Efflux Plasma Charge Sensor for Weld Joint Penetration in Keyhole Plasma Arc Welding

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Abstract. An efflux plasma charge sensor is proposed to monitor weld joint penetration in keyhole plasma arc welding. For convenience of application, the sensor is integrated as part of the fixture. Based on experimental data, a linear model is fit to estimate the joint penetration from the output of the sensor. To understand the principle of the proposed sensor, the physical process associated with plasma jet and space charge is analyzed. Experiments have also been conducted to examine the potential of the proposed sensor in monitoring burn-through and keyhole collapse.

Introduction

Robustness, economy, and accuracy are among the major criteria to evaluate sensors for automated welding systems. Due to its robustness with respect to the harsh environment during arc welding and its great economy, through-the-arc sensing has found applications in arc length control and seam tracking (Refs. 1-6). It has also been used to analyze the oscillation of the weld pool for monitoring weld joint penetration in gas tungsten arc welding (GTAW) (Ref. 7) due to the relationship between the oscillation of the weld pool and its penetration.

Keyhole plasma arc welding (PAW) is one of the primary arc welding processes for precision joining of critical metal components (Refs. 8-9). To ensure weld quality, the penetration must be monitored and controlled. It is known that the weld pool is subject to the impact of the high speed
plasma jet in keyhole PAW and that no studies have disclosed relationships, if any, between pool oscillation and weld penetration. Hence, although utilization of the arc has great advantages in terms of robustness and economy, highly desired by welding industry, through-the-arc methods have not found applications in penetration control for keyhole PAW. If an arc based robust, economical penetration sensor can be developed for keyhole PAW, its potential in application could be quite positive.

During keyhole PAW, the plasma jet penetrates through the workpiece, forming a funnel-shape cavity referred to as keyhole, as shown in Fig 1 (Ref. 10-11). To determine possible correlation between penetration and plasma arc, characteristics associated with the keyhole should be taken advantage of. In an early study, the light of the plasma efflux from the keyhole was measured for maintaining the keyhole (Ref. 12). Another example involved detecting specific spectral lines of metal vapor for keeping the keyhole through which the vapor of base metal escapes (Ref. 13). Recently, the authors studied the possibility of using the diameter of the keyhole to monitor penetration (Ref. 14). Experimental results showed that, after the keyhole is established, increasing/decreasing the welding current/welding speed increases joint penetration until burn-through. Similarly, decreasing/increasing the welding current/welding speed decreases the joint penetration until the keyhole collapses. However, experiments also revealed that the diameter of the keyhole does not change with the heat input which alters the joint penetration (Ref. 14) after the keyhole is established. This implies that the existence of or the diameter of the keyhole does not provide sufficient information for monitoring joint penetration.

This study aims at developing a penetration sensor, referred to as efflux plasma charge sensor (EPCS), for keyhole PAW based on the residual of the energy of the plasma jet exiting from the keyhole. This idea is understandable because, for a given material of base metal, the stronger the
residual energy is, the more energy the bottom of the workpiece should absorb from the plasma jet; thus the wider the back-side width of the weld pool should be. For possible practical applications, the sensor has been integrated as a part of the fixture. It is expected that the results of this study would provide foundations to develop a cost effective, robust, and accurate sensor for joint penetration in keyhole PAW.

**Experimental Apparatus and Procedure**

Keyhole mode is used in most PAW applications. Chill clamping and gas backup shown in Fig. 2 (Ref.11) provide an underside shield which is necessary for metals such as stainless steel, titanium. For weld joints which require or allow gas backup, the proposed sensor can be applied with a minor modification of the backing bar. Fig. 3 shows the proposed sensor built into the backing bar by using an insulator, a capacitor, and a resistor. The insulator is used to prevent the voltage, caused by the space charge of the plasma jet, from being short-circuited so that it can establish a voltage drop across the resistor. The voltage drop serves as the output of the sensor. The capacitor, $0.01 \ \mu F$ in this study, is used to form a filter with the resistor. A computer data acquisition with high input impedance of measurement circuit and software program was used to sample the output voltage of the sensor. Because the sensor measures the space charge generated by the efflux plasma jet, it is referred to an efflux plasma charge sensor.

In the proposed method, the backup bar can be either moving or fixed. In this study, a fixed design as shown in Fig. 4 was used. The distance between the workpiece and the detection plate, referred to as measurement height $h$, was 1 inch (25.4 mm). Pure argon was used as shielding gas for both the top-side and the back-side. To identify the model of the sensor, the resistance of the output resistor of the sensor, $R_e$, was adjustable. The output signal of the sensor was recorded by a data acquisition
system. The back-side width of the weld was measured off-line after experiment using a vision sensor developed earlier (Ref. 15).

Bead-on-plate welds were made on stainless steel (304) plates using a constant current (CC) inverter. The current ranged from 10 A to 200 A. The dimensions of the workpiece were 260×65×3.2 mm (10.2×2.55×0.125 in.). Welding current and welding speed were changed in order to change the joint penetration and the process mode (keyhole or non-keyhole). Other welding parameters shown in Table 1 were constant during experiments.

### Table 1 Constant Welding Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orifice diameter</td>
<td>1.57 mm (0.062 in.)</td>
</tr>
<tr>
<td>Flow rate of plasma gas</td>
<td>1.4 L/min (3 ft³/h)</td>
</tr>
<tr>
<td>Flow rate of shielding gas</td>
<td>11.5 L/min (25 ft³/h)</td>
</tr>
<tr>
<td>Flow rate of backing gas</td>
<td>9.2 L/min (20 ft³/h)</td>
</tr>
<tr>
<td>Stand-off</td>
<td>6 mm (0.24 in.)</td>
</tr>
</tbody>
</table>

### Results and Discussion

#### Penetration Prediction

Experiments have been conducted by using various welding currents and speeds to change the joint penetration. Figs. 5 and 6 plot the experimental data. It can be seen that no matter the cause of penetration change, whether varying the welding current or the welding speed, the output of the sensor gives us a very good idea of the back-side width of the weld pool.

To further verify the correlation between joint penetration and sensor output, the experimental data in Figs. 5 and 6 are plotted as \( \{v_e, w_b\} \) pair in Fig. 7. It can be seen that if the sensor output is used to predict the back-side width of the weld pool based on the following equation:

\[
w_b = 0.55v_e + 0.8 \quad (2V \leq v_e \leq 6.5V)
\]
where \( v_e \) and \( w_b \) are measured by volt and mm respectively, the maximum error is approximately \( \pm 0.5 \text{ mm} \). Such an accuracy should be sufficient for weld penetration control in most applications.

**Process Diagnosis**

In addition to the joint penetration, the proposed sensor may also monitor the collapse of the keyhole. Fig. 8 shows an experiment in which keyhole collapse occurred. During the initial period, the output from the sensor was zero. The weld penetration corresponding to this period is partial. When the current increased to 70A from 65 A, the sensor output rose to a significant level which indicated the establishment of the keyhole. However, the back-side width of the weld pool then decreased gradually due to process disturbances. At approximately \( t = 20 \text{s} \), the output of the sensor suddenly oscillated between zero and 2 V. The keyhole oscillated between collapsing and opening. When the current was increased to 75 A, the output of the sensor became stable and so did the keyhole. At \( t = 42 \text{s} \), the current was decreased to 65 A and the keyhole closed. The resultant output of the sensor was zero. It can be seen that, when the keyhole closes, no plasma jet exits from the keyhole. The output of the sensor is zero. Hence, the sensor output provides information to monitor the existence of the keyhole.

Similarly, if burn-through occurs, a strong plasma jet will exit from the workpiece. The resultant output of the sensor will be much higher than in a normal keyhole process. In the experiment shown in Fig. 9, the welding speed was decreased from 2.7 mm/s to 0.8 mm/s at \( t = 35 \text{s} \). Before the change, the output of the sensor was approximately 3.5 V. After the change, the output of the sensor suddenly increased to above 8 V. Burn-through occurred immediately. Hence, the output of the sensor provides information to monitor the burn-through.
Sensor Fundamentals

According to the plasma physics, in an ionized plasma, the mean thermal velocities of the electrons and the mean positively-charged ions are determined by their temperatures as well as the Boltzmann’s constant (Ref. 16):

\[
V_e = \left( \frac{8kT_e}{\pi m_e} \right)^{1/2}
\]  

(2)

\[
V_i = \left( \frac{8kT_i}{\pi m_i} \right)^{1/2}
\]  

(3)

where \( k \) is Boltzmann’s constant, \( V_e, T_e, m_e \) the velocity, temperature, and mass of the electron, and \( V_i, T_i, m_i \) the velocity, temperature, and mass of the ion. The ratio between \( V_e \) and \( V_i \) is therefore

\[
\frac{V_e}{V_i} = (m_i / m_e)^{1/2} (T_e / T_i)^{1/2}
\]  

(4)

Because the lightest specie of the positive ions is over 2000 times heavier than the electron (Ref. 17) and the temperatures of the electrons and ions are approximately the same (as the temperature of the plasma), the above velocity ratio

\[
\frac{V_e}{V_i} = (m_i / m_e)^{1/2} \leq \sqrt{2000} = 44
\]  

(5)

This implies that in the efflux plasma, the mean velocity of the electrons is at least 40 times higher than that of the ions.

Based on the results in (Ref. 17), the difference between the velocities of the negatively-charged electrons and the positively-charged ions results in a space charge being established around the plasma until the opposing filed due to this space charge retards approaching electrons sufficiently for a charge balance to occur. However, such a charge balance would never occur if the stream of the (new) efflux plasma is maintained. Hence, as long as the keyhole exists such that the continuous stream of the efflux plasma is kept, the efflux plasma caused space charge maintains a potential \( v_0 \) between
workpiece and detection plate. As derived in (Refs. 17, 18), such potential can be determined by the following equation:

\[
v_0 \approx \frac{2.5kT_p}{e}
\]

(6)

where \(e\) is the charge of the electron, and \(T_p\) is the temperature of the efflux plasma.

In the equivalent circuit of the sensor shown in Fig. 10, a voltage source \(v_0\) and an interval resistor \(R_0\) are used to approximate the efflux plasma. The voltage drop on the output resistor \(R_v\), denoted as \(v_v\), is measured as the output of the sensor. (Note that the potential of the detection plate is negative in relation to the workpiece ground.) Disregarding the capacitor which is used to filter the noise, the sensor’s model can be written as:

\[
v_v = \frac{v_0 R_e}{R_0 + R_v}
\]

(7)

In Eq. (7), \(R_v\) is exactly known, \(v_v\) is the measurement, and \(R_0\) and \(v_0\) are unknown. The following qualitative analysis will show that \(v_0\) can be used as the critical parameter for determining joint penetration.

The essence of the proposed method lies in a possible relationship between joint penetration, measured by the back-side width of the weld pool, and the residual energy of the plasma jet, i.e. the energy of the efflux plasma. In fact, for keyhole PAW, the width of the weld pool varies slightly along the thickness direction of the workpiece. This suggests that the radial-axis heat transfer from the plasma jet, rather than the heat transfer along the thickness direction, is dominant in the workpiece. This implies that the width of the weld pool in a particular layer during keyhole PAW may be mainly determined by the heat absorbed in this layer from the plasma jet. On the other hand, the heat transfer rate, thus the heat absorption, in general increases when the local temperature gradient between the
heating source and the object being heated increases. When the temperature of the object being heated is insignificant in comparison with the temperature of the heating source, the local temperature gradient is determined by the temperature of the heating source. Hence, the residual energy of the efflux plasma controls the local temperature gradient, thus the heat absorption and the width of the weld pool, on the bottom layer of the workpiece. Such residual energy may be used to determine the back-side width of the weld pool:

\[ w_b = f(Q_r) \]  

(8)

where \( Q_r \) denotes the residual thermal energy of the plasma jet. Further, the thermal energy of the efflux plasma can be determined by its temperature (Ref. 19):

\[ Q \propto kT_p \]  

(9)

On the other hand, the temperature determines the voltage of the space charge \( v_0 \), equation (6). Hence,

\[ w_b = g(v_0) \]  

(10)

That is, the back-side width of the weld pool can be determined by the voltage of the space charge of the efflux plasma. We should therefore determine \( v_0 \) based on the measurement \( v_c \) to monitor the joint penetration.

Eq. (7) gives

\[ v_0 = \frac{R_0 + R_c}{R_c} v_c \]  

(11)

It can be seen that in order to calculate \( v_0 \) based on Eq. (11), \( R_0 \) must be known. The electrical resistivity of encounters between charged particles (Ref. 20) can be expressed as:

\[ \eta = 6.53 \times 10^3 \frac{\ln \Lambda}{T_p^{3/2}} \text{ ohm/cm} \]  

(12)
where $\ln \Lambda$ is a constant determined by the electron density of the plasma and the plasma temperature. Because $R_0$ is determined by both the measurement height $h$ and the electrical resistivity $\eta$, $R_0$ varies with the temperature of the plasma.

To learn more about $R_0$, the authors have conducted experiments to determine it. Suppose two measurements, $v_e^{(1)}$ and $v_e^{(2)}$, are available. If they are caused by the same $v_0$ under the same $R_0$, but two different $R_e$ ($R_e^{(1)}$ and $R_e^{(2)}$), we will have

$$
\begin{align*}
\begin{cases}
    v_0 = \frac{R_0 + R_e^{(1)}}{R_e^{(1)}} v_e^{(1)} \\
    v_0 = \frac{R_0 + R_e^{(2)}}{R_e^{(2)}} v_e^{(2)}
\end{cases}
\end{align*}
$$

(13)

It is evident that the two unknown parameters $v_0$ and $R_0$ can be exactly determined from equation system (13). Hence, if we can accurately control the welding parameters and conditions to perform keyhole plasma arc welding, we will be able to repeat the time-varying processes of $v_0$ and $R_0$: $v_0(1), v_0(2), ..., v_0(N)$ and $R_0(1), R_0(2), ..., R_0(N)$. When the time-varying processes of $v_0$ and $R_0$ are repeated, we can use different $R_e$ ($R_e^{(1)}$ and $R_e^{(2)}$); thus the respective measurements will be $v_e^{(1)}(1), v_e^{(1)}(2), ..., v_e^{(1)}(N)$ and $v_e^{(2)}(1), v_e^{(2)}(2), ..., v_e^{(2)}(N)$:

$$
\begin{align*}
\begin{cases}
    v_0(i) = \frac{R_0(i) + R_e^{(1)}}{R_e^{(1)}} v_e^{(1)}(i) \\
    v_0(i) = \frac{R_0(i) + R_e^{(2)}}{R_e^{(2)}} v_e^{(2)}(i)
\end{cases}
\end{align*}
$$

(i = 1, 2, ..., N)

(14)

Hence, each pair of $\{v_0(i), R_0(i)\} (i = 1, 2, ..., N)$ can be determined from equation system (14).

Based on the above principle, two different $R_e$ s, 10 K and 350 K, were used to conduct experiments using the exact the same conditions and sequence of welding parameters. The experimental data are
shown in Fig. 11. Fig. 12 plots the resultant \( v_0(1), v_0(2), ..., v_0(N) \) and \( R_0(1), R_0(2), ..., R_0(N) \). It can be seen that \( R_0 \) significantly varies with welding conditions and parameters.

The variation of \( R_0 \) complicates the determination of \( v_0 \) from the measurement \( v_e \). Fig. 12 shows \( 10k\Omega \leq R_0 \leq 80k\Omega \). If we choose a very large \( R_e \geq R_0 \),

\[
v_0 \approx \frac{R_0^* + R_e}{R_e} v_e
\]

where \( R_0^* = 45k\Omega \) is an estimate of \( R_0 \). In this study, \( R_e = 360k\Omega \), the maximum error is \( \pm35/360 = \pm10\% \). Hence, \( R_e = 360k\Omega \) can ensure that \( v_0 \) be determined based on \( v_e \) with an acceptable accuracy. Because of this mapping relationship between \( v_0 \) and \( v_e \), it is reasonable to determine the weld penetration based on \( v_e \).

**Conclusions**

Efflux plasma charge sensor technology for joint penetration has been developed for the keyhole plasma arc welding process. To understand the proposed sensor, efforts have been made to analyze the sensing fundamentals. Experimental results showed that joint penetration can be monitored by the proposed sensor with \( \pm0.5 \) mm accuracy. The proposed sensor may also be used to monitor the existence of the keyhole and the burn-through.

**Acknowledgement**

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**References**

Fig. 1 Keyhole in plasma arc welding.
Fig. 2 Typical backing bar for keyhole plasma arc welding [11].

Fig. 3 Integrated sensor and fixture.
Fig. 4 Schematic of clamping apparatus.
Fig. 5 Penetration prediction experiment 1. Travel speed: 2.5mm/s.
(a) Sensor output and welding current.
(b) Back-side width of weld pool.
(c) Weld back-side photo.
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(a) Sensor output and welding parameters.
(b) Back-side width of weld pool.
(c) Weld back-side photo.
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Fig. 10 Sensor equivalent circuit.

Fig. 11 Sensor output with different load resistors.
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