Welding Penetration Control for Aluminum Pipe Welding Using Omnidirectional Vision-based Monitoring of Molten Pool*

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This paper presents a study on a new method of welding penetration control for aluminum pipe in Tungsten Inert Gas (TIG) welding using omnidirectional vision-based monitoring of molten pool. As circumferential butt-welded pipes and the application of aluminum alloy in pipe welding that has been use in various industrial sectors requires new technique of welding monitoring process. For pipe welding using constant arc current and welding speed, the bead width becomes wider as the circumferential welding of small diameter pipes progresses. In order to avoid the errors and to obtain the uniform weld bead over the entire circumference of the pipe, the welding conditions should be controlled. This research studies the intelligent welding process of aluminum alloy pipe 6063S-T5 in fixed position using the AC welding machine. The monitoring system used an omnidirectional camera to monitor backside image of molten pool. A new method of image processing algorithm was implemented to process the captured image and to recognize the edge of molten pool. Back bead width as the result of detection was delivered into fuzzy inference system to control welding speed. From the experimental results it shows the effectiveness of the control system that is confirmed by sound weld of experimental results.

Key Words: Welding Penetration Control, Aluminum Pipe, Omnidirectional Vision-based Molten Pool Detection, Fuzzy Inference System

1. Introduction

For many applications in automation of welding process, the need for higher weld quality and reduced manufacturing cost has become increasingly important. Advanced welding technology takes part to reduce manufacturing cost, however its use requires a means of sensing and monitoring of error in the process. As the application of pipe welding in power stations, offshore structures, and process industries, it is important to investigate the characteristic of the welding process.

There have been problems in automating arc welding processes such as sensing, monitoring and line tracking. Therefore, to achieve full automation of aluminum pipe welding, the welding penetration should be controlled. Since the early 1960's sensing and control systems have been successfully implemented in applications where the sensor could be placed on the backside of the weld and moved in synchronism with the welding torch¹⁾.

Intelligent control systems has been developed for modeling and controlling the welding process using neural network²⁻³⁾ and fuzzy techniques⁴⁻⁵⁾. Another difficulty to control of an arc welding process is how to detect weld pool geometrical features, such as weld bead width and penetration, either from the topside or backside, conveniently and in real-time. The experiment using the vision sensing to control the TIG weld width for stainless steel²⁾ and aluminum alloy^{3,5)} pipe has been conducted with the algorithm of image processing to detect molten pool's edge using

plain mirror that rotates along the welding torch during the pipe welding process.

This research studies the intelligent welding process of aluminum alloy pipe 6063S-T5 in fixed position using the AC welding machine. The proposed monitoring system used an omnidirectional vision-based monitoring of molten pool to capture wide view of backside image of molten pool circumferentially without rotated part of mirror. This camera consists of a perspective camera and a hyperboidal mirror allowing a central projection by reflected rays. The constant AC current of TIG welding process was used and the welding speed derived from the back bead width of molten pool image was controlled. Image processing algorithm was constructed to detect edge of molten pool. In this experiment, the fuzzy inference system was used to control welding penetration by modifying speed.

2. Experimental procedure

2.1 Experimental device

Figure 1 shows the pipe welding system developed in this study. The major functional elements of the experimental system are a circumferential welding manipulator, CCD camera and the image board (256×220pixels, 8bit), the personal computer (CPU: 1.2MHz), A/D board to measure arc current and voltage, TIG welding machine, and motor board to control stepping motors. Base metal used in this experiment was aluminum alloy pipe A6063S-T5. Pulsed TIG AC welding machine with square-wave current and pure argon shielding gas was used.

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Fig. 1 Schematic of pipe welding system

Fig. 2 Hyperboloidal mirror

Fig. 3 Detail of monitoring system

Fig. 4 Flowchart of image processing

In this paper, omnidirectional vision-based molten pool detection system consists of a CCD camera and a hyperboloidal mirror. A CCD camera captured the backside image of molten pool and sent the image to personal computer through the image digitizer. Time required for capturing a single frame was 1/60s. Figure 2 (a) and (b) present the top view of the hyperboloidal

mirror and its dimension, respectively. Detail of monitoring system is shown in Fig. 3.

Table 1 Material properties and welding conditions

Base metal	Al-6063S-T5
Diameter of pipe (mm)	37.8
Thickness of pipe (mm)	2.0
Density (g/cm ³)	2.69
Melting point (°C)	615-655
Thermal conductivity (W/m.K at 25°C)	209
Welding machine	AC
Electrode	2% Th-W (Ø 2.4 mm)
Nominal arc length (mm)	1.5
Welding current, I (A)	50 ~ 70
Pulse current frequency, f (Hz)	50 ~ 100
EN ratio	0.5
Welding speed, v (mm/s)	0.83 ~ 3.33
Shielding gas	100% Ar
Shielding gas, q (l/s)	0.13 ~ 0.25

2.2 Edge Detection of Molten Pool

Figure 4 presents the flowchart of image processing algorithm. Due to the low melting point of aluminum, brightness of molten pool is low; therefore the stable and robust image processing algorithm must be constructed. The detail of edge detection of molten pool will be discussed as follows.

(a) Histogram Analysis: First, the image of molten pool was analyzed to get the histogram information. Original image size was 256 x 192 pixels. Comparing with the stainless steel, the edge of molten pool in aluminum is very difficult to be detected. After the observation to find the exact position of molten pool and compared to the real back bead width, it is found that the edge of molten pool aligned between the edge detection range. This range defined as the range between inner and outer brightness as shown in Fig. 5 (a). In this study, the same method of⁴⁾ to find the edge was applied.

From the histogram analysis, the frequency of brightness value of the image was obtained. The average brightness, g_{avg} and accumulation of the percentage of average brightness, p_{avg} were obtained by the Eqs. (1) and (2), respectively.

$$g_{avg} = \frac{\sum_{i=0}^{i=255} (f(i) \times i)}{\sum_{i=0}^{i=255} i} \quad (1)$$

$$p_{avg} = \frac{\sum_{i=0}^{i=avg} f(i)}{\sum_{i=0}^{i=255} f(i)} \times 100\% \quad (2)$$

where $f(i)$ is the frequency of brightness at i .

Unlike the previous method which applied some rule to obtain the percentage of top threshold or outer brightness, p_{out} and bottom threshold or inner brightness, p_{in} ⁴⁾, the new method directly add the constant into the value of those percentages, which are defined as:

(a) Illustration image of molten pool

(b) Inner and outer brightness frequency ($\theta=180^\circ$)

Fig. 5 Histogram analysis for edge detection

(a) Panorama transformed image

(b) Differential brightness at $x=261$

(c) Bottom edge position

(d) Top edge position

Fig. 6 Edge detection of molten pool

$$p_{out} = p_{avg} + \Delta p_{out}(\%) \quad (3)$$

$$p_{in} = p_{avg} + \Delta p_{in}(\%) \quad (4)$$

In this experiment as shown in Fig. 5 (b), the value of Δp_{out} and Δp_{in} are 0.3% and 0.8%, respectively. Then the value of outer brightness, $g_{out} = 41$ and inner brightness, $g_{in} = 45$ can be obtained.

(b) Panorama Transformation: All of the image will be

transformed into panorama extended image as shown in Fig. 6 (a). The panorama transformation algorithm used in this paper was developed from⁶⁾. Assumed an image coordinate $p(u,v)$ and a real-world three-dimensional position $P(X,Y,Z)$ are defined. The hyperboloidal equation of the proposed mirror is represented as:

$$\frac{X^2 + Y^2}{A^2} - \frac{(Z + (C + D))}{B^2} = -1 \quad (5)$$

where A and B are parameters of the hyperboloidal mirror shape, $C = \sqrt{X^2 + Y^2}$, and D is the distance between lens to a center

Fig. 7 Comparison result of measured and detected molten pool

Fig. 8 Fuzzy sets and decision table for fuzzy control

point of the camera. Relationship equations between Z and X, Z and Y in the image coordinate $p(u, v)$ are described as follows:

$$Z = \frac{-f(B^2 + C^2)2BC\sqrt{u^2 + v^2 + f^2}}{(C^2 - B^2)u}X + (2C + D) \quad (6)$$

$$Z = \frac{-f(B^2 + C^2)2BC\sqrt{u^2 + v^2 + f^2}}{(C^2 - B^2)v}Y + (2C + D) \quad (7)$$

where f is the focal length of a CCD camera.

For the proposed omnidirectional camera, $A = 1$, $B = 2$, $D = 16$ mm, $f = 1.6$ mm and the size of CCD is $6.59 \text{ mm} \times 4.94 \text{ mm}$. Panorama image size was 512×186 pixels.

(c) Set Window: After finding the center of gravity, set window was created automatically to locate the scanning area and reduce the time of edge detection. The set window was created from the points of left, right, top and bottom as shown in Fig. 6 (a). Maximum size of set window was 150×100 pixels.

(d) Top and Bottom Edge Detection: From the original image, the vertical scanning was performed to find top and bottom edge detection. Edge detection was performed on the differential value of brightness along vertical axis $g'(i, j)$ ⁴⁾:

$$g'(i, j) = g(i, j + 1) - g(i, j) \quad (8)$$

where $g(i, j)$ is the brightness value of a pixel at (i, j) as shown in Fig. 6 (b). Edge position was determined within this range of searching. By applying the inner brightness and outer brightness, the bottom edge position can be detected by finding the minimum position within the range as shown in Fig. 6 (c). In contrary, the top edge position was detected from maximum position within the range as shown in Fig. 6 (d). This process was repeated along x position inside the set window.

(e) Width Detection: In order to find the width of molten pool, the scanning of widest value of top and bottom edges was conducted. Figure 7 shows the example of detected edge and width of molten pool.

2.3 Result of Image Processing Algorithm

Figure 7 shows the comparison of measured back bead width and detected molten pool width using proposed image processing algorithm in preliminary experiment without control. Image resolution is 0.093 mm/pixel . It is clearly seen that image processing algorithm could detect the molten pool width with good approximation. However, some errors still occur during the monitoring process with the Root Mean Square Error (RMSE) is 0.66 mm and standard deviation is 0.42 mm . The cause of the errors might come from the inner and outer brightness as the range for scanning the edge of molten pool. Another reason of this error came from the error of the measurement of bead width.

2.3 Fuzzy Inference System

Welding process was conducted autogenously for 360° of circumference and in fixed position of pipe. In constant welding current of 60 A , the torch started to initiate the arc until the initial penetration was produced. The experiment with control conducted using fuzzy inference system as control system⁷⁾. The output of the image processing which is the width of molten pool, w will become the input of fuzzy control. The output of fuzzy control is the correction of welding speed.

In this step, the proposed fuzzy control took two variables to be fuzzified. One was an error (e), which was the difference of back bead width ($w(n)$) at the concerned time step (n) from the reference back bead width (w_r):

$$e = w_r - w_n \quad (9)$$

and w_r was set at 5 mm .

The other was the change of an error defined as:

$$\Delta e = w_{n+1} - w_n \quad (10)$$

Three kind of membership (N – Negative, Z – Zero, P – Positive) and triangular membership functions were used to fuzzify the inputs. Figure 8 (a), (b) and (c) shows the membership functions and ranges for each fuzzy variable. The decision table

(a) Back bead width and welding speed

(b) Back bead appearance

Fig. 9 Result of experiment with control

for the fuzzy control of welding speed is shown in Fig. 8 (d).

3. Result and discussion

In control experiment, to produce stable arc condition, the welding speed of 1.17 mm/s at $\theta = 0^\circ - 45^\circ$ was kept constant. Figure 9 (a) shows the experiment result of back bead width and welding speed using fuzzy controller. Fuzzy control determined the correction of welding speed to keep the back bead width in the target range of 5 ± 1 mm. The result of experiment with control yields the Root Mean Square Error (RMSE) is 0.29 mm and standard deviation is 0.54 mm. At $\theta = 45^\circ - 135^\circ$, the welding speed increased from 0.83 – 1.67 mm/s and the back bead width increased. However, by maintaining and increasing the welding speed until 2.33 mm/s, the back bead width was kept to 5 mm at $\theta = 180^\circ$. Accordingly, by proper control of welding speed, it will produce excellent back bead width. The experiment result shows that the bead was smooth in appearance and there was no crack, porosity, undercut and burn through along the circumference as shown in Fig. 9 (b). The back bead width also aligned in the range target of 4 – 6 mm. In this study, the welding condition was changed during the welding proceeded along the circumference of the pipe. However, the suitable welding condition for producing the good result was obtained at welding current, $I = 65$ A, pulsed current frequency, $f = 50$ Hz, minimum welding speed, $v_{\min} = 0.83$ mm/s, and maximum welding speed, $v_{\max} = 2.5$ mm/s. In general, the proposed automatic welding system produced sound weld of aluminum pipe by monitoring backside image of molten pool using omnidirectional camera.

4. Conclusions

Welding penetration control of aluminum pipe using omnidirectional vision-based monitoring of molten pool was constructed. An algorithm to obtain to detect edge of molten pool from panorama image of molten pool was proposed. From the experimental results using fuzzy inference system, it shows the effectiveness of the control system.

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