Numerical simulation and vision-based sensing of key-holing process in plasma arc welding†

LIU Zuming*, WANG Xiaojie*, WU Chuan Song*

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1. Introduction

To overcome the shortcomings of conventional plasma arc welding (PAW), the 'controlled pulse key-holing' strategy is proposed and the waveform-controlled keyhole PAW experiment system is developed [1]. During the waveform-controlled PAW process, the key-holing process takes place, i.e., keyhole establishing, expanding, sustaining, contracting and closing, in each pulse cycle. Sensing and describing the keyhole shape and geometry with proper methods are of great significance for optimizing the welding process parameters and enhancing the stability of weld quality [2]. In this study, the key-holing behaviors are visualized through both numerical simulation and experimental measurement.

2. Experimental measurement

The developed waveform-controlled PAW experimental system consists of the computer, PAW machine, data acquisition unit, welding current sensor, efflux plasma voltage sensor and CCD camera. The computer is the central unit for adjusting welding current, and sampling the signals of welding current, efflux plasma voltage and keyhole images. On one hand, a measuring bar mounted underneath the workpiece to be welded and kept insulated electrically is employed to detect the efflux plasma voltage when the keyhole is established. On the other hand, a CCD camera is aimed at the weld pool from the backside to capture the keyhole images.

Figure 1 shows the measured welding current and efflux plasma voltage signals. At the dropping stage of welding current from the peak level to the base level, two sub-stages of current decreasing with different slopes are added. The signal of the efflux plasma voltage is around zero before the keyhole is established, while it exceeds a certain value after the keyhole is established. It is clear that each pulse produces one keyhole during the welding process. **Figure 2** is the images of both the plasma arc and the efflux plasma captured from a side view. **Figure 3** shows an image of keyhole from the backside of the workpiece.

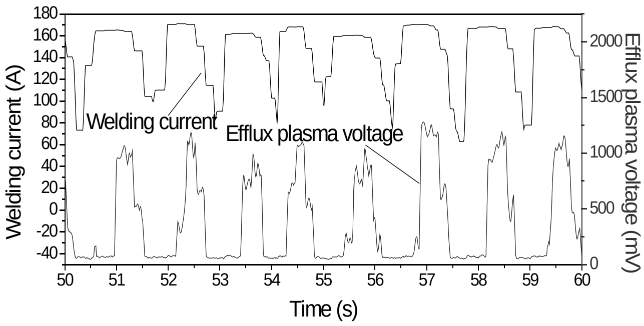

Fig.1 The measured welding current and efflux plasma voltage

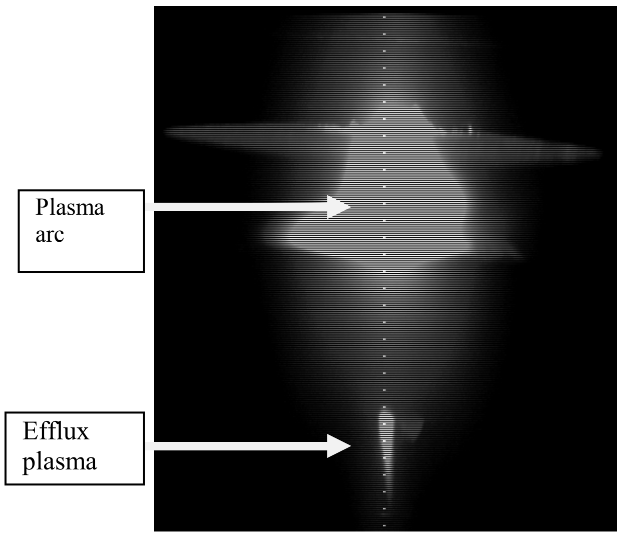

Fig.2 The captured images of both the plasma arc and the efflux plasma

3. Simulation of keyhole shape and size

The modeling and simulation of keyhole behaviors in transient waveform-controlled PAW process are very complicated. As a first step, the level-set method is used to track the keyhole boundary in stationary continuous-current PAW process [3]. As shown in **Fig. 4**, the level-set function φ is defined as a signed distance function $\varphi(\overline{x},t)=\pm d$, where d is the actual distance from the keyhole boundary,

† Received on 30 September 2010
* Institute of Materials Joining, Shandong University, China

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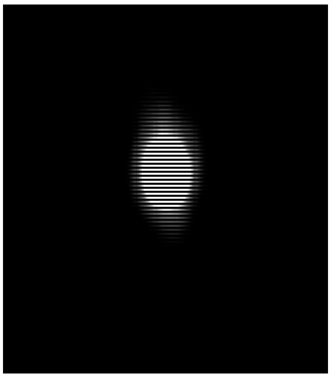

Fig.3 The captured image of keyhole at backside

$\overline{X}$ is the space variables, and t is time. The level-set function has the value of 0 on the keyhole boundary. The plus (minus) sign denotes the outside (inside) of the keyhole boundary. By using the level-set method the keyhole boundary tracking problem can be transformed into a partial differential equation, which can be numerically solved with other governing equations. The general form of the level-set equation is

$$\frac{\partial \varphi}{\partial t} + F\left|\nabla \varphi\right| = 0 \qquad (1)$$

where F is the speed function in the normal direction of the keyhole boundary. To get the function φ, the fluid flow in both the plasma and weld pool must be known. The combined volumetric heat source model is used to numerically analyze the transient temperature field and then to determine the weld pool geometry. The algorithm of level-set theory combined with the transient thermal conduction model is used to determine the evolution of both keyhole and weld pool geometry at different time steps. **Figure 5** demonstrates the simulated keyhole profile during stationary PAW under following conditions: stainless steel plate of 6-mm thickness, welding current 180 A, arc voltage 24.5 V, plasma flow rate 3.0 L/min, shield flow rate 20.0 L/min, torch standoff distance 6 mm. It is found that a complete keyhole is established at 2.5 s for current levels of 180 A. The numerical analysis of keyhole formation is verified by measuring the efflux plasma voltage signals at the moment of key establishing.

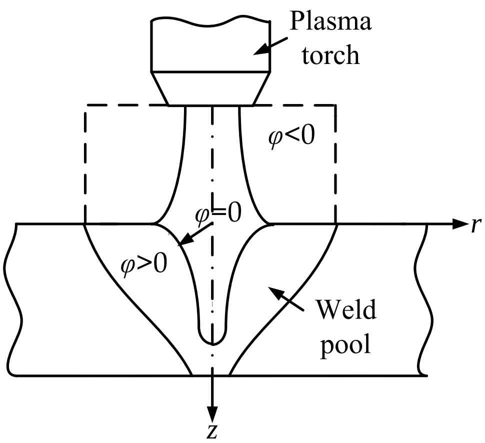

Fig.4 The definition of level-set function

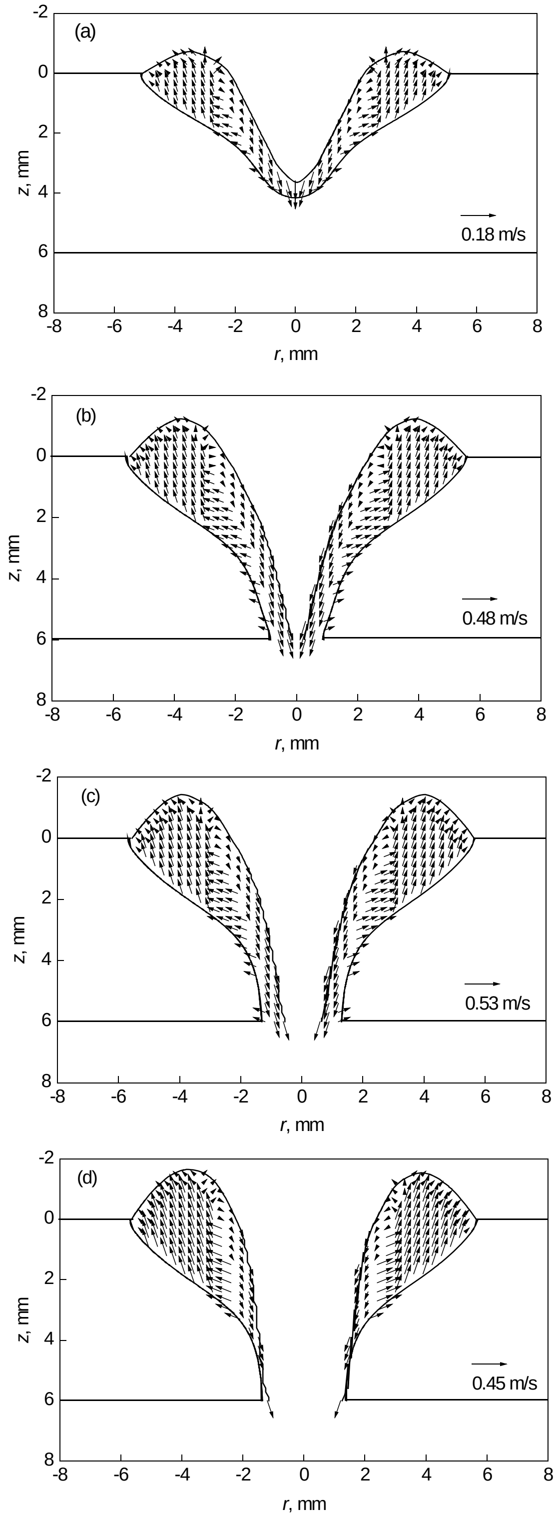

Fig.5 Keyhole profiles in stationary PAW at (a) t=1.5 s, (b) t=2.5 s, (c) t=2.8 s, (d) t=2.9 s
(The direction and length of arrows inside the pool indicate respectively the direction and velocity of fluid flow)

4. Conclusions

A waveform-controlled PAW system is developed to implement the controlled pulse key-holing strategy. A special current waveform is designed with two sub-stages of current decreasing with different slopes at the dropping edge of pulse, and the mode of one keyhole in each pulse is realized. The CCD camera and efflux plasma voltage sensor are used to measure and characterize the keyhole shape and size. Based on the level-set theory, a numerical model is developed to describe and simulate the keyhole behaviors in stationary PAW, and is employed to track the evolution process of keyhole boundary.

Acknowledgments

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