{y})^2/(n-1)$$

$$\text{simple mean } \bar{x} = \sum_i^n x_i/n$$

$$\text{simple mean } \bar{y} = \sum_i^n y_i/n$$

$$\text{covariance}(x,y) = (\frac{1}{n-1})\sum_i^n (x_i - \bar{x})(y_i - \bar{y})$$

The parameter x used in equation (1) means the value of welding variables which is corresponding to (-1) or (+1) in Table 2. The correlation parameters from the equation (1) are listed in Table 4. From Table 3, the tendency of the welding conditions effect on the weld bead shape was found to be inn a good accordance with the data in Table 4.

Table 4 Correlation parameters for each fillet weld surface profile

	Correlation Parameter, R				
	WELDING SPEED	ARC VOLTAGE	WELDING CURRENT	GAS FLOW RATE	OFFSET DISTANCE
LEG LENGTH 1	-0.83	0.29	0.32	-0.09	-0.20
LEG LENGTH 2	-0.85	0.25	0.36	-0.14	0.00
PENETRATION	0.17	-0.32	0.81	-0.01	0.06
THROAT THICKNESS	-0.80	0.28	0.37	0.00	-0.18
REINFORCEMENT HEIGHT	-0.14	-0.35	0.33	0.29	0.35

3. Selection of welding conditions

3.1 Neural network method

The non-linear behavior of the welding arc and the lack of detailed understanding for the metal transfer process have been major impediments in the effort to produce a reliable mathematical model of the welding process. To overcome these difficulties, the neural network was proposed.

The neural network has its ability to transform the non-linear mathematical modeling into a simplified black box structure. One of the most successful approaches that have yielded good results in developing the networks is known as the back propagation method. In this method, the training process is to minimize the error between all of the desired values in the training set and an arbitrary value from the output layer. The error can be expressed by a cost function as follow[6].

$$J=(1/2)\sum_{p}\sum_{k}(d_k-a_k)^2 \qquad (2)$$

Fig. 4 is a representation of the weights and the mechanism for the neural network to achieve the appropriate welding conditions for the desired fillet welded joint shape. The input variables can be selected arbitrarily by the user after training the neural network. In horizontal fillet MIG welding, a bead of almost equal leg length can be obtained by using a torch angle 45° and root positioning, and the leg length ratio(L1/L2) in the sound bead formation is 0.94 - 1.03[7].

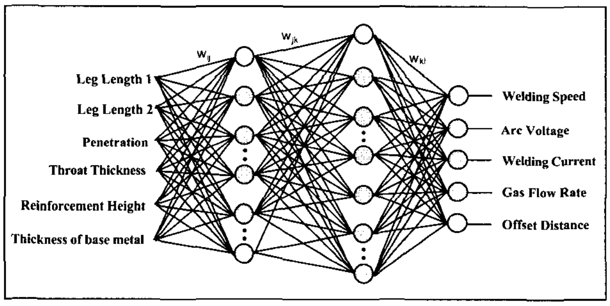


Fig.4 Schematic diagram of neural network for estimating welding conditions for desired weld bead shape

The comparison between the experimental and estimated data from this neural network structure was performed, and the error percentages between the experimental and estimated data are shown in Fig. 5. The experiments were performed twelve times for estimating the performance of the neural network. The error percentages covered the range from +20% to -20%, which indicates that the neural network could successfully express the non-linear welding process.

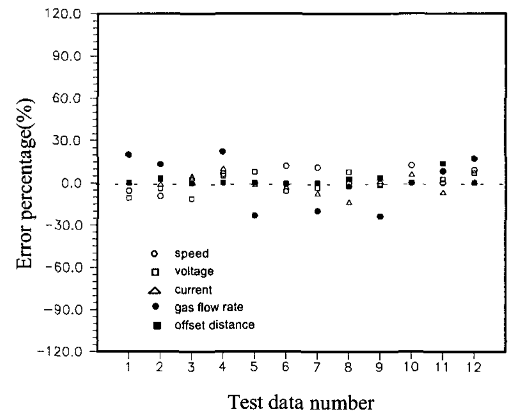


Fig.5 Result of error percentage between experimental data and data estimated by using neural network

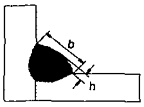
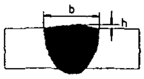
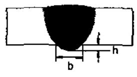
3.2 Preview of the weld defects

The welding processes contain many kinds of weld defects such as undercut, overlap, porosity, incomplete penetration, insufficient throat, insufficient leg, excess concavity and excess convexity. In the case of the undercut and overlap, these defects can be a source for cracks that can ultimately cause a part to fall. Adding too little weld metal reinforcement such as the excess concavity reduces the joint strength. Too much weld metal reinforcement such as the excess convexity not only wastes expensive filler metal but can actually reduce the strength of weld joint, rather than increase it. In the case of insufficient throat, the weld metal section is too small, and therefore the weld will not be strong enough. The insufficient leg would probably also produce the undercutting of the base metal, where a crack can start. Among these weld defects, the undercut, overlap, and excess convexity mainly appear in the horizontal fillet welding, which induce the poor mechanical properties in the welded area. Therefore, the prevention of weld defects is needed to increase the performance of the welding process and to implement the welding automation. To achieve a satisfactory weld bead geometry without the weld defects, it is necessary to study the effects of welding conditions affecting the weld bead geometry, and also necessary to study the tendencies of weld defects for the various welding conditions. However, the arc welding process has the complex and non-linear characteristics related with the arc and melting phenomena. Because of this reason, many experiments are required to get the appropriate welding conditions for each desired weld bead geometry.

In this study, the experiment was conducted based on the European Standard.. The Table 5 shows the European Standard[8].

Table 5 European Standard for guidance on quality levels for imperfections of arc-welded joints in steel

Group	Evaluation group
D	Low
C	Middle
B	High

Remark	D	C	B
	h<1mm+0.25b max. 5mm	h<1mm+0.15b max. 4mm	h<1mm+0.1b max. 3mm
	h<1mm+0.25b max. 10mm	h<1mm+0.15b max. 7mm	h<1mm+0.1b max. 5mm
	h<1mm+1.2b max. 5mm	h<1mm+0.6b max. 4mm	h<1mm+0.3b max. 3mm

The undercut occurs under the conditions when the welding current is too high, the welding speed is too low or high and the electrode-holder angle is improper. In case of the overlap, it appears at the condition of high currents or low welding speeds. The excess convexity may occur under the conditions when the welding current is too high in spite of moderate welding speed, or welding speed is too low in spite of low welding current. The experiments were carried out for various ranges of the base metal thickness, welding current, arc voltage and welding speed. Fig. 6 shows the results of the experiments carried out to show which parameters play a dominant role in the weld defects. These experimental results showed a good accordance with those of other literature[7,9,10].

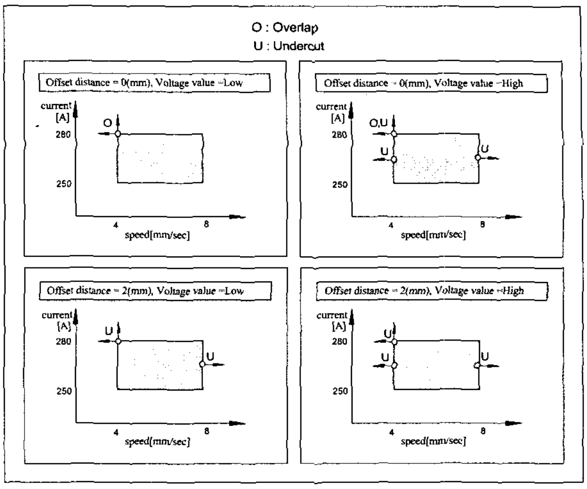


Fig.6 Feasible ranges of welding conditions to avoid weld defects

3.3 Fuzzy rule-based method (fuzzy 1) : checking the weld defects

The selection of the appropriate welding conditions in horizontal fillet welding and the process for checking the welding conditions as to whether the weld defects would occur or not are strictly different processes. But they are yet not regarded as the independent processes, because the weld defects are correlated with the welding conditions and their combination. The process in the selection of welding conditions for avoiding the weld defects is complicated by the difficulty and complexity of the non-linear relationships. Furthermore, when the welding conditions are likely to induce the weld defects, it is difficult to adjust the welding conditions to keep the pre-specified weld bead geometry.

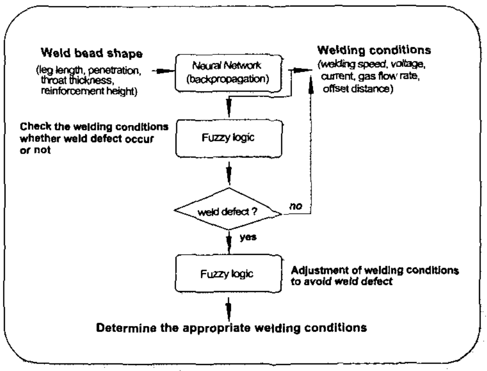


Fig.7 Schematic diagram for determining welding conditions to avoid weld defects

To overcome these difficulties, the neuro-fuzzy system was used as shown in Fig. 7. The neural network method was used to achieve the appropriate welding conditions for the desired weld bead geometry, and the fuzzy rule-based methods to check whether these welding conditions would cause weld defects. This method was also used to adjust the welding conditions for avoidance of weld defects, keeping the weld bead geometry derived from the neural network.

3.3.1 Definition of the fuzzy input/output variables

In the fuzzy system, the welding current, arc voltage, welding speed and offset distance were used as input variables. The combination of these variables were used to predict the weld defects such as undercut, overlap and excess convexity which were used as the output variables.

3.3.2 Fuzzification of the selected variables

In the following procedure, the crisp values of fuzzy variables are converted into the fuzzy values by putting a title above each fuzzy variable. For the fuzzification of fuzzy variables, the fuzzy subsets of the input and output variables were defined as follows :

S : Small, M : Medium, L : Large

Fig. 8 shows the fuzzification of each fuzzy variable, where the membership functions of all the variables used in the fuzzy system were of the triangular type .

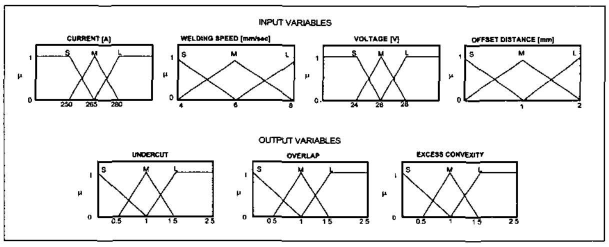


Fig.8 Fuzzy rule base for checking welding conditions as to whether weld defect would occur or not

3.3.3 Designing the rule base with the fuzzified variables

The fuzzy rules were constituted of the linguistic representations for the relationships between the input variables(welding current, arc voltage, welding speed, offset distance) and the output variables(undercut, overlap, excess convexity). The fuzzy rules had the following form.

Ri : **IF** welding current(*I*) is A1 and arc voltage(*V*) is A2 and welding speed(*S*) is A3 and offset distance(***OD***) is A4 **THEN** undercut(***U***), overlap(***O***) and excess convexity(***E***) are, $\underline{U}$, $\underline{O}$ and $\underline{E}$ respectively

where, Ri means the ith rule, and the welding current, arc voltage, welding speed and offset distance are the linguistic variables representing the process state variables. Undercut, overlap and excess convexity are the linguistic variables representing the control variable, and A1, A2, A3, A4, $\underline{U}$, $\underline{O}$ and $\underline{E}$ are the linguistic values of the linguistic variables representing the welding current, arc voltage, welding speed, offset distance, undercut ,overlap, and excess convexity respectively.

3.3.4 Inference with the rule base

To derive the results of inference, the maximum-minimum operation was used and consequently the value of each fuzzified output variable $\underline{U}$ and $\underline{O}$ could be represented as follows[11].

$$C=\max_{x1,x2,x3,x4}[R(I, V, S, OD, U, O, E) \wedge x(I) \wedge y(V) \wedge z(S) \wedge w(OD)] \tag{3}$$

where I means the welding current, V the arc voltage, S the welding speed, OD the offset distance, U the undercut, O the overlap and E the excess convexity, and x, y, z and w are inputs, and C is the result of inference.

3.3.5 Defuzzification of the fuzzified output variables

For the defuzzification of the undercut and overlap, the center of area method was used.

$$U=\frac{\sum_{i=1}^{3}\mu(\underline{U}i)\cdot\overline{Ui}}{\sum_{i=1}^{3}\mu(\underline{U}i)},\quad O=\frac{\sum_{i=1}^{3}\mu(\underline{O}i)\cdot\overline{Oi}}{\sum_{i=1}^{3}\mu(\underline{O}i)},\quad E=\frac{\sum_{i=1}^{3}\mu(\underline{E}i)\cdot\overline{Ei}}{\sum_{i=1}^{3}\mu(\underline{E}i)} \tag{4}$$

where $\overline{Ui}$, $\overline{Oi}$ and $\overline{Ei}$ are the centers of the fuzzy subsets $\underline{U}$, $\underline{O}$ and $\underline{E}$ respectively. The values of the U , O and E were used as a measure for the magnitude of the undercut , overlap and excess convexity respectively.

3.4 Fuzzy rule-based method (fuzzy 2) : adjusting the welding conditions

The fuzzy 1 system was to check the welding conditions for the weld defects. Although this method could determine if there would be weld defects, it was difficult to adjust the welding conditions to prevent the weld defects by keeping the weld bead geometry obtained from the neural network. Therefore, another fuzzy rule-based method(fuzzy 2) was used to achieve satisfactory results. A considerable amount of experiments and experiences for the arc welding process are required to achieve the appropriate welding conditions. In this paper, a mathematical model based on various experimental results(non-linear regression method) and the welding data from the literature were used to determine the delicate relationship between the welding conditions and weld bead geometry [7,8,9,12].

3.4.1 Definition of the fuzzy input/output variables

The input variables were the undercut, overlap, and excess convexity while the output variables were the welding current, arc voltage, welding speed and offset distance. Because the weld defects were correlated with the welding conditions, a precise selection of each welding condition was required.

3.4.2 Fuzzification of the selected variables

For the fuzzification of fuzzy variables, the fuzzy subsets for the output variables were defined as follows :

NL : Negative Large,
NM : Negative Medium,
NS : Negative Small,
Z : Zero,
PS : Positive Small,
PM : Positive Medium,
PL : Positive Large

Fig. 9 shows the fuzzification of each fuzzy variable. For the precise control, the ranges of the welding current, arc voltage, welding speed and offset distance were divided into several fuzzy subsets. In this case, the incremental and decremental change of each welding condition was used to represent the fuzzy subsets, because of the difficulty in controlling the welding conditions which occurred in using the absolute values instead of the change of the welding conditions as the fuzzy subsets. Therefore, the modified output variables were determined by the previous set value, plus the value determined by the fuzzy rule-based method.

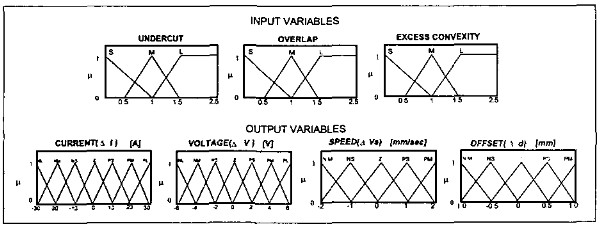


Fig.9 Fuzzy rule base for selecting appropriate welding conditions

The following procedures such as designing the rule base with the fuzzified variables, inference with the rule base and defuzzification of the fuzzified output variables were implemented similar to those of fuzzy 1.

4. Experimental results

Fig. 10, 12 and 14 show the typical weld defects usually occurring in horizontal fillet welding, while Fig. 11, 13 and 15 show the sound weld bead geometry modified from the previous results by using the fuzzy rule-based method. At first, the welding conditions for the desired weld bead geometry were determined by the neural network. However, these conditions would cause the undercut or overlap. Therefore, the fuzzy rule-based method was used for the purpose of avoiding these weld defects by modifying the given welding conditions.

Fig. 10 and 11 show that the undercut could be eliminated by using the proposed fuzzy rule-based method. In this case, the desired weld bead shape based on Table 1 was as follows.

Thickness of base metal = 7mm, Leg length 1 = 5.5mm, Leg length 2 = 5.5mm, Penetration = 1.5mm, Throat thickness = 3.6mm, Reinforcement height = 1mm.

The fuzzy 1 system was used to check whether the weld defects would occur or not, and the fuzzy 2 system to adjust the welding conditions to eliminate the possible weld defects. In this case, the welding speed was too high compared with other conditions, thus it was a dominant factor in causing the undercut. Therefore, the welding speed had to be modified by the fuzzy 2 system, and its result is shown in Fig. 11.

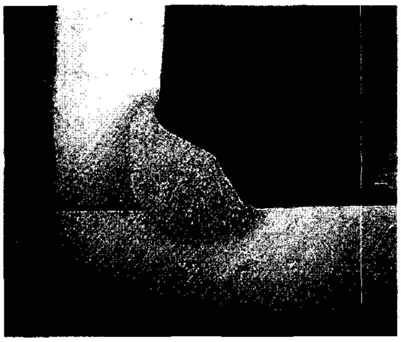


Fig.10 Weld bead with undercut obtained by welding conditions determined from neural network for desired bead shape(welding speed=7.6(mm/sec), arc voltage=25(V), welding current=240(A), gas flow rate=16(l/min), offset distance=0(mm))

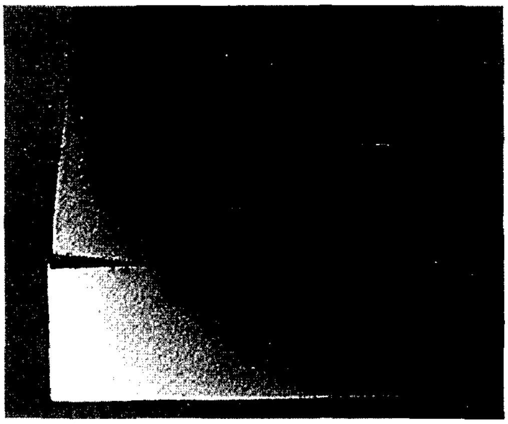


Fig.11 Sound weld obtained by modified welding conditions determined from fuzzy rule-based method(welding speed=5.6(mm/sec), arc voltage=27(V), welding current=235(A), gas flow rate=16(l/min), offset distance=0(mm))

Fig. 12 shows the overlap which was one of the weld defects which frequently occur in fillet welding. The desired weld bead shape was as follows.

Thickness of base metal = 7mm, Leg length 1 = 10mm, Leg length 2 = 10mm, Penetration = 2mm, Throat thickness = 5.5mm, Reinforcement height = 1.5mm.

In this case, the welding speed/voltage/current combination was likely to have induced the overlap, because the welding speed and arc voltage were too low, while the welding current was relatively high when compared with these values. To reduce the overlap, the welding speed, arc voltage and welding current were modified by the fuzzy 2 system, and the result is shown in Fig. 13.

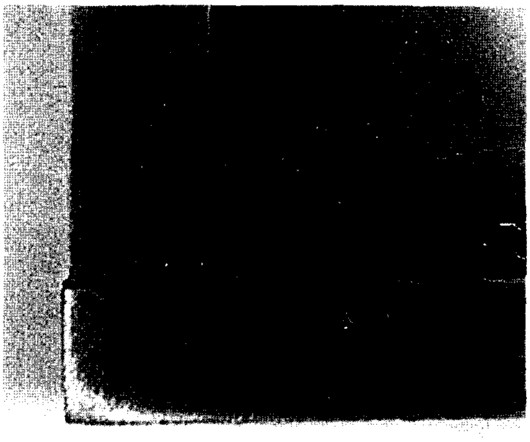


Fig.12 Weld bead with overlap obtained by welding conditions determined from neural network for desired weld bead shape(welding speed=4(mm/sec), arc voltage=29(V), welding current=280(A), gas flow rate=16(l/min), offset distance=0(mm))

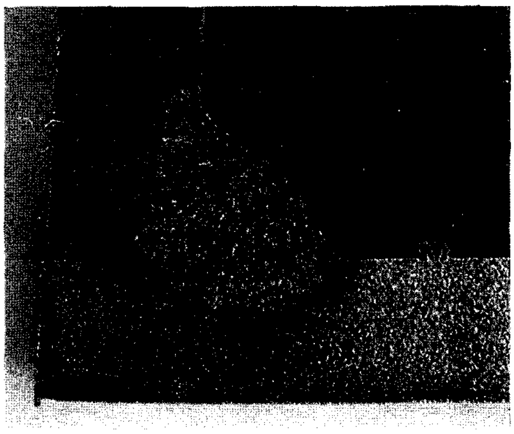


Fig.13 Sound weld bead by modified welding conditions determined from fuzzy rule-based method (welding speed=6(mm/sec), arc voltage=33(V), welding current=285(A), gas flow rate=16(l/min), offset distance=0(mm))

Fig. 14 shows the case of excess convexity. The excess convexity exerts a bad influence on the quality of the welded joints. The desired weld bead shape was as follows.

Thickness of base metal = 4mm, Leg length 1 = 5mm, Leg length 2 = 5mm, Penetration = 1.2mm, Throat thickness = 3.5mm, Reinforcement height = 1mm.

In this case, the welding speed and current combination was likely to have induced the excess convexity, because the welding speed was too low compared with the magnitude of the welding current. To eliminate the excess convexity, the welding speed and welding current were modified by the fuzzy 2 system, and the result is shown in Fig. 15.

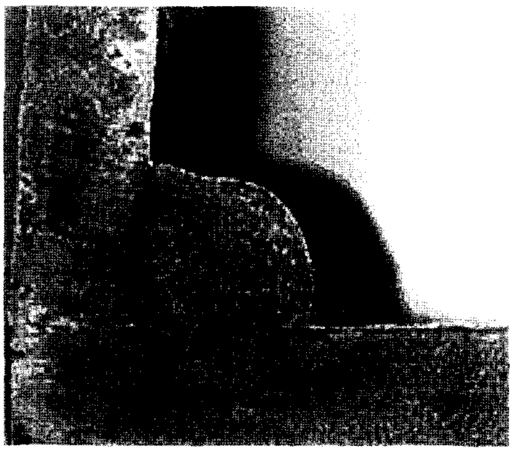


Fig.14 Weld bead with excess convexity obtained by welding conditions determined from neural network for desired bead shape(welding speed=4.2(mm/sec), arc voltage=21(V), welding current=200(A), gas flow rate=18(l/min), offset distance=0(mm))

Fig.15 Sound weld obtained by modified welding conditions determined from fuzzy rule-based method(welding speed=5.8(mm/sec), arc voltage=20(V), welding current=220(A),gas flow rate=18(l/min), offset distance=0(mm))

According to the previous results, the fuzzy rule-based method caused some errors in the dimension of the weld bead geometry, which were however negligibly small.

5. Conclusion

In this paper, the neural network method for selecting the appropriate welding conditions and the fuzzy rule-based method for examining the welding conditions for weld defects were investigated. Because of the non-linear characteristics and complexity of the arc phenomena, the fuzzy rule-based method utilized was based on the mathematical modeling derived from the experimental results.

The fuzzy rule-based method in conjunction with the neural network method could be used to effectively predict the welding conditions for the desired weld bead geometry and also to check whether weld defects would occur or not for the given welding conditions. Finally this system could adjust the welding conditions so as to prevent the weld defects such as undercut, overlap and excess convexity. To evaluate the performance of the proposed method, experiments were executed for three typical weld defects occurring in horizontal fillet welding. In conclusion, the proposed neuro-fuzzy method could be effectively used for the selection of the adequate welding conditions to produce the required bead geometry but not to induce the weld defects in horizontal fillet welding.

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