Simultaneous Sensing of Weld Pool and Keyhole in Controlled-Pulse PAW

The behaviors of the keyhole and the weld pool in plasma arc welding can be used to indicate weld quality

BY G. K. ZHANG, J. CHEN, AND C. S. WU

ABSTRACT

The behaviors of the keyhole and the weld pool are dynamically-coupled in controlled-pulse plasma arc welding and can be used to indicate weld quality. The vision system was improved to detect the geometries of both the keyhole and weld pool at the backside simultaneously during a whole controlled-pulse keyholing period by one single CCD camera without auxiliary illumination. With the assistance of an appropriate optical filter system, the unchanged aperture and exposure time of the camera was also adopted and can be used under a different current period. An image processing method was then proposed to extract the keyhole boundary in open keyhole status and weld pool boundary for the whole welding process. The influences of current waveform parameters on the welding process are studied and discussed. It was found that dimensions of the weld pool at the backside are determined by the heat input of the plasma arc and keyhole duration. The keyhole moves forward during the welding process while the weld pool maximum width at the backside is located behind the keyhole center.

KEYWORDS

• Simultaneous Detection • Controlled-Pulse Keyholing • Plasma Arc Welding
• Dynamic Behavior

Introduction

Plasma arc welding (PAW), as a kind of high-density-beam welding, can be operated in keyhole mode because of the high power of the plasma arc. This open keyhole moves forward to melt more metal during the welding process (Ref. 1), which makes PAW achieve deeper penetration than gas tungsten arc welding (GTAW) and more tolerant of joint preparation than laser beam and electron beam welding (Ref. 2). It shows great application potential in manufacturing airplanes, automobiles, and rockets (Refs. 3–6).

The keyhole and weld pool stability, which are critical issues in PAW applications, is sensitive to welding parameters in conventional keyhole PAW (Refs. 7, 8). During PAW, a small change of welding current can disturb the plasma arc heat and force balance, which leads to keyhole closure or weld pool discontinuity (Ref. 9). To improve the weld quality and widen the application of the keyhole PAW process, the “one pulse, one keyhole” strategy was proposed. The square pulse waveform was used to weld 4.0–6.7-mm-thick workpieces (Refs. 10, 11), yet it is only focused on establishment of the keyhole without controlling keyhole closure. Thus, the quasi-keyhole PAW process was proposed and used to control keyhole behavior. A high-quality weld bead was achieved on a 3.6-mm-thick workpiece through controlling keyhole establishment time and keyhole sustaining time (Ref. 12). To control keyhole behavior and improve keyhole stability in the thicker workpiece, the controlled-pulse keyholing PAW system was developed (Ref. 13).

As shown in Fig. 1, the welding current waveform, which consists of peak current (Ip), base current (Ib), duration of base current (Tb), two different slopes (f1 and f2), and falling time (Tf1 and Tf2) at the falling stage of welding current, is specially designed to adjust behaviors of weld pool and keyhole. Under this control strategy of welding current, the efflux plasma voltage starts to be detected by the efflux plasma charge sensor at t2 after the Ip is applied for a certain time. It means that an open keyhole appears. At t3, the open keyhole signal reaches its maximum value, which is a little higher than the given voltage (Sp) because of a delay of the feedback system, and then this signal starts to decrease with decreasing (descending slope f1) welding current. So the duration of peak current (Tp) varies and depends on peak current, the thickness of the material, and welding speed. At t4, the current decreases at a steeper descending slope f2 (f2 > f1) to make sure that the keyhole is closed completely. After the Ib is applied at t5 to sustain the weld pool, the current is switched to the Ip again to begin a new cycle at...
A periodic open keyhole generated by proper waveform parameters can produce deep penetration welds without melt-through defects by PAW. Detecting and analyzing relationships among welding current, weld pool behavior, and keyhole behavior is essential for optimizing current waveform parameters and improving weld quality. Much research has been done to study keyhole status by backside efflux plasma voltage or by front side plasma cloud discharge voltage between the workpiece and detection bar. Photo-transistor can also be used to identify keyhole status by the light of the efflux plasma or plasma cloud. If the environmental noise is very low, sound signal is another effective method to describe evolution of keyhole status, such as nonkeyhole, keyhole, and cutting. However, these detection methods are all indirect approaches to reflect the keyhole behavior and cannot provide dimension parameters of the keyhole, let alone the information of the weld pool. Vision-based sensing can give sufficient information to directly analyze the behaviors of weld pool and keyhole, respectively. For example, a vision-based sensing system was used in GTAW to measure the 3D weld pool surface in real time, which can provide sufficient information to predict the backside bead width. The 3D weld pool surface characteristic can also be used to control the welding process and build a welding training system. Because of the big volume of the PAW torch, it is hard to apply a 3D weld pool surface sensing system from the upside. While the backside keyhole is close to the front edge of the weld pool, the plasma arc and keyhole will disturb detection of the weld pool information at the backside. An ultra-high shutter speed vision system was used to acquire images of the weld pool and keyhole during the conventional PAW keyhole period. This observation system was too expensive to be applied in industry. A low-cost visual system was developed to observe the keyhole and weld pool from the backside of the workpiece during the open keyhole period of conventional PAW process. However, the dynamic behaviors of the keyhole and weld pool, especially the weld pool in blind keyhole period during controlled-pulse keyholing PAW process, still lacks research. And the image system should also be optimized as the light intensity changes severely during this welding process.

In this study, a cost-effective vision system with a single camera was employed to detect and monitor the dynamic status of both the keyhole and weld pool from the backside of the workpiece in the controlled-pulse keyholing PAW process. The influences of welding parameters on the welding process were studied by analyzing geometrical dimensions of keyhole and weld pool in a whole pulse cycle (keyhole formation, expansion, contraction, and closure).

**Fig. 1 — Schematic of controlled pulse keyholing PAW.**

**Fig. 2 — Schematic of the experimental system for controlled-pulse keyholing PAW.**

**Fig. 3 — LTE spectrum for Ar (Ref. 27).**
Experiment Setup and Observation Strategy

Setup

The experimental setup for the controlled-pulse keyholing PAW system is shown in Fig. 2. A commercially available PAW machine was used for the investigation. The plasma arc initiated from the welding torch was under the control of a computer. At the same time, the computer could monitor process signals via input/output interfaces from Hall sensors and a vision sensing camera.

A Hall current sensor was used to detect welding current, which was adjusted in real time according to the feedback of efflux plasma voltage (Ve) measured by a Hall voltage sensor.

The CCD camera (AM1101A), fixed under the workpiece, was equipped with an infrared filter to simultaneously observe images of both the keyhole and the weld pool from the backside. The observation angle was set to 70 deg, and the distance between the camera lens and the target was 200 mm.

The bead-on-plate welding experiments were conducted on stainless steel (201) plates. The flow rate of argon shielding gas was 20 L/min at topside and 10 L/min at backside. The orifice diameter and throat length of the torch were 2.8 and 3.0 mm, respectively. The torch standoff distance to the workpiece was 5.0 mm. The tungsten electrode setback was 2.0 mm. Table 1 lists the various process parameters for different test conditions.

Observation Strategy

Imaging Principle

Plasma arc, welding pool, and base metal have different radiation intensities because of their different emissivities and temperatures during the controlled-pulse keyholing PAW process. The purpose of this vision system is to detect these three kinds of radiation information at one observation window, which is emitted from the backside of the workpiece. For the stainless steel, there are two important temperatures at the backside of the workpiece. Melting point (1800 K) stands for the boundary between weld pool and base metal. Table 1 lists the various process parameters for different test conditions.

Table 1 — Parameters of Welding Current Waveform

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Ip (A)</th>
<th>Tp (ms)</th>
<th>Tp (ms)</th>
<th>Tp (ms)</th>
<th>Ip (A)</th>
<th>Tp (ms)</th>
<th>Welding Speed (mm/min)</th>
<th>Plate Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Varied</td>
<td>Varied</td>
<td>250</td>
<td>100</td>
<td>60</td>
<td>100</td>
<td>120</td>
<td>8</td>
</tr>
<tr>
<td>2–5</td>
<td>140–170</td>
<td>Varied</td>
<td>40</td>
<td>60</td>
<td>60</td>
<td>100</td>
<td>120</td>
<td>6</td>
</tr>
<tr>
<td>6–9</td>
<td>150</td>
<td>Varied</td>
<td>40</td>
<td>60</td>
<td>60</td>
<td>100</td>
<td>100–130</td>
<td>6</td>
</tr>
<tr>
<td>10–13</td>
<td>150</td>
<td>Varied</td>
<td>20–80</td>
<td>60</td>
<td>60</td>
<td>100</td>
<td>120</td>
<td>6</td>
</tr>
</tbody>
</table>
and base metal. Boiling point (3000 K) means the boundary between plasma arc and weld pool, respectively. If the emissivity of the weld pool is assumed to be a constant value at a different temperature, the range of workpiece radiation at the backside can be calculated by Plank’s law (Ref. 33),

\[ B_T(\lambda) = \frac{2h\lambda^2}{3k^2} \times \frac{1}{e^{h\lambda/kT} - 1} \quad (1) \]

Under the action of \( I_p \), the workpiece was fully penetrated. Once an open keyhole was established first in the weld pool, the plasma efflux flowed out from the keyhole channel, which induced a strong interference in the visual signals of the camera. Getting clear images of the weld pool during the open keyhole period was a primary consideration.

To get rid of the influence of Ar radiation on CCD signals, two observation windows (660 and 1080 nm) were selected as shown in Fig. 3, which was a LTE spectrum for Ar (Ref. 34). The black body infrared radiation ratios at different temperatures (1800 and 3000 K) and different wavelengths (660 and 1080 nm) are listed as,

\[ \frac{B_{1800K}(660 \text{ nm})}{B_{3000K}(660 \text{ nm})} = 1/127, \]
\[ \frac{B_{1800K}(1080 \text{ nm})}{B_{3000K}(1080 \text{ nm})} = 1/19. \]

It is clear that there is a significant difference (1:127) in the weld pool radiation between 1800 and 3000 K at the observation window of 660 nm, which means the radiation difference between the unmelted and melted zone was low for an 8-bit gray scale image. So it was hard for the camera to identify the weld pool boundary. On the contrary, the weld pool radiation difference (1:19) between 1800 and 3000 K at an observation window of 1080 nm was proper to identify the weld pool boundary and the radiation intensity of weld pool was still strong enough to be detected without illumination. Hence, an observation window of 1080 nm was also a good choice for the detection of whole weld pool during the blind keyhole period. Meanwhile, exposure time and lens aperture of the camera should be optimized to capture the keyhole and weld pool evolution continuously in a complete pulse period with infrared filter (central wavelength was 1080 nm, bandwidth was 20 nm and transparency was 90%). Figure 5 was captured when the exposure time was 1 ms and aperture was F1/8. It shows that not only can both keyhole and weld pool be detected during the open keyhole period, but also that the weld pool image can be captured during the blind keyhole period.

**Image Analysis**

According to the principles of camera sensors, pixel gray values of images are the reflection of objective infrared intensity. For a constant emissivity,
higher temperature results in stronger infrared radiation intensity. Therefore, the gray levels of images are indirect reflections of temperature and can be used to analyze backside weld pool images.

Figure 6 is the pixel gray graph that Y-direction scanning was conducted in Fig. 5 along three lines from the rear part to the front part (X = 100, 150, 200 pixels in Fig. 6A and X = 150, 200, 250 pixels in Fig. 6B).

During the open keyhole period, the plasma arc penetrated the workpiece and pushed the weld pool away. Accordingly, the gray level distribution of the backside weld pool image was affected by efflux plasma arc, which induced the central peak (X = 100, 150) in Fig. 6A. The influence of efflux plasma arc on gray level gradually diminishes at the rear part of the weld pool (X = 200).

During the blind keyhole period, efflux plasma disappeared as the keyhole was closed. The shape of gray levels presents a ‘basin’ as shown in Fig. 6B. According to Figs. 5B and 6B, the unfused metal reaches its highest temperature and peak infrared radiance intensity (peak gray level) at the boundary of the weld pool. Then the gray level obviously decreased in the weld pool though its temperature is higher than unfused metal. The reason is that the radiance of gray body was determined by both temperature (T) and emissivity (ε) as shown in Stefan-Boltzmann law (Ref. 33)

\[ j = \varepsilon \sigma T^4 \]  

ε was influenced by the surface condition. The smoother the surface appeared, the lower the ε became. The emissivity of the weld pool was much less than unfused metal since weld pool can be regarded as a mirror. Thus, the radiation intensity (j) of the weld pool was relatively lower than solid metal as well as the gray level. And the gray level discrepancy between melting weld pool and solid metal also made the weld pool edge easily detected.

During the blind keyhole period, the peaks of gray level were selected as weld pool boundary for each Y-direction scanning line, as shown in Fig. 6B. Through image processing, the weld pool boundary can be obtained by linking the peak points (dashed lines in Fig. 6). The sharp transition area from maximum gray level to ‘basin’ is the mushy zone, which is made of both solid and molten metal. As shown in Fig. 6A, the efflux plasma can only form peak in front of the weld pool. The same method can be applied to detect weld pool boundary during the keyhole period. For each Y-direction scanning line, the first and third peaks were selected as the weld pool’s front-side boundary, while the peaks of gray level were selected as the weld pool boundary at the weld pool’s rear.

As the gray level of the keyhole was higher than 200, it could be divided from the backside image through image segmentation, and then a canny edge detector was used to detect keyhole boundary, which is described in previous research (Ref. 32).

By using the image processing methods above, the edge and sizes of keyhole and weld pool were obtained offline after experiments in different situations, as shown in Fig. 7.

**Results and Discussion**

**Keyhole and Weld Pool Size Evolution**

During controlled-pulse keyholing PAW, the behaviors of keyhole and weld pool can affect the process stability and weld quality. For Test 1, welding current and arc voltage are shown...
in Fig. 8A and efflux plasma voltage is shown in Fig. 8B. The images of both keyhole and weld pool in a whole pulse cycle are illustrated simultaneously in Fig. 9. The length and width of keyhole and weld pool are defined as geometrical dimensions and perpendicular to the welding direction, respectively. Figure 10 is the dynamic variation of keyhole and weld pool dimensions in one whole cycle.

During the base current period (15.5–15.7 s), backside keyhole was closed and the temperature of the weld pool dropped. However, the temperature of the weld pool at the backside is still higher than the melting point as heat energy was continuously transferred from plasma arc and melted metal in the weld pool. As a result, the dimension of the backside weld pool could keep constant.

During the peak current period (15.6–17.1 s), high welding current provided sufficient heat input and heat accumulation to the weld pool. This peak current period can be divided into two parts: blind keyhole period and open keyhole period. At the first part (15.7–16.6 s), the depth of the keyhole increased under high welding current and plasma arc force, while the geometry of the backside weld pool remained the same, which means that major heat input mainly acted on the internal weld pool instead of the backside of the workpiece.

At the second part of the peak current period (16.6–17.1 s), once an open keyhole was established after welding current was exerted for enough time, the plasma arc heated and melted more metal. As the plasma arc force was bigger than gravity and surface tension, the size of the keyhole expanded gradually to make a new weld pool generate and grow in the old weld pool that formed in the last pulse. Meanwhile, the temperature of the old weld pool decreased step by step because its position moved far away from the heat source. At 16.7 s, the old weld pool solidified and the length of the total weld pool decreased sharply. However, the new weld pool continued growing from 16.7 to 17.1 s.

Once keyhole size was high enough, the backside keyhole closed to avoid melt-through defects during the welding current falling period (17.1–17.27 s). As plasma arc force is mainly decided by welding current, a slowly decreasing welding current (slope f1) was used first to make sure that the size of the keyhole decreased smoothly without keyhole collapse. Then a steeper slope f2 was utilized to completely close the backside keyhole. Figures 9 and 10 also show the size of the backside weld pool reached its highest value at 17.27 s when the backside keyhole closed completely.

**Keyhole and Weld Pool Dynamic Position**

Figure 9 shows that the relative position of keyhole and weld pool...
changed over time under controlled-pulse keyholing PAW. The dynamic behaviors of the keyhole center and weld pool front edge on the backside workpiece in one pulse cycle are illustrated in Fig. 11. Position 0 is the intersection of the welding torch axis and backside workpiece.

The weld pool movement in the blind keyhole period determined the position where the keyhole appears in controlled-pulse PAW. During the peak welding current period, the plasma arc, which flowed to the workpiece along the welding torch axis, penetrated the workpiece and appeared on the backside. However, the keyhole position was far away from the welding torch axis when the backside keyhole began to appear. Compared with the low-temperature solid metal, flow resistance in a high-temperature melting weld pool was much smaller. As a result, the plasma arc flowed and penetrated the workpiece along the front edge of the weld pool, which was formed in the last pulse. Under the heat function of plasma arc generated by peak welding current, the melting rate of base metal in the front of keyhole was greater than the welding speed. Hence, the front edge of the weld pool moved forward and the position of the keyhole center became close to 0 position (the axis of the welding torch) at the keyhole period in Fig. 11. The plasma arc in keyhole, which is affected by current, gradually became weak if welding current decreased. If metal melting rate in the front of the keyhole was less than or equal to the workpiece movement speed, the keyhole would stop moving forward (welding current falling period), which is shown in Figs. 9 and 11. The behavior of the keyhole affected weld pool behavior and position in the keyhole period. The keyhole and weld pool were coupled together and the front edge of the keyhole formed the weld pool front edge. Plasma arc in the keyhole heated the base metal and made the metal transfer from the workpiece to the weld pool. Therefore, the movement of the keyhole was the direct reason why the weld pool expanded along welding direction. When the open keyhole stopped moving and closed at the base current period, the weld pool could not move forward anymore. On the contrary, the weld pool would move backward with the workpiece, as shown in Fig. 11.

During PAW, the keyhole was located in the front of the weld pool. The maximum temperature of the backside workpiece was located at the position of the keyhole. However, the keyhole was always located between the solid metal and the molten pool due to its movement. As shown in Fig. 12, the widest position of weld pool and the location of keyhole have a certain lag because of thermal hysteresis.

Influences of Welding Parameters

During controlled-pulse keyholing
PAW, the current waveform and welding speed are critical to keyhole and weld pool behaviors. It is essential to analyze the influence of welding parameters on controlled-pulse keyholing PAW. It is clear that the function of $I_b$ was to keep a proper weld pool at the backside during $T_b$ and to protect it from overheating. Meanwhile, $T_b$ is the major parameter to guarantee the continuity of backside reinforcement between neighboring pulses during the welding process. In this research, both $I_b$ and $T_b$ are fixed to constant values. $I_p$, $T_{f1}$, and welding speed were selected to study the relationship between welding current parameters and keyhole/weld pool behaviors. To decrease the influence of keyhole forming resistance (gravity) and highlight the effect of welding parameters, Experiments 2–13 were conducted on 6-mm-thick plate instead of 8-mm-thick plate. The plasma gas flow rate was 2.8 L/min. The welding parameters are listed in Table 1.

According to previous analysis, keyhole is the heat source and the force source to widen weld pool size and drive the weld pool moving forward. If the duration of the keyhole is very short, weld discontinuities will appear because of inadequate melting on the backside. However, the welding speed is very short, weld discontinuities will appear because of inadequate melting on the backside. However, if the duration of keyhole is very long, the weld pool will burn down because of overheating. At the end of each pulse, the weld pool reaches the largest size, which reflects the result of heat and force effects of plasma arc. To investigate the influence of welding current waveform parameters $I_p$, $T_{f1}$, and welding speed on the welding process, only one parameter was changed in each test based on experiment design.

1) Influence of peak current

In this part, only peak current was changed to observe the behaviors of keyhole and weld pool. In tests 2–5, $I_p$ was set from 140 to 170 A. Figure 13 illustrates the keyhole area and weld pool size at the backside workpiece in different tests.

With the decrease of peak current, it became difficult to produce open keyhole as shown in Fig. 13A. Especially when peak welding current decreased to 140 A, the plasma arc could not penetrate the workpiece because of low heat input. As shown in Fig. 13B, keyhole size increased with the growth of peak current. However, the duration of keyhole was almost the same at different peak currents as it was controlled by $S_p$ and $T_{f1}$. As a result, the size of the weld pool was mainly determined by the heat input during the open keyhole period. A higher peak current would lead to a larger weld pool, which should be controlled in case of burn down.

2) Influence of welding speed

Welding speed was one of the most important parameters to control welding heat input. In tests 6–9, only welding speed was changed from 100 to 130 mm/min to observe the behaviors of keyhole and weld pool. Figure 14 illustrates the keyhole area and weld pool size at different welding speeds.

The keyhole area is large at a low welding speed because of high heat input. A bigger keyhole brings more heat to melt base metal and increase the weld pool size under decreasing welding speed.

3) Influence of welding current falling time ($T_{f1}$)

In controlled-pulse keyholing PAW, welding current had two falling slopes. The purpose of the first slope ($f_1$) was to drive the keyhole to close smoothly. The duration of the keyhole could be controlled by $T_{f1}$. In tests 10–13, $T_{f1}$ was set as 20, 40, 60, and 80 ms, respectively.

For a fixed thickness workpiece, there exists the minimum welding current that makes arc force equal to gravity and surface tension to keep the keyhole open. During $T_{f1}$, the welding current was still higher than the minimum welding current to keep the keyhole open. However, $T_{f1}$ was much more than $T_p$, so the heat input during $T_{f1}$ was much smaller than the total heat input in one cycle. Increasing $T_{f1}$ mainly increased the duration of keyhole time instead of keyhole size as shown in Fig. 15A. Similarly, though a longer $T_{f1}$ would give the plasma arc more of a chance to increase weld pool size, both the length and width of the weld pool increased a little, which is shown in Fig. 15B.

Conclusion

1) A vision system combined with an image processing strategy was developed to detect both keyhole and weld pool information during a whole controlled-pulse keyholing period without illumination.

2) During the blind keyhole period, heat input mainly acted on the internal weld pool to increase keyhole volume and the weld pool varied little at
the backside. The keyhole position and the maximum width position of the backside weld pool were located behind the welding torch axis because of thermal hysteresis.

3) The location of backside weld pool was at rest relative to the workpiece during the blind keyhole period. It only moved forward driven by keyhole under open keyhole status. The sizes of weld pool and keyhole were more susceptible to peak current and weld speed than welding current falling time \((T_{nf})\).

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References