Observation and Control of Keyhole in Robotic Plasma Welding *

by Takaaki Hirano**, Weixi Wang**, Satoshi Yamane***, Toru Nakajima****, Kazumichi Hosoya**** and Hikaru Yamamoto****

Since arc narrows in the plasma welding, heat concentration ratio is higher than other welding. This heat source generates the keyhole in the high current region, which penetrates base metal. The base metals are joined by closing the keyhole. The quality of welding depends on state of the keyhole. However, the keyhole may become unstable due to behavior of molten metal. In this research, observations of the keyhole and molten metal under various welding conditions were performed by using high speed video camera to investigate the behavior of the keyhole in the plasma welding. Length from torch cap to bottom edge of the keyhole in high speed video camera picture was proportional to plasma gas flow rate. On the other hand, the length was mostly kept constant regardless of change of welding current. When plasma gas flow rate was changed during the welding in real time, appearance of the keyhole and shape of bead were changed. Control of stabilization of the keyhole is tried based on relationship between the length found by image processing and plasma gas flow rate. The authors tried to design the digital controller controlling the length by plasma gas flow rate to obtain the stable keyhole.

Key Words: Plasma Welding, Robotic Welding, Keyhole, CMOS Camera, High Speed Camera, Plasma Gas Flow Rate, Welding Current, Image Processing, Stabilization of Keyhole, Controller design

1. Introduction

The welding is one of the joining technology in manufacturing field. However, there are the following problems in the practical field of welding. Automation of the welding with high efficiency and a high quality are required due to the globalization of the field of manufacturing, and the decrease of the welding engineer\(^1\). In the CO\(_2\) welding, spatter and fume occur. Moreover, in the thick welding, groove is needed, and thermal strain becomes large. In the TIG welding, welding speed is low. In the laser welding, equipment and running cost are expensive, high accuracy of the joint is required. Therefore, the plasma welding solving the above mentioned disadvantages attracts attention\(^2\).

Since arc narrows by nozzle in the plasma welding, heat concentration ratio is higher than other welding\(^3\). This heat source generates the keyhole which penetrates base metal in high current region. The base metals are joined by closing the keyhole\(^3\). Since bead width is narrow and deep penetration is obtained, welding deformation and strain are reduced. However, it is difficult to teach the welding line to the robot because the electrode cannot be detected directly. In addition, it is necessary to grasp welding state in real time because the quality of welding depends on state of the keyhole. Thus, control of the welding based on the sight information is important.

The authors observed molten metal by using CMOS camera tracking the welding line in the plasma welding\(^3\). The welding line was detected by observation, i.e. the center of the molten metal flowing behind the keyhole. The keyhole and welding line was detected by using pattern matching.

However, the keyhole becomes unstable due to behavior of molten metal and the gap between the base metals. In this research, observation and evaluation of the keyhole and molten metal under various welding conditions were performed using high speed video camera. Furthermore, stabilization of the keyhole is investigated on relationship between the quantity of characteristic found by image processing and welding conditions. The authors tried to design the digital controller the length from torch to keyhole by plasma gas flow rate.

2. System Configuration

Robotic plasma welding system is shown in Fig.1. There are three kinds of personal computers. Two are for control of welding power source and robot on real time. Welding conditions are stored in the robot control PC. This PC sends welding conditions to the PC to control the power source. The trigger signal to open the shutter of the camera is synchronized with welding current waveform\(^5\). The camera sends the captured image as digital value to the third PC by using ethernet. The PC processes the image, detects the edge of the molten pool, and sends its length to the robot control PC by RS232C. The base metal was mild steel plate with the Y groove. The CMOS camera was fixed to the rear of plasma torch. The high speed video camera was also set to take the weld pool from rear of welding. The welding condition is listed in Table 1.

* Received: 2016.10.17  
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Table 1 Welding condition.

<table>
<thead>
<tr>
<th>Base metal thickness</th>
<th>9.0 [mm]</th>
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<tbody>
<tr>
<td>Nozzle inner diameter</td>
<td>3.2 [mm]</td>
</tr>
<tr>
<td>Stand off</td>
<td>6.0 [mm]</td>
</tr>
<tr>
<td>Welding speed</td>
<td>15 [cm/min]</td>
</tr>
<tr>
<td>Plasma gas</td>
<td>Ar: 2.0, 3.0, 4.0 [L/min]</td>
</tr>
<tr>
<td>Shield gas</td>
<td>Ar: 10 [L/min]</td>
</tr>
<tr>
<td>Welding current</td>
<td>225, 235, 245 [A]</td>
</tr>
</tbody>
</table>

3. Observation of weld pool

The fundamental experiment was carried out to investigate the behavior of the molten metal. The keyhole was observed by the CMOS camera as shown in Fig.2 when the current is reduced to 30 A. In this experiment, welding condition was kept constant. The keyhole was identified in first half of the welding as shown in Fig.2 (a), but it was hard to identify the keyhole in the latter half as shown in Fig.2 (b). Since the CMOS camera was fixed to the welding torch, the view of the CMOS camera was the same. However, the shape of the keyhole was changed. Thus, it is estimated that behavior of the molten metal around the keyhole was affected. If the keyhole on the image is too big, the burn through occurs. If it is too small, the back bead becomes thinner. In order to obtain a stable bead, the size of keyhole is important.

4. Effect of welding condition on keyhole

In order to investigate the relationship between the keyhole and the welding condition, the fundamental experiments on 3 patterns of plasma gas flow rate (2.0, 3.0, 4.0 L/min) in welding current (225, 235, 245 A) were carried out. The experimental results are shown in Fig.3. This figure shows comparison at the same travelling distance and timing.

First, effect of the plasma gas flow rate under the same welding current on keyhole was investigated. The length between edge of the torch cup and the edge of keyhole was investigated in the image, since the CMOS camera was fixed and this length corresponds to the size of keyhole. If the keyhole becomes big, the bead on the rear side becomes unstable. The length increased according to the plasma gas flow rate under the same welding current. The length at the welding current of 225 and 235 A was proportional to plasma gas flow rate. However, the result of 245 A was not proportional, and the change of the plasma gas flow rate did not affect on the size of keyhole if welding current was big and the size of keyhole was big. In addition, humping bead on the rear side occurred at 250 A.

Next, the effect of the welding current under the same plasma gas flow rate on keyhole was investigated. When the plasma gas flow rate was kept constant, the length was approximately constant regardless of the change of the welding current as shown in Fig.4. The change of the welding current did not affect on the size of the keyhole. Therefore, the state of the keyhole depends on plasma gas flow rate.

The keyhole diameter is limited by the surface tension acting on the rear of the keyhole such that the arc pressure separates the two sides of the weld pool, preventing joining, and burn through occurs. When the keyhole diameter and the penetration of the
weld pool decreased, the behavior of the molten metal becomes unstable and variation occurs in the bead\(^7\). Since the large keyhole pushes down the surrounding molten metal, the distance from the torch edge also increases. From the above mentioned, the length from torch to keyhole is one of key factor of stability.

5. Dynamic behavior of keyhole

The plasma gas flow rate was changed on the keyhole from 2.0 L/min to 4.0 L/min at welding current 235 A to investigate the effect on the keyhole. In this condition, the bead appearance and keyhole images are shown in Fig.5. In before and after of the change, the size of the keyhole changed and the length from torch to keyhole increased, too. In addition, about bead shape, the width of the bead on the front side decreased, and the height of the bead on the rear side increased according to plasma gas flow rate. The much molten metal was appeared according to the plasma gas flow rate. The effect of the plasma gas flow rate was identified on the image during the welding.

The length was detected by image processing and evaluated influence of the plasma gas flow rate in order to control the keyhole. First, the relationship between mean value of the length and the plasma gas flow rate in steady state is shown in Fig.6. The length was proportional to the plasma gas flow rate as shown in Fig.3. This gradient indicates the influence degree of the plasma gas flow rate.

Next, in order to investigate the transient response of the keyhole, the plasma gas flow rate in the real time is changed as shown in Fig.7. The length from the torch edge to the edge of the keyhole was changed after changing of the plasma gas flow rate. The size of keyhole becomes big. The behavior of the length can be described by using first order differential equation. The steady state and the transient state can be used to find the first order differential equation.

6. Design of the digital controller

A single loop digital feedback control system was applied to control of the keyhole. The block diagram of the control system is shown in Fig.8. \(E(z)\) corresponds to Z transform of the error, which is the difference between the reference length and image processing result. \(D(z)\) represents the relationship between the manipulating value and the error. The desirable response \(X(z)\) to the transfer function \(G(z)\) in the plant was found when input \(R(z)\) is given.

The behavior of the length \(x(t)\) has the time delay to change of the plasma gas flow rate \(u(t)\) as shown in Fig.7. This response of the length \(x(t)\) for plasma gas flow rate \(u(t)\) is approximated by a first order differential equation as follows:
where $\lambda$ and $b$ are the time constant and the coefficient. Eq.(1) is described by continuous time system of the keyhole. When the step input of the reference value $r(t) = U_0 \delta(t)$ was given, the desirable response of $x(t)$ is given by

$$x(t) = U_0 \delta(t) \left(1 - e^{-\alpha t}\right)$$

Thus, $\lambda = 0.42 \text{s}^{-1}$ of Eq.(2) is found from the transient response on Fig.7. This value corresponds to time constant $T = \lambda$. Moreover, because of $dx(t)/dt = 0$ at the steady state in Eq.(1), $b = 24.5 \text{pixel/(Lmin}^{-1}s)$ is found from correspondence with gradient in Fig.6. $\alpha$ is the eigenvalue.

When continuous time system is changed to discrete time system, transfer function $G(z)$ in plant is obtained as follows:

$$G(z) = \frac{b}{\lambda} \left(1 + e^{-\lambda T} \right) z^{-2}$$

In order to apply the digital controller, the plant $G(z)$ is needed. The plant $G(z)$ is described by the relationship between the plasma gas flow rate $u(t)$ and the length $x(t)$. Eq.(4) shows how to determine characteristic $D(z)$ of the digital controller. Eq.(4) is transformed to the discrete time system as mentioned in Eq.(5).

$$D(z) = \frac{U(z)}{E(z)} = \frac{1}{G(z)} \frac{X(z)}{R(z)}$$

$$u[n] - u[n-1] = d_0 e[n] - d_1 e[n-1]$$

$$d_0 = (1 - e^{-\lambda T})q \quad d_1 = p d_0 \quad q = b \left(1 - e^{-\lambda T}\right) / \lambda$$

Therefore, the amount of changed plasma gas $\Delta u[n]$ are found by the present deviation $e[n]$ and the difference in the deviations $\Delta e[n]$.

7. Evaluation of the digital controller

The purpose of feedback control is the control of the plant regardless of disturbance, such as the change of gap. In order to check the performance of the digital controller under the variation of parameter $b$, the numerical simulation was carried out.

The parameter $b$ in Eq.(1), corresponding to the root face in the base metal, is increased from 24.5 to 30.0. The simulation result is shown in Fig.9. Even if $b$ is increased from 20 to 40 sec, the digital controller adjusted the plasma gas flow rate decreased from 3.19 to 2.20 L/min, and the length $x(t)$ was almost kept constant. The validity of the proposed controller was verified from the simulation result. It is possible to use this response for a change in the shape or the root face of the base metal.

8. Conclusions

The observation of keyhole and molten metal under some welding conditions has been performed in plasma welding. Length from torch cap to bottom edge of the keyhole was proportional to plasma gas flow rate. On the other hand, the length was mostly kept constant regardless of change of welding current. The length depends on the plasma gas flow rate. When plasma gas flow rate was changed during the welding in real time, the keyhole and shape of bead was changed. The authors detected the length by image processing, and the digital controller based on first order system was designed from relationship between the length and the plasma gas flow rate. The performance of designed digital controller were confirmed by the simulation in the fluctuation of the parameter and the reference value.

Reference

4) S. Yamane, “Tracking of the welding line using image processing” Image laboratory, (2016) 44-51
7) A.B. Short, D.G. McCartney, P. Webb, E. Preston, Science and Technology of Welding and Joining, 16 (2011) 446-452