Study on the Simultaneous Control of the Seam Tracking and Leg Length in a Horizontal Fillet Welding Part 2: Seam Tracking

H. S. Moon and S. J. Na

Abstract

For the horizontal fillet welding with one plate in a vertical position, there will be a higher tendency of weld metal falling down rather than for the butt-welding in flat position. Such phenomenon could bring about the overlap or deflection of weld pool, and consequently induce the poor mechanical strength of weldments. Therefore, a precise position control of welding torch in conjunction with the weld quality plays an important role in welding robot applications. In the present study, an experimental method was proposed for deriving a mathematical model between the leg length and the welding conditions. Finally, an algorithm was proposed for weld seam tracking and improvement of the weld quality. The reliability of the proposed algorithm was evaluated through various experiments, which showed that the proposed algorithm can be very effective for tracking the weld line and simultaneously achieving the sound weld bead.

Key Words : Automatic seam tracking; Weld quality improvement ; Experimental model; Adaptive Resonance Theory(ART2)

1. Introduction

Generally, the arc welding process is substantially nonlinear, in addition to being a highly coupled multivariable system. Frequently, not all the variables affecting welding quality are known, nor easily quantified. All these complexities contribute to the difficulty of designing reliable welds and determining desirable welding conditions [1)].

In fillet welding, a stable weld quality is required for wide range of leg lengths. However, an unequal leg length caused by the overlap may induce the poor mechanical properties of weldments[2,3,4)]. Therefore, prevention of the overlap is urgently needed to increase the performance of welding processes and to successfully implement the welding automation in fillet welding.

The welding current is an essential parameter needed to monitor the GMAW process of horizontal fillet joints and to implement the automatic seam tracking[5,6,7,8)]. Therefore, the adequate signal-processing algorithm for welding current is indispensable to improve the performance of arc sensors. However, the arc sensor algorithms already developed usually focus only on the weld seam tracking capability without considering the weld quality.

In this paper, various experiments were carried out to investigate the tendency of weld defects in automatic fillet welding. The experimental method based on 2^n factorial design was proposed to derive the mathematical model between the leg length and the various welding conditions such as welding current, voltage etc. Finally, an algorithm for weld seam tracking was developed to track the weld line of horizontal fillet joints in conjunction with the improvement of weld qualities.

2. Mathematical model in between the leg length and welding parameters

The welding current influences on the deposition rate, and consequently on the weld bead shapes. With increase of welding current, there is a corresponding increase in current density and weight of wire fused per unit of time, and consequently the size of weld pool increases. In horizontal fillet welding, the weld pool shape is also affected by the gravitational force, which causes the weld pool formed in the fillet joint area to flow downward, Therefore the larger the welding current, the larger the

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force which acts on the weld pool area. In viewpoint of these phenomena, the magnitudes of two leg lengths in a fillet joint can be different. The difference in magnitudes of leg lengths causes the variation in strength of fillet joints. Therefore, the equal leg length is a crucial condition to achieve the sound weld. In this study, an experimental model was proposed to examine the relationship between the various welding parameters and the magnitude of leg length.

2.1 Second factorial experiment

The 2^n factorial design provides the smallest number of treatment combinations with which n factors can be studied in a complete factorial arrangement [9]. As there are only two levels for each factor, the results of the experiment are reliable when the response is approximately linear over the range of the factor levels chosen.

The 2^n factorial design method provides the individual effects and interaction effects. The individual effect of a variable is the independent effect, and an interaction effect is the dependent effect for two or more variables' effects. In this study, the results of the experiment were used to derive the mathematical model of the leg length for each weld parameter. The individual factors chosen are welding speed(V_w), welding current(I), offset distance(O_D) and weaving length(W_L), and the experimental results are leg length($L1$) for the vertical plate and leg length($L2$) for the horizontal plate in horizontal fillet welding. The corresponding graphical representation for each individual variable and the experimental results are shown in Fig. 1.

The relationship between the difference of leg lengths ($L=L2-L1$) and the welding parameters can be fitted in the following equation, if only the effect of individual factors and two factor combinations are considered.

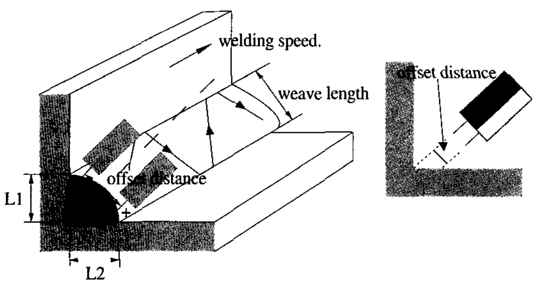


Fig. 1 Definition of individual factors and experimental results

$$L2-L1 = k_1 + k_2 \cdot V_w + k_3 \cdot I + k_4 \cdot O\_D + k_5 \cdot W\_L + k_6 \cdot V_w \cdot I + k_7 \cdot V_w \cdot O\_D + k_8 \cdot V_w \cdot W\_L + k_9 \cdot I \cdot O\_D + k_{10} \cdot I \cdot W\_L + k_{11} \cdot O\_D \cdot W\_L \quad (1)$$

Using the matrix form, equation (1) can be expressed in the following equation.

$$[L] = [A][K] \quad (2)$$

Then, using the least square method, the coefficients $[K]$ can be determined in the following equation.

$$[K] = \{[A]^T[A]\}^{-1}[A]^T[L] \quad (3)$$

After the calculation of equation (3), equation (1) can be expressed as follows.

$$L2-L1 = k_1 + k_2 \cdot V_w + k_3 \cdot I + k_5 \cdot W\_L + k_6 \cdot V_w \cdot I + k_8 \cdot V_w \cdot W\_L + k_{10} \cdot I \cdot W\_L + (k_4 + k_7 \cdot V_w + k_9 \cdot I + k_{11} \cdot W\_L)\, O\_D \quad (4)$$

Thus, ($L=L2-L1$) can be determined as in response to the offset distance for the welding conditions that are arbitrarily chosen within the level of respective factors.

2.2 Experimental results and discussion

The welding power source used here was the switching transistor type and the welding gun was mounted directly on a robot welding system equipped with a controller. The welding current and voltage were controlled by personal computer, while the welding speed, weaving length, weaving time and dwell time were set by the robot controller. Bead-on-plate welds were made in the flat position, with a vertical gun moving at a pre-specified constant speed on the stationary work-piece. The diameter of electrode wire and shielding gas used here were 1.2mm and 80%Ar+20%CO_2 , respectively. The schematic diagram of experimental apparatus is shown in Fig. 2.

In horizontal fillet welding, a bead with almost equal leg length on two plates could be obtained by using a torch angle of 45°[3]. In the case of improper welding conditions, however, the magnitude of $L2$ can be larger than that of $L1$, which can cause the weld defect such as overlap. To investigate the tendency of overlap according to various

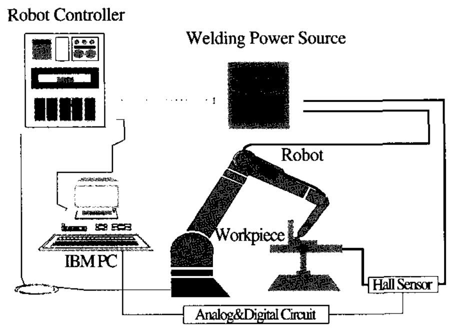


Fig. 2 Schematic diagram of experimental apparatus

welding conditions, 16(=2^4) experiments were performed. The individual magnitudes of experimental variables and the experimental results are shown in Table 1 and 2, respectively. Using the above results and procedure, the coefficients [*K*] in equation (3) can be determined. The relationship between the leg length and the offset distance can be expressed in the following equation for arbitrary welding speed, welding current and weaving length.

$$L2 - L1 = -0.2281 - 0.4344V_w - 0.0003I + 1.6404W\_L + 0.0016V_wI - 0.1063V_wW\_L - 0.0034IW\_L + (0.6312 - 0.0019I + 0.2875V_w - 0.0125W\_L)O\_D \quad (5)$$

The feasible range of welding conditions that can be applied to equation (5) is shown in Table 1. Although the welding current can be a main parameter of the magnitude of *L2* - *L1* in case of zero weave length and

Table 1 Standardized variables of experimental variables for mainly covering overlap

	Experimental variables (factor)	LEVEL	
		Low level(-)	High level(+)
80% Ar^+	Welding speed V_w *(A)*, [mm/sec]	3	5
20% CO_2	Welding current *I (B)*, [A]	310	350
ER70S 1.2mm dia.	Offset distance *O_ D (C)*, [mm]	-1.5	+1.5
	Weave length *W_ L (D)*, [mm]	3	5

• Fixed welding conditions : Arc voltage = 32[V], Weaving time = 0.4 [sec], Dwell time = 0.15 [sec]

zero offset distance, the difference between *L2* and *L1* is dominantly affected by the welding speed, weave length and offset distance when the weave length and offset distance parameters are added. The equation (5) can tell the difference between *L2* and *L2*. However, it is very difficult to describe an exact physical meaning of the equation, because this equation represents the relative difference between *L1* and *L2*. The equation (5) can be

Table 2 Welding conditions based on 2^n factorial experimental method and results of welding

Trial No.	Order	FACTOR A	B	C	D	WELDING CONDITION Welding speed [mm/sec]	Welding current [A]	Offset distance [mm]	Weave length [mm]	WELD BEAD SHAPE Leg length1 [mm]	Leg length2 [mm]
1	1	-	-	-	-	3	310	-1.5	3	10.6	9.7
2	2	+	-	-	-	5	310	-1.5	3	8.5	6.4
3	9	-	+	-	-	3	350	-1.5	3	12.2	11.6
4	10	+	+	-	-	5	350	-1.5	3	9.3	7.1
5	3	-	-	+	-	3	310	+1.5	3	10.1	12.3
6	4	+	-	+	-	5	310	+1.5	3	7.2	9.3
7	11	-	+	+	-	3	350	+1.5	3	11.2	12.4
8	12	+	+	+	-	5	350	+1.5	3	7.8	10.0
9	5	-	-	-	+	3	310	-1.5	5	12.1	11.9
10	6	+	-	-	+	5	310	-1.5	5	9.7	7.9
11	13	-	+	-	+	3	350	-1.5	5	12.8	12.2
12	14	+	+	-	+	5	350	-1.5	5	10.7	8.3
13	7	-	-	+	+	3	310	+1.5	5	10.5	12.8
14	8	+	-	+	+	5	310	+1.5	5	8.3	10.5
15	15	-	+	+	+	3	350	+1.5	5	11.5	13.4
16	16	+	+	+	+	5	350	+1.5	5	8.8	10.6

expressed in equation (6), equation (7) and equation (8) under the following welding conditions

Welding current : 310 [A], Offset distance : 0 [mm], Weave length : 3 [mm]

$$L2\text{-}L1 = 1.4381 - 0.2573V_w \quad (6)$$

Welding current : 310 [A], Offset distance : 1 [mm], Weave length : 3 [mm]

$$L2\text{-}L1 = 1.4428 + 0.0302V_w \quad (7)$$

Welding current : 310 [A], Offset distance : -1 [mm], Weave length : 3 [mm]

$$L2\text{-}L1 = 1.4334 - 0.5448V_w \quad (8)$$

Equation (6) shows that slower welding speed, larger *L2* - *L1* because of weld pool sag. However, the magnitudes of *L2* -*L1* are dramatically changed when the offset distance is involved. *L2* is greater than *L1* in case of 1mm offset distance regardless of welding speed. In case of -1mm offset distance and 3mm/sec welding speed, *L2* is almost equal to *L1* because of weld pool sag.

3. Seam tracking

With the introduction of automated welding into the industry, sensors for different purposes were developed to compensate for various kinds of tolerances such as inaccurate seam preparation, inaccurate work-piece positioning and thermal distortion. In general, sensors are employed for seam tracking, for finding the beginning and ending position of the weld seam, for determining the profile of the seam and bead height control. A lot of different physical principles have been used for these purposes.

Among the position sensing methods used for weld seam tracking, the arc sensor which utilizes the electrical signal obtained from the welding arc itself is one of the most prevalently used methods, because it has the advantage that no particular sensing device is necessary and real time sensing of a groove position is possible directly under the arc. The welding current signal in GMA welding is dominantly affected by the tip-to-work-piece distance for the given welding voltage and wire feed speed. Thus, armed with a means of measuring the welding current, an increase of contact-tip-to-work-piece distance results in a decrease of welding current and vice versa. In other words, the weld joint geometry can be obtained by weaving the arc back and forth across the line of travel. However, the signal processing method for the weld seam tracking cannot guarantee the weld quality in fillet joints, because it can sometimes cause the overlap in case of high welding current or low welding speed. Therefore, a seam-tracking algorithm that simultaneously recognizes the overlap just by measuring the welding current signal is urgently needed for a successful automation in horizontal fillet welding.

3.1 Recognition of overlap by using welding current signal

The welding current signals measured during every weaving motion depend on the welding torch position and the volume of deposited metal. The algorithms that have been published for seam tracking were generally based only on the correction of torch position according to the variation of groove position. It means that the existing control algorithms of the seam tracking merely focus on the detection of weld centerline without considering the weld quality.

The high deposited weld metal may not influence the reliability of the arc sensor, however, it can influence the weld quality by causing the overlap. For such several reasons mentioned above, the signal processing algorithm for the recognizing of whether the deposited weld metal forms overlap or not is urgently needed therein. For this purpose, in this paper, Adaptive Resonance Theory(ART2) was proposed and examined in previous work (Part 1).

3.2 Seam tracking in horizontal fillet welding

3.2.1 Algorithm for seam tracking

In the real situation, the welding current shows a signal with fluctuations due to the various factors such as metal transfer and arc characteristics. For acquiring the information of the torch position from the welding current, other researchers[10,11] usually used a moving-averaged welding current signal, which is a kind of low pass filtering method. Because this moving-averaging method has the advantage of easy determination for the cutoff frequency by changing the weighting factor, it can be effectively used together with a hardware low pass filter that has a variable cutoff frequency. But the fluctuation in the averaged and filtered signal still remains some time lag arises, which may exert a bad influence on predicting the torch position.

To determine the actual welding current value at the end of weaving, the welding current signals were fitted to a curve for extracting the useful information of the torch position. A quadratic curve fitting was performed by using the least square method [12,13].

If the welding currents at every end point of weaving are obtained by using the signal processing method, the difference of these two current values can be used to determine the deviation of actual torch position from the weld center line[12,13].

Finally, the transverse correction data are calculated and transferred to the robot controller for adjusting the torch position to move along the weld line. If the overlap occurs during weaving, the trace of weaving should be modified to a direction that can prevent the overlap as well as the resultant unequal leg length.

Supposing the magnitude of *[L2 - L1]* from equation (5) is at zero, the offset distance for an additional correction data can be represented by the following equation from equation (5)

$$O\_D = \{-0.2281 - 0.4344V_w - 0.0003I + 1.6404W\_L + 0.0016V_wI - 0.1063V_wW\_L - 0.0034IW\_L\} / (-0.6312 + 0.0019I - 0.2875V_w + 0.0125W\_L) \quad (9)$$

Preliminary results of the 2^n factorial design were used to modify the trace of weaving for achieving the similar leg length when the overlap occurs. ART2 was used to recognize whether or not the overlap occurs during weaving.

The flow chart for seam tracking and simultaneous compensation of overlap in horizontal fillet welding is shown in Fig. 3. The welding current signal is measured for every weaving and then fitted to a curve. After calculation of the current at the end of weaving, the difference in current values of the previous and present weaving is calculated, and finally the correction data for the next weaving is determined. The occurrence of overlap is checked by ART2 for every weaving. If there exists an overlap, an additional correction data is determined using the mathematical model based on the 2^n factorial design to obtain the equal leg length equal and to avoid the overlap.

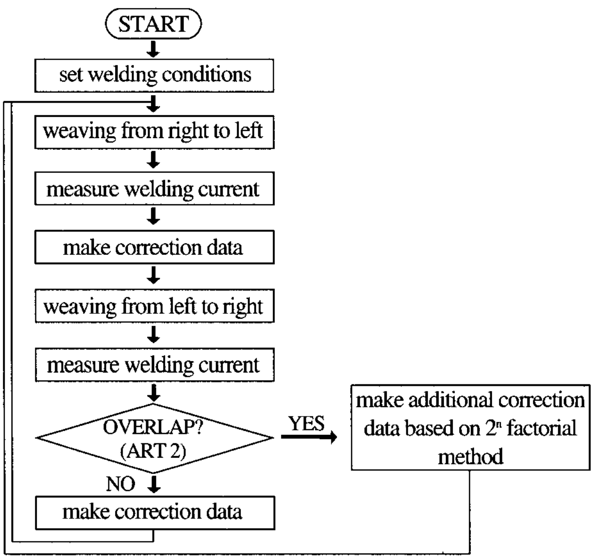


Fig. 3 Flow chart for seam tracking by considering overlap

3.2.2 Experimental results and discussion

The welding experiments were carried out with five different welding conditions in Table 3 to consider the effect of deviation angle on the overlap. Figure 4 shows some definitions in seam tracking of horizontal fillet joints.

The Figure 5 and 6 shows the traces of torch motion and the photographs of resultant weld bead for case (1) and

Table 3 Experimental welding conditions for seam tracking

	welding speed [mm/sec]	welding current [A]	welding length [mm]	
case(1)	4	320	3	seam tracking w/o ART2 (deviation angle=0°)
case(2)	4	320	3	seam tracking w/ ART2 (deviation angle =0°)
case(3)	3	315	3	no seam tracking (deviation angle =5°)
case(4)	3	315	3	seam tracking w/o ART2 (deviation angle=5°)
case(5)	3	315	3	seam tracking w/ ART2 (deviation angle=5°)

Fixed welding conditions
- Arc voltage = 32[V]
- Weaving time = 0.4 [sec]
- Dwell time = 0.15 [sec]

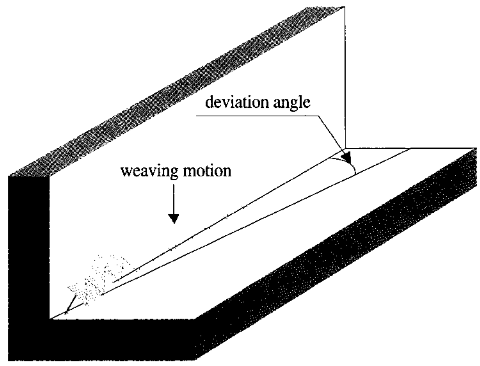
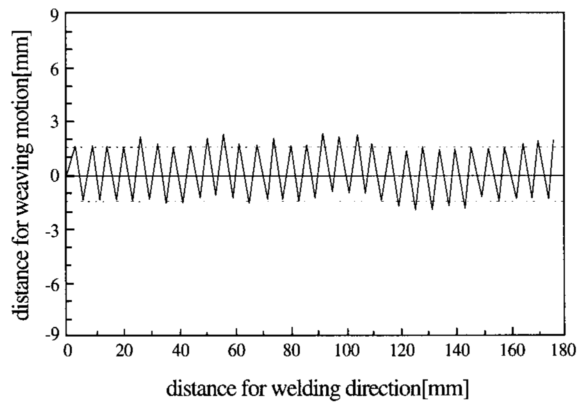
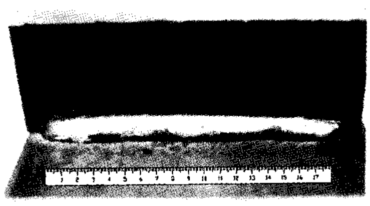


Fig. 4 Definitions in seam tracking for horizontal fillet joints

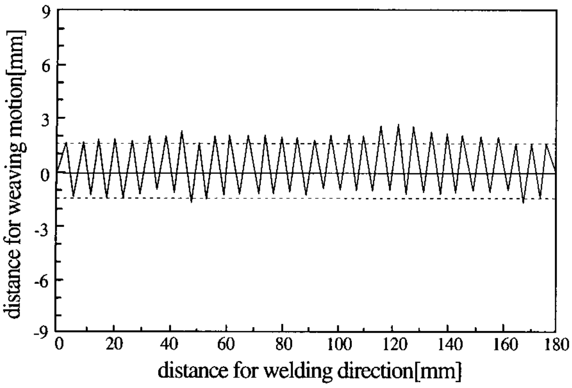


(a) Trace of torch motion

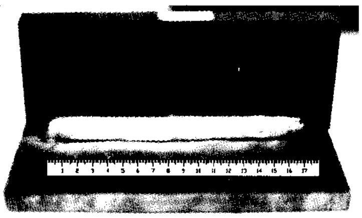


(b) Resultant weld bead

Fig. 5 Seam tracking without considering overlap, case(1) of Table 3

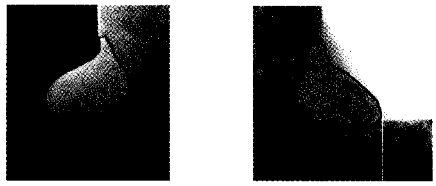


(a) Trace of torch motion



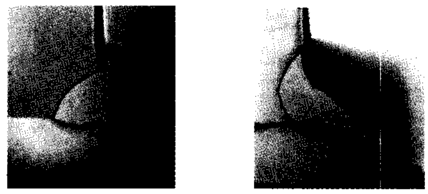
(b) Resultant weld bead

Fig. 6 Seam tracking by considering overlap, case(2) of Table 3



(a) (b)

Fig. 7 Cross-sectional area of weldment for case(1) of Table 3
(a) 4mm away from welding start
(b) 8mm away from welding start



(a) (b)

Fig. 8 Cross-sectional area of weldment for case(2) of Table 3
(a) 4mm away from welding start
(b) 8mm away from welding start

case (2) shown in Table 3 respectively. The leg lengths of the resultant weld bead on the horizontal and vertical plate revealed somewhat discrepancy for case(1), mainly due to the effect of gravity. For case(2), a correction data was determined through the ART2 and the 2^n factorial design to modify the torch position, and the resultant weld bead showed almost equal leg lengths. The leg lengths measured at the various positions away from the initial welding position are as listed in following; 4mm: *L1* = 9.5, *L2* = 11.1 for case (1) and *L1* = 10.1, *L2* = 9.8 for case(2), 8mm: *L1* = 9.6, *L2* = 11.1 for case (1) and *L1* = 9.9, *L2* = 10.1 for case (2), and 12mm: *L1* = 9.4, *L2* = 11.2 for case (1) and *L1* = 10.2, *L2* = 10.3 for case (2).

The cross-sectional shapes of weldments for case(1) and case(2) are shown in Fig. 7 and 8. The experimental results show that overlap was obviously formed for case(1), while the weld bead shape for case(2) showed a little tendency of the overlap but somewhat deflection of the weld pool, especially at the position 8mm away from the welding start.

Figure 9 shows the photograph of resultant weld bead of case(3), for which no seam tracking was applied. Figures 10 and 11 show the traces of torch motion and the photographs of resultant weld bead for case(4) and case(5) respectively. The traces of torch motion show a excellent tracking capability in these two cases, for which the deviation angle of 5° was applied. As in experiments without the deviation angle (case(1) and case(2)), the weld bead of case(5), for which overlap was considered during seam tracking, showed a better symmetry than the case without the overlap consideration. The leg lengths measured at various positions away from the initial welding position are : 4mm ; *L1* = 10.1, *L2* = 11.5 for case (4) and *L1* = 10.2, *L2* = 10.5 for case (5), 8mm ; *L1* = 10.2, *L2* = 11.4 for case (4) and *L1* =10.4, *L2* = 10.3 for case (5), 12mm ; *L1* = 10.2, *L2* = 11.4 for case (4) and *L1* = 10.6, *L2* = 10.7 for case (5).

The cross-sectional shape of weldments for case(4) and case(5) are shown in Fig. 12 and 13. The experimental results show that overlap was formed for the case(4), while the weld bead shape for case (5) showed a little tendency of overlap but somewhat deflection of the weld pool, especially at the position 8mm away from the welding start.

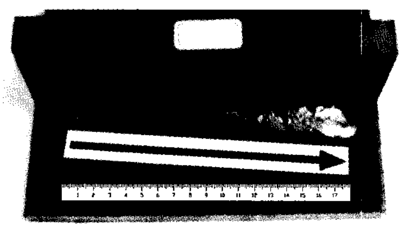
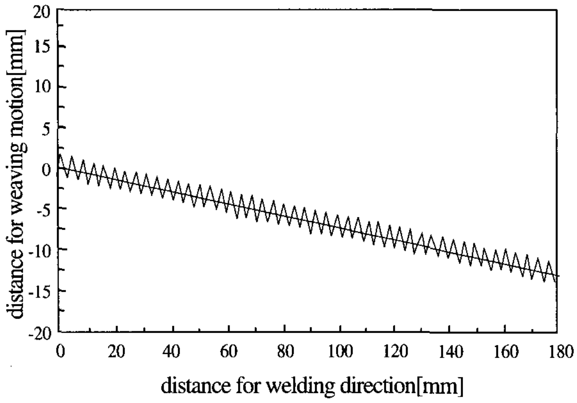
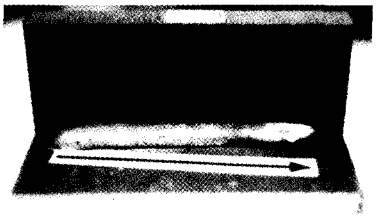


Fig. 9 Resultant weld bead of welding without using arc sensor, case(4) of Table 3

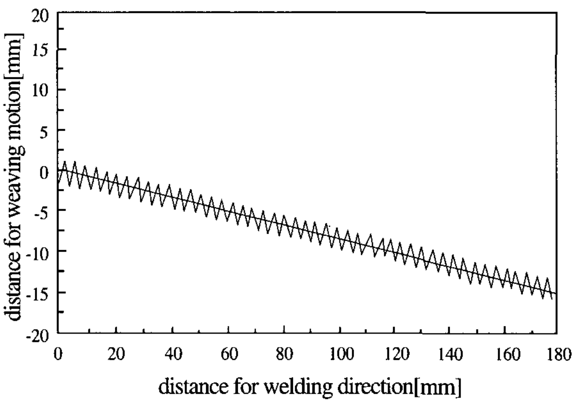


(a) Trace of torch motion

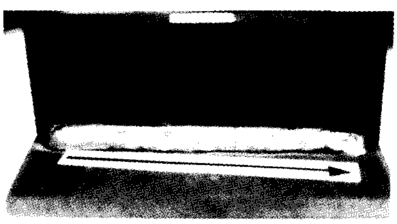


(b) Resultant weld bead

Fig. 10 Seam tracking without overlap consideration, case(4) of Table 3

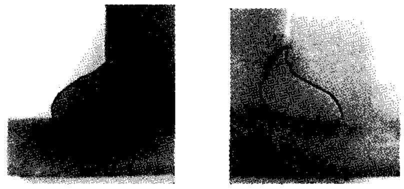


(a) Trace of torch motion



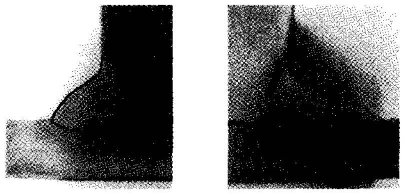
(b) Resultant weld bead

Fig. 11 Seam tracking with overlap consideration, case(5) of Table 3



(a) (b)

Fig. 12 Cross-sectional area of weldment for case(4) of Table 3
(a) 4mm away from welding start
(b) 8mm away from welding start



(a) (b)

Fig. 13 Cross-sectional area of weldment for case(5) of Table 3
(a) 4mm away from welding start
(b) 8mm away from welding start

4. Conclusion

In the horizontal fillet welding, overlap, or deflection of the weld pool caused by the arc and gravity force can bring about the unequal leg lengths, and consequently, decrease the weld quality henceforth. Therefore, the prevention of overlap and deflection of the weld pool is urgently needed in order to increase the performance of the welding processes and adequately implement the welding automation.

In the present paper, the tendency of weld defects in robotics welding was experimentally investigated. Based on the above results, a mathematical model by using the 2nd factorial design method was used to investigate the relationship between the offset distance and the magnitudes of leg length for other welding conditions fixed constant. The mathematical model was also used to determine the adequate offset distance for acquiring the equal leg lengths. Moreover, the ART2 was also used to classify the weld bead shapes with and without overlap by measuring the welding current signal during every weaving. Finally, based on the above results such as mathematical model and ART2 network, the automatic seam tracking was implemented to trace the weld line in conjunction with the simultaneous control of leg lengths. From the results of the seam tracking, it could be concluded that the proposed method can be effectively used for automatic seam tracking and leg length control in horizontal fillet welding.

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