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Single vision system for simultaneous observation of keyhole and weld pool in plasma arc welding

Guokai Zhang[a,b], Chuan Song Wu[a,b,*], Xinfeng Liu[a,b]

[a] MOE Key Lab for Liquid-Solid Structure Evolution and Material Processing, Shandong University, Jinan 250061, PR China
[b] Institute of Materials Joining, Shandong University, Jinan 250061, PR China

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ABSTRACT

A common CCD camera was equipped with a specially designed filter to constitute a vision system, which was used to capture the weld pool and the keyhole images during plasma arc welding process. Through image processing and calibration, the shapes and sizes of both the keyhole and the weld pool were measured under different welding conditions. The dynamic variations of the keyhole/weld pool sizes with time and their relations with the main process parameters were experimentally determined. Six stages of the keyhole/weld pool evolution were observed during the whole welding process. The observation results lay solid foundation for optimizing the welding process parameters and implementing process control of plasma arc welding.

1. Introduction

The arc used in plasma arc welding (PAW) is constricted by a small nozzle and has much higher velocity and heat input intensity than that in gas tungsten arc welding (GTAW). As a result, PAW has many advantages over GTAW in terms of penetration depth, joint preparation and thermal distortion. PAW in keyhole mode could make full-penetration welds in relatively thick material in a single pass. Compared to laser welding and electron beam welding, keyhole PAW is more cost effective and more tolerant of joint preparation, though its energy is less dense and its keyhole is wider, as reported by Wu et al. (2013). Martikainen and Moisio (1993) and Wu (2011) proved that the behaviors of the weld pool and the keyhole as well as their interaction, which all depend on the physical properties of the workpiece and the welding parameters, play critical roles in determining the weld quality. Thus, experimental sensing of the keyhole and its surrounding weld pool is essential to investigate the correlation between the welding parameters and the high-quality welds.

During the PAW process, the keyhole status could be characterized by the indirect signals (generated when keyhole is formed) and direct signals (keyhole shape and size). Zhang and Zhang (2001), Jia et al. (2009) and Wu et al. (2010) measured the electrical potential induced by the efflux plasma from the keyhole exit, which is just an indirect indicator. Chen et al. (2004) detected the plasma arc sound. Saad et al. (2006) obtained acoustic signals identifying the keyhole and weld pool status in variable polarity PAW. The sound signal based sensors are not reliable because they are easily disturbed by environmental noises. Zhang et al. (2001) sensed the status of plasma cloud to judge keyhole status (blind or open keyhole). However, all these detected information could only be used to demonstrate the establishment of an open keyhole (completely penetrated keyhole), but could not give the dimension information of keyhole, not to mention the information of the weld pool size.

Because the keyhole exists inside the weld pool, and both interact with each other during PAW process, the weld pool contains much information on the welding process. Vision-based sensing can give direct information on shape and size of weld pool or keyhole. For laser drilling process, Chryssolouris (1994) and Stournaras et al. (2010) used optical sensors to monitor and control the diameter of the hole. Saeed and Zhang (2007) conducted vision sensing of gas tungsten arc weld pool, while Wu et al. (2009) observed gas metal arc weld pool in high speed welding. Sensing of the keyhole or weld pool in laser welding process was made by Fabbro et al. (2005) and Fujinaga et al. (2000). Zhang and Zhang (1999) used an ultra-high shutter speed vision system to acquire images of the weld pool and the keyhole in PAW. However, such a system was large in volume and expensive in cost, which made it unsuitable

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* Corresponding author at: Institute of Materials Joining, Shandong University, 17923 Jingshi Road, Jinan 250061, PR China. Tel.: +86 0531 88392711; fax: +86 0531 88392711.
E-mail address: wucs@sdu.edu.cn (C.S. Wu).

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Table 1
The welding conditions used in experiments.

Torch offset (mm)	Shielding gas (L/min)	Electrode setback (mm)	Orifice diameter (mm)	Throat length (mm)
5	Ar 20 (upside) Ar 10 (backside)	2	2.8	3

for application in industry. Liu et al. (2013) developed a low-cost visual system for monitoring the keyhole behavior in PAW process. However, only keyhole, without the surrounding weld pool, was imaged. Zhang et al. (2014) used an optical sensor and an infrared camera to capture the images of keyhole and its surrounding thermal field during plasma arc welding process, respectively. Although the weld pool boundary was obtained from the gray distribution of the temperature field, the twin-sensor information integration had to be performed. If a single camera based vision sensor is able to observe both the keyhole and the weld pool simultaneously, it is not only timesaving in coordinate transformation and information integration, but also cost effective.

The investigation of the applicability of a single CCD camera for simultaneous monitoring both the keyhole and weld pool in PAW is the main topic of this study. Compared with other monitoring technologies used in PAW, the proposed method can provide sufficient and direct information on both weld pool and keyhole. A suitable filter was selected to suppress the interference from the plasma efflux and to make the near infrared radiations from the keyhole exit and its surrounding weld pool comparable in brightness and contrast. Through image analysis and image calibration, the dynamic variations of the weld pool and keyhole at underside were measured, and the stages of their variation from the welding start to the welding end were classified. The relationships between the keyhole/weld pool sizes and the welding parameters were obtained. The in-process sensing approach can also offer support to PAW closed-loop control scheme.

2. Experimental details

2.1. Experimental system and design

Fig. 1 shows the schematic illustration of the experimental system in PAW. The PAW machine included a digital welding power source, a plasma module, a PAW torch and a working table. A control PC was used to adjust the process parameters and monitor the process signals via the input/output interfaces. The vision sensor consisted of an image acquisition card and a CCD camera with the filter. The CCD camera was fixed at the backside of workpiece. The observation angle between the camera axis and horizontal plane was 70 degrees. The distance between the camera and the target was 200 mm. In welding tests, the workpiece was driven to move at the preset speed, while the vision sensor and the welding torch were kept stationary.

The material to be welded was stainless steel 201 with a thickness of 8 mm. For the experiments, some of the welding conditions were constant as listed in Table 1, while the main process parameters were varied to obtain open keyhole and quasi-steady state weld pool during the PAW processes. As pointed out by Martikainen and Moisio (1993) and Wu et al. (2013), the main process parameters are welding current, welding speed and plasma gas flow rate in PAW.

The experiments were conducted in such a way so as to produce the keyhole and weld pool of different geometrical characteristics and to establish the relationships between the main welding process parameters and the sizes of both weld pool and keyhole. To avoid two extreme cases, i.e., lack of penetration and burn-through, the heat input must be selected within appropriate ranges. For the stainless steel plates of thickness 8 mm, some preliminary tests were performed to find out the suitable ranges of the main process parameters. Then, the welding current and welding speed were changed independently within the ranges. Because the orifice design was fixed, the plasma gas flow rate should be set in nominal range. Table 2 lists the varied process parameters for different tests.

Table 2
The process parameters used in experiments.

Test case no.	Welding current (A)	Welding speed (mm/min)	Plasma gas flow rate (L/min)
1	165	120	2.8
2	170	120	2.8
3	175	120	2.8
4	180	120	2.8
5	170	110	2.8
6	170	130	2.8
7	170	120	2.7
8	170	120	2.9
9	170	120	3.0

2.2. Optical filter design

When the workpiece is fully penetrated and an open keyhole is established, the plasma efflux exits from the keyhole channel. The plasma efflux has strong interference to the vision sensor. To obtain clear images of both the keyhole and the weld pool, an appropriate filter strategy is critical.

According to the book by Yonemoto (2006), the CCD sensor is made of Si single crystal. The maximum length of light wave that the CCD can sense is around 1100 nm. According to Wien's displacement law in book by Wannier (1978), there is an inverse relationship between the wavelength of the peak of the emission of a black body and its temperature,

$$\lambda_{\max} T = b \tag{1}$$

where $\lambda_{\max}$ is the peak wavelength, T is the absolute temperature of the black body, and b is a constant of proportionality called Wien's displacement constant, equal to 0.002897 m K. During the welding process of stainless steel plates, the temperature of the workpiece around the weld pool at underside is between 1500 K and 1700 K, thus the peak wavelength of weld pool boundary radiation is about 1600–1900 nm. Because the emission coefficient of the workpiece is lower than 1.0, and the temperature of the molten weld pool is higher than that of the pool boundary, the peak wavelength of the weld pool is shorter than the calculated value of 1600–1900 nm. To ensure the infrared intensity from the weld pool at backside of the workpiece, the center wave of the filter should be close to the peak wavelength and less than 1100 nm. The plasma efflux light from the keyhole exit is a strong interference to the weld pool observation, and such interference must be suppressed or eliminated. Jia et al. (2013) discovered that the spectrum curves from the welding arc were superposition of many kinds of spectrum radiation and continuous infrared spectrum. In this study, the plasma gas was pure Ar, and the radiation from Ar dominated the plasma arc radiation. The most part of Ar radiation is distributed in the wave band from 700 nm to 900 nm. As a result, the minimum of narrow band filter range should be higher than 900 nm. Finally, a near infrared narrow band filter was chosen to combine with the CCD camera. The central wavelength of this filter was 1080 nm and the bandwidth was 20 nm. With this filter, the images of both the weld pool and the keyhole could be captured by a single CCD camera.