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Correlation of keyhole exit deviation distance and weld pool thermo-state in plasma arc welding process

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ABSTRACT

Keyhole behavior is believed to determine the process stability in keyhole plasma arc welding, and thermal state of weld pool is one of the most critical factors to affect keyhole stability. To evaluate the correlation of the keyhole behavior to the thermal state of weld pool, vision observation system is employed to image the keyhole exit. Keyhole exit deviation distance is proposed to characterize the thermal state of weld pool. In the normal fully penetrated keyhole welding process, backside keyhole exit deviates a distance away from the torch axis. When the thermal energy in the weld pool and keyhole is increased by increasing the welding current, decreasing the welding speed or slowing the heat dissipation speed, the keyhole exit deviation distance decreases; when the weld pool thermal energy is decreased, the deviation distance increases. Dynamic performance of the new proposed thermal state factor is sound. Correlation mechanism between the keyhole exit deviation distance and the thermal state is established in view of the dependent relationship of the keyhole leading wall (leading melting side) to the keyhole exit deviation distance. The observation results lay solid foundation for deeply understanding of the keyhole behavior and further control of the keyhole process in plasma arc welding process.

1. Introduction

Plasma arc welding (PAW) process has high penetration ability by using a highly constricted arc as the energy source [1,2]. During the PAW process, the plasma arc jet hits the weld pool surface with high pressure and the liquid metal is displaced away, a keyhole forms in the weld pool. When the heat input is high enough, the workpiece is melted through and the keyhole is fully penetrated [3]. The keyhole state highly correlates to the heat and mass transfer behavior in the weld pool. In a normal stable keyhole PAW welding process, the thermal field and the pressure field in keyhole and weld pool both get quasi balanced, respectively. If the heat input is increased or decreased, the transient thermal field is out of stable balance before the "keyhole-weld pool" system gets the new quasi-steady state [4]. In other words, if the weld pool changes its thermal state, the keyhole should change its state parameters as a response. It is a well-known fact that, in keyhole PAW process, the keyhole will close when the weld pool is less heated and will collapse when the weld pool is over heated, margins from the stable keyhole to closure or to collapse are narrow [5,6]. So it is of great significance to find a keyhole parameter to characterize the thermal state of weld pool in PAW.

Many kinds of keyhole state parameter have been proposed and studied in PAW. For example, acoustic signature [7–9], in-tube shielding gas pressure [10], light radiation [11] and discharge voltage [12] of the back-side efflux plasma, electrical potential of the front-side plasma cloud [13]. All of these sensing methods, however, set the focus to reflect the keyhole state transformation from fully-penetration (open) to partially-penetration (close), or reverse. The indirect signals are hard to reflect the keyhole thermal behavior. Keyhole image can directly display the welding process appearance, by using vision sensors, the front side keyhole and weld pool are imaged [9,14]. But, it is difficult to capture the complete front-side keyhole image and weld pool boundary because of the very short standoff distance of the plasma torch compared to its large diameter. An ultra-high shutter speed camera with laser illumination has been used to simultaneously capture the image of backside keyhole and weld pool [15]. It was found that, once the fully penetrated keyhole was established, the keyhole width did not change when the welding current increases or the welding speed decreases. In other words, the keyhole width is not sensitive

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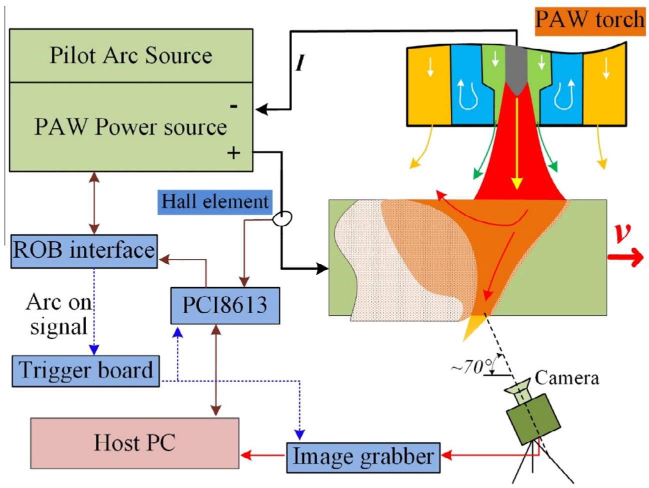

Fig. 1. Observation system.

Table 1
Chemical composition of AISI 304 (wt.%).

C	Si	Mn	P	S	Cr	Ni
0.07	0.87	1.79	0.03	0.02	18.92	9.16

Table 2
Welding process parameters.

Test No.	Plate thickness (mm)	Welding current (A)	Welding speed (mm/min)	Plasma gas flow rate (L/min)
1	8.0	180	140–100	3.0
2	6.0	140	100–150	2.8
3	8.0	Pulse*	140	3.0
4	6.0	150	120	2.8
5	8.0	180	100:10:160	2.8

* In the pulse current, peak current is 185 A, base current is 85 A, duty percent is about 70%, frequency is 2.0 Hz.

to the thermal state changing in the weld pool or the process stability [16]. The authors did the further research work, by using a filter glass to eliminate the illumination interference of the efflux plasma, a cost-effective vision system has been developed to capture the backside keyhole image [17,18]. Keyhole exit size parameters [18], including the keyhole length along the welding direction and the keyhole width perpendicular to the welding direction, and the keyhole positional parameter [19], i.e., keyhole exit deviation distance, are extracted from the keyhole image sequence. It is first found that the keyhole deviation distance is more sensitive to the penetration ability of the weld arc than the keyhole dimensional size parameters [19]. The backside keyhole exit geometry was employed to monitor the weld joint penetration state during VPPAW welding process [20,21]. The temperature field surrounding the backside keyhole is also monitored by an infrared camera system [22]. The weld pool was extracted from the infrared camera image. It was found that the weld pool area was enlarged as the welding current was increased. However, the imaging speed of the used infrared camera is too low and the developed infrared image process algorithm is relatively complicated, it is so expensive and less-comfortable to use such a large volume infrared camera as the feedback sensor to control the PAW welding process.

In this research, an industrial CCD (Charge Coupled Device) camera is used to monitor the keyhole PAW welding process, keyhole parameters are extracted. Experiments are carried out on stainless steel plates to observe the keyhole dynamic behavior when the heat input from the arc or the heat conduction property of the workpiece is changed. The observation results are carefully analyzed to reflect the correlation mechanism between the keyhole exit parameter to the thermal state of weld pool. The results lay foundation for the understanding the thermo-dynamic behavior of the keyhole and set a basic knowledge for the further control algorithm design in the keyhole PAW process.

2. Experimental set-up and procedure

2.1. Experimental setup

The experimental system setup is shown in Fig. 1. The welding system is produced by FRONIUS Company, it consists of a digital TS 5000 PAW power source, plasma generator model, PMW 350 welding torch, and a coolant box. The welding power works on the constant current (C–C) model. The welding current is controlled by the host computer via the PCI 8613 (made by Beijing Art Technology Company) card and the communication interface (ROB interface). The welding current is captured by the data acquisition system; the keyhole image is monitored and acquired by a back-side mounted CCD camera (model AM1101A made by Beijing JoinHope Image Technology Company) with a filter glass group (central wavelength is 655 nm, bandwidth is 40 nm, and transparency is 85%) to eliminated the illumination interference of the efflux plasma. The CCD camera captures the keyhole mage at 48 fps with the image size of 300 * 300. The data acquisition process and the image acquisition process are trigged to start at the instant of the transfer arc (welding arc) burning. The workpiece is

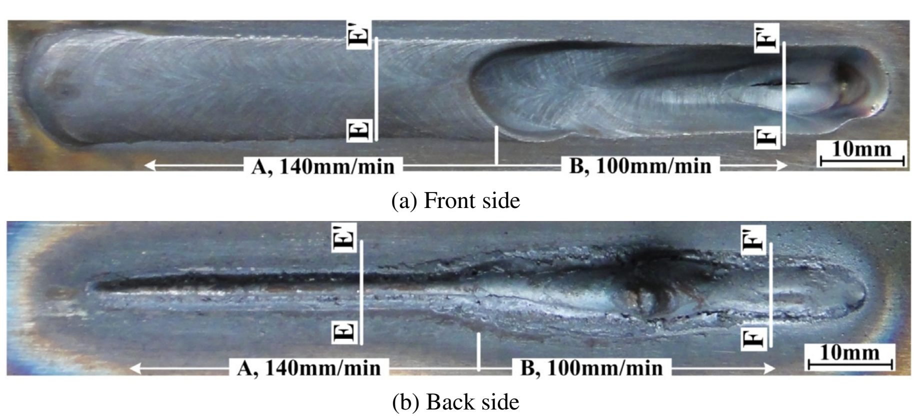

Fig. 2. Weld surfaces in Test 1.