Article ID: 1003 - 6326(2004)01 - 0116 - 05

Closed-loop control of weld penetration in keyhole plasma arc welding①

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Abstract: To improve the penetrating ability and the welding quality of keyhole plasma arc welding, a novel penetration closed-loop control system was established. In the system, welding current and plasma gas flow rate were selected as adjusting variables. The wavelet method was used to detect penetration status from welding arc voltage in real-time. The control strategy of one-keyhole-per-pulse was adapted to fulfill stable and high quality welding process. Experimental results show that the developed system can apparently increase the penetrating force of plasma arc and keyhole plasma arc welding is realized successfully in stainless steel with 10 mm in thickness. Moreover, the disturbances of gradual change and break change from 3 mm to 6 mm in thickness are come over due to the good response property of the developed system.

Key words: plasma arc welding; penetrating force; plasma arc; penetration; closed-loop control

CLC number: TG 456.2 **Document code:** A

1 INTRODUCTION

Plasma arc welding (PAW) has lower costs and higher productivity than other high-energy welding processes. Due to the keyhole effect, keyhole PAW has many advantages, and has been widely used in the welding of important structures and parts, especially in aerospace industry[1].

Many investigations have been done in order to improve the penetrating force of plasma arc and realize stable and high quality keyhole PAW. Ameliorated nozzle or magnetic compressing and pneumatic compressing methods have been used to enhance the penetrating ability of plasma arc[2-4]. Relations between welding parameters (such as welding current, welding voltage, rate of plasma gas flow) and weld quality have been investigated, optimum combinations of welding parameters have been established to obtain sound weld seam[5]. Signals of arc voltage, sound, efflux plasma charge, arc light radiate intensity, keyhole image and so on have been measured and analyzed in order to detect and control the welding quality of keyhole PAW in real-time[6-15]. But all the above-mentioned methods could not simultaneously give attention to the respects of increasing penetrating force of plasma arc, establishing and maintaining stable keyhole welding process and acquiring sound weld formation on both front and back sides, especially in the PAW process of work piece thicker than 6 mm.

A penetration closed-loop control system, taking welding current and plasma gas flow rate as the adjusting variables, has been developed in this study. The wavelet method has been used to detect the keyhole status from welding arc voltage correctly in real-time. Through synergic control of welding current and plasma gas flow, the one-keyhole-per-pulse welding process has been realized successfully. The experimental results show that the developed system can not only apparently increase the penetrating force of plasma arc, but also have good response property to guarantee the stability of keyhole PAW.

2 PENETRATION CLOSED-LOOP CONTROL SYSTEM

As shown in Fig. 1, the penetration closed-loop control system is composed of operating unit, signal sampling unit, welding pool system, hardware of the computer and software to fulfill one-keyhole-per-pulse control strategy. The operating unit can do pulsed adjustment of welding current and plasma gas flow at the same time. The plasma arc is started with a high frequency arc exciter. The signal sampling unit is used to acquire arc voltage signal in real-time for the detection of keyhole status. The pulsed welding current control is realized simply by modulating the output of arc welding power source. The pulsed plasma gas flow control is accomplished by a special plasma gas flow route, which includes a constant flow route and a pulse flow route. According to the detected

① **Foundation item:** Project(59975050) supported by the National Natural Science Foundation of China; project supported by the Key Laboratory Foundation of National Defense Science and Technology

Received date: 2003 - 05 - 18; **Accepted date:** 2003 - 08 - 10

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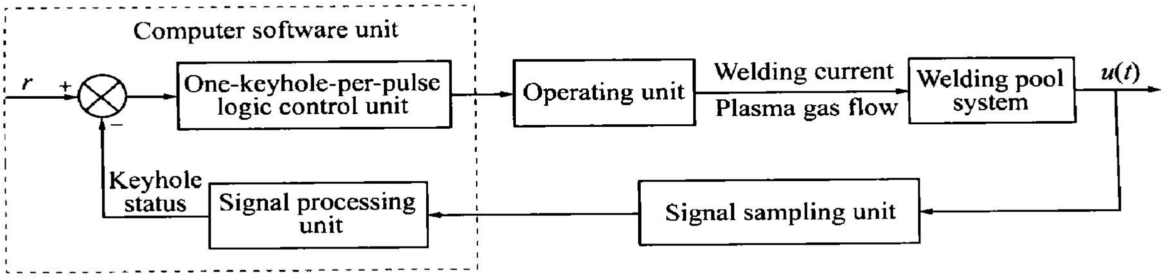

Fig. 1 Schematic diagram of penetration closed-loop control system for PAW

keyhole status of weld pool, only the pulsed plasma gas flow route is adjusted, while the constant flow route is kept stable.

3 DETECTION OF KEYHOLE STATUS

To detect out keyhole status fast and correctly is the sticking point to carry out closed-loop control of weld in keyhole PAW. The wavelet transform method has been selected to detect keyhole status directly from arc voltage signal, on condition that reasonable wavelet scale and wavelet packed base have been utilized[16].

Wavelet packed base of Symlets2 has been chosen to process arc voltage signal $u(t)$, the wavelet transform of $u(t)$ can be expressed as

$$WT_u(a, k) = \frac{T_s}{\sqrt{a}} \sum u(n)\, \phi\left(\frac{n-k}{a}\right) \qquad (1)$$

where $WT_u(a, k)$ is a dimensionless value of wavelet transform, T_s is the sampling period (1/30 ms in this paper), $u(n)$ is the discrete sampled value of signal $u(t)$, n is the sampling number, a is the scale factor, k is the position factor, and ϕ is the mother wavelet.

Fig. 2 shows the wavelet transforming results of arc voltage signal of keyhole PAW. It can be found that there is a step rising in the reference light signal from backside as soon as the keyhole is formed. Corresponding to this moment, the wavelet transform result of voltage signal $WT_u(430, k)$ will generate a pulse signal. Similarly, there is a step dropping in the reference light signal when the keyhole is closed and the wavelet transform result of voltage signal $WT_u(55, k)$ will generate another pulse signal. Further experiments show that this keyhole status detection method has high veracity and can provide reliable keyhole status signal for penetration feedback control of keyhole PAW.

4 SELECTION OF CONTROL VARIABLES

In order to obtain enough penetrating force to form and maintain stable keyhole, reasonable control variables and their adjusting range must be examined. Independently increasing welding current or plasma

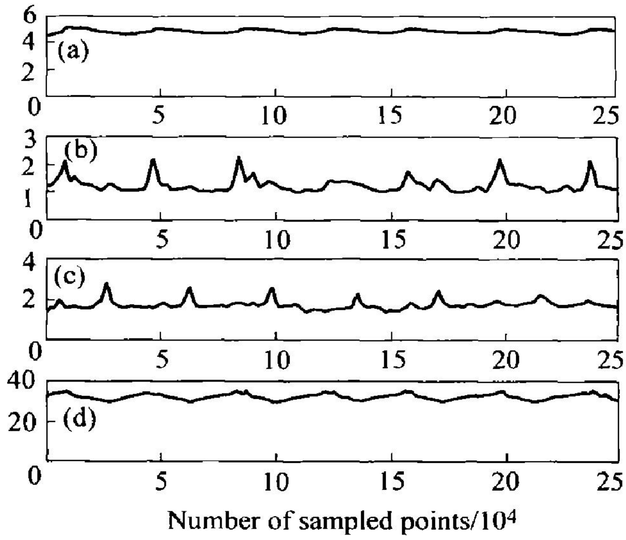

Fig. 2 Wavelet transforming results of arc voltage
(a) —Reference light signal (V);
(b) —Keyhole formation signal $WT_u(430, k)$ (dimensionless);
(c) —Keyhole closure signal $WT_u(55, k)$ (dimensionless);
(d) —Arc voltage signal(V)

gas flow rate may enhance penetrating force of plasma arc to a certain extent, but the energy density of plasma arc and the mechanical penetrating force are only improved respectively, the penetrating force of plasma arc is not large enough to carry out keyhole PAW on thicker work piece. Investigations have been done on 3 − 6 mm thick stainless work pieces with the plasma flow gas control, welding current control and synergic control of them respectively.

Fig. 3 illustrates the experimental results of different control strategies. It is found that the synergic control method can simultaneously improve the energy density of plasma arc and the mechanical penetrating force. With the same welding current or plasma gas flow rate, the higher penetrating force is achieved using the synergic control method than the single variable control. So that the synergic control method is more adaptive to carry out keyhole PAW on thicker work piece.

In the case of weld seam formation, when the work piece becomes more and more thick, the increase of welding current makes the width of front

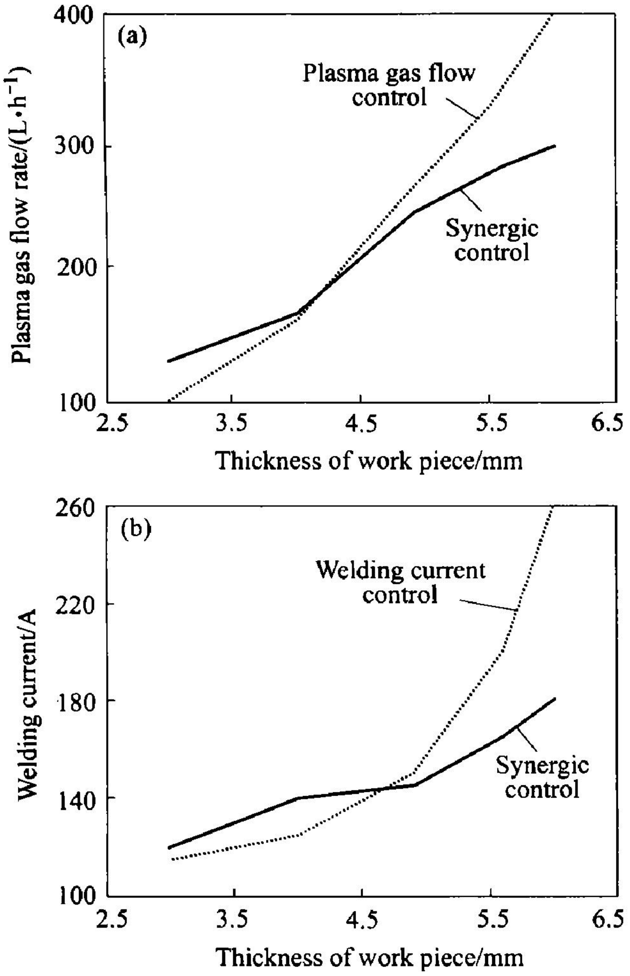

Fig. 3 Comparison of plasma gas flow control, welding current control and synergic control

side of weld seam apparently increased; the increase of plasma gas flow rate has slight effect on the width of front side, but it has large effect on arc stiffness, so that the width of back side of weld seam will be increased. With the synergic control method, to acquire same arc penetrating force in thicker work piece, the welding current and plasma gas flow rate are lower than the single variable control, so that the formation of both side of weld seam is slightly changed, uniform and sound weld seam is obtained.

Therefore, it can be concluded that the synergic control method possesses the advantages of both welding current control and plasma gas flow control, effectively enhances the arc penetrating force and gives a reliable approach to attain stable keyhole PAW process and high quality weld seam.

5 ONE-KEYHOLE-PER-PULSE CONTROL

The experimental results show that during the long time keyhole PAW process, the keyhole can not maintain stable due to lots of disturbances. Defects of excessive penetration and cutting through may appear with the enlargement of keyhole size, or there can not form keyhole due to the inadequate penetrating force of plasma arc. Therefore, when the large penetrating force is adopted to carry out PAW on thicker work piece, the keyhole can be formed and sustain stable only at a short time and a limited parameter range.

For these reasons, the one-keyhole-per-pulse control strategy has been designed to accomplish stable keyhole PAW on thicker work piece. Here, the previous long time keyhole penetrating process is divided to a series of continuous stable keyhole penetrating. The control strategy is as follows: a large pulsed current is adopted to form keyhole at first, then the welding current is decreased to base level to let the weld pool cool down and solidify, as soon as the keyhole is closed the welding current will be increased to pulse level to begin a new one-keyhole-per-pulse cycle. If the penetrating force of plasma arc is large enough to form keyhole and the system designed to carry out one-keyhole-per-pulse control strategy has good response property to come over the thermal inertia of PAW process, small and continuously connected keyholes are generated to form uniform and high quality weld seam, as shown in Fig. 4.

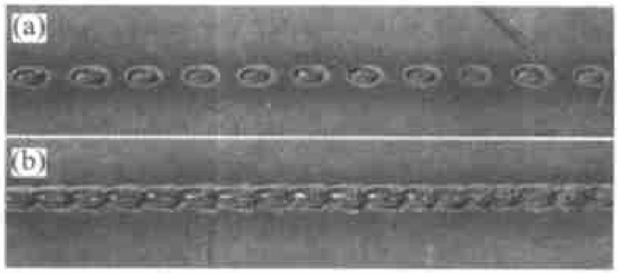

Fig. 4 Back side formation with one-keyhole-per-pulse control strategy
(a) —Back side formation of incontinuous keyhole PAW;
(b) —Back side formation of continuous keyhole PAW

To effectively control the welding current and plasma gas flow rate and realize one-keyhole-per-pulse control, Visual C^{++} 6.0 has been used to program the real-time keyhole status detection and penetration control software. The flow chart of one-keyhole-per-pulse strategy is shown as Fig. 5. The status of weld pool is detected at first to judge whether the keyhole is formed, so as to decide whether the weld current should be increased or kept in constant. If there is non-keyhole, the amplitude of pulsed current should be increased. When the keyhole is generated, the maintenance time of keyhole is compared with the predefined value T. If the maintenance time is longer than T, the amplitude of the pulsed current should be decreased. Otherwise, keep the parameters of pulsed current unchanged. The pulsed control of plas-

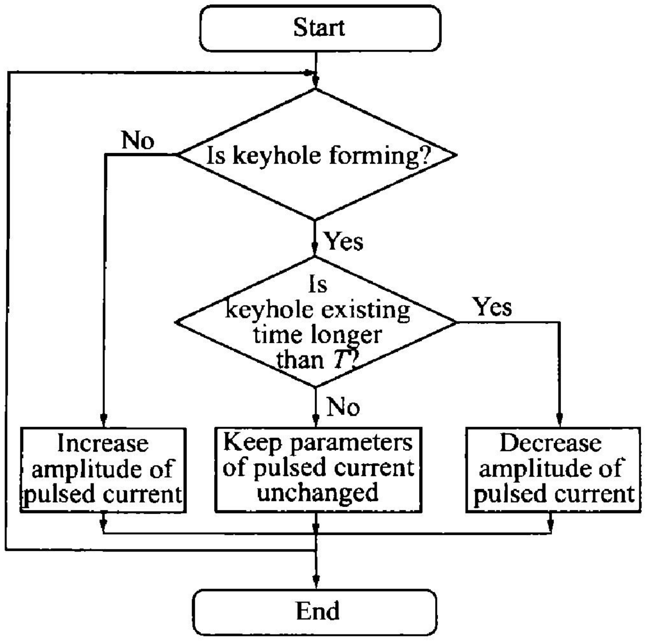

Fig. 5 Flow chart of one-keyhole-per-pulse control strategy

ma gas flow is carried out through opening or closing the pulse flow route of plasma gas after the welding current has been increased or decreased. Both the amplitude and frequency of pulsed current are adjustable in real-time, so that the one-keyhole-per-pulse control strategy is carried out successfully (as shown as Fig. 4).

6 EXPERIMENTS AND DISCUSSIONS

To testify the performance of developed penetration closed-loop control system for keyhole plasma arc welding, three types of typical specimens have been designed to study the penetrating ability of plasma arc, adaptability of stable keyhole PAW and fast response ability of the system.

6.1 Test of plasma arc penetrating force

The experimental result reveals that the penetrating force of plasma arc has been apparently increased and the keyhole plasma arc welding has succeeded in 10 mm thick stainless steel (shown as Fig. 6). The welding parameters are as follows: base current 150 A, peak current 180 A, pulse frequency 6 Hz, duty ratio 60%, rate of plasma gas flow 450 L/h, welding speed 23 cm/min, rate of shielded gas (Ar) flow 1 200 L/h, the distance between nozzle and work piece 6.0 mm.

6.2 Test of adaptability of stable keyhole PAW

For the stainless work piece, the thickness to carry out keyhole PAW gradually changed from 3 mm to 6 mm (shown as Fig. 7). In order to generate penetrated keyhole and keep the welding arc stable, the heat input and the mechanical digging force must be enhanced to strengthen the penetrating force, other-

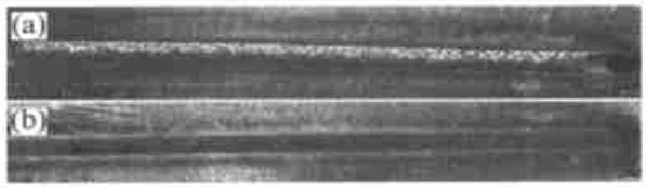

Fig. 6 Weld seam formation of 10 mm thick stainless work piece
(a) —Front side formation;
(b) —Back side formation

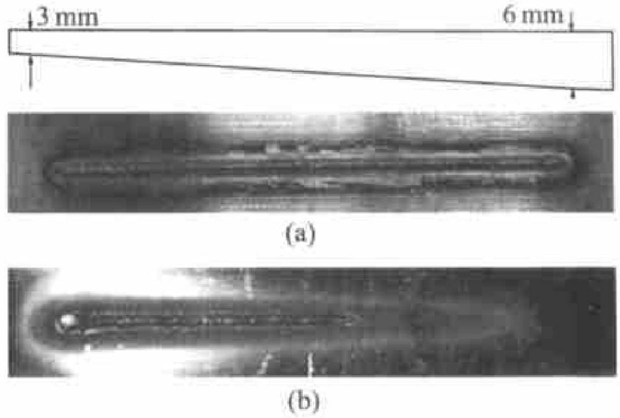

Fig. 7 Back side formation thickness gradually changed work piece
(a) —With penetration synergic control method;
(b) —Without penetration closed-loop control

wise the keyhole will slowly decrease till disappear. The experimental results show that the closed-loop control system can automatically adapt the change of thickness through adjusting pulse parameters in real-time, so that continuous and stable keyholes are achieved during the process of thickness change. The system has good adaptability and the application range of stable keyhole PAW has been enlarged. The welding parameters of Fig. 7 is as follows: welding speed is 260 mm/min, rate of shielded gas (Ar) flow is 1 200 L/h, the distance between nozzle and work piece is 6.0 mm, welding current is adjusted within 140 – 200 A, rate of plasma gas flow is within 150 – 250 L/h.

6.3 Test of fast response ability of system

In order to testify system's fast response ability to break change of thickness, experiments have been done on stainless specimen as shown in Fig. 8. The welding parameters are as follows: welding speed is 260 mm/min, flow speed of shielded gas (Ar) is 1 200 L/h, the distance between nozzle and work piece is 6.0 mm, welding current is adjusted within 140 – 200 A, rate of plasma gas flow is within 150 – 250 L/h. It is shown that during the process of thickness suddenly changed from 6 mm to 3 mm, or from 3 mm to 6 mm, the closed-loop control system always has fast response ability, the arc penetrating force can be instantaneously regulated to complete keyhole PAW. The process of keyhole

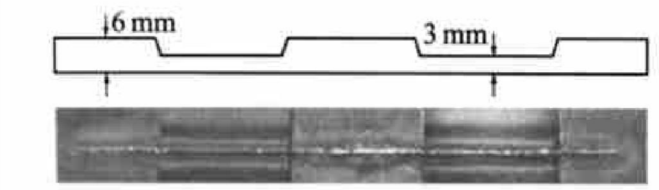

Fig. 8 Backside formation of grooved work piece

PAW is stable and the backside formation of weld seam is uniform.

7 CONCLUSIONS

1) A penetration closed-loop control system taking welding current and plasma gas flow control as adjusting variables has been established.

2) The keyhole status of weld pool can be detected from arc voltage signal fast and correctly in real-time with the wavelet transform method, which lays a foundation for the closed-loop control of weld penetration in keyhole PAW.

3) The one-keyhole-per-pulse welding process has been successfully realized with the synergic control of welding current and plasma gas flow rate.

4) The experimental results show that with the developed system the penetrating force of plasma arc has been increased apparently, the disturbances of gradual change and break change from 3 mm to 6 mm in thickness have been come over due to the system's good response property, and continuous, stable and reliable keyhole PAW on thicker work piece could be carried out.

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(Edited by YUAN Sai-qian)