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Experimental observation of both keyhole and its surrounding thermal field in plasma arc welding

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ABSTRACT

Keyhole plasma arc welding is a complicated thermal process and has great application potential in joining important metal structures. It is of great significance to sense and monitor the keyhole geometry and its surrounding temperature distribution for seeking deep insight into the process mechanisms. In this study, an optical sensor and an infrared camera are simultaneously used to capture both the images of keyhole and its surrounding thermal fields during plasma arc welding process. Special filtering measures are taken to eliminate any interference and ensure the imaging quality. Based on appropriate imaging processing and calibration, the information from two sensors are integrated and coupled, and the shapes and sizes of both the keyhole and the weld pool are determined under different welding conditions. The observation results lay solid foundation for controlling the keyhole and weld pool dynamics, optimizing the process parameters, and validating the numerical models of thermo-physical behaviors in keyhole plasma arc welding.

1. Introduction

Plasma arc welding (PAW) is a welding process that melts and joins metals by heating them with a constricted arc established between a tungsten electrode and the metals. Because of the squeezing action of the constraining nozzle, the arc in PAW is concentrated and straight so that plasma jet is of high energy density and high velocity. With sufficient heat intensity and momentum, the plasma arc produces a molten pool immediately when it starts to deposit heat on the workpiece, and an open keyhole (penetrating entirely through the thickness of the workpiece) is established inside the weld pool. The entire central core of keyhole consists of plasma surrounded on all sides by an envelope of molten metal [1]. In this way, the face of the two joint elements can be melted, the molten material flows back into the molten weld pool, metallurgical continuity is obtained, and solidification can occur to produce a weld. Due to the establishment of keyhole inside the weld pool, the PAW process can penetrate thicker workpieces with a single pass and produce welds with large aspect ratio (penetration depth to width) [1,2]. Hence, the keyhole PAW has found wide applications in industry [2–5].

However, in keyhole PAW the quality of the weld depends on the keyhole stability, which itself depends on a large number of factors, especially the physical characteristics of the material to be welded and the welding process parameters to be used [6]. Thus, keyhole PAW is susceptible to the variation of welding process parameters, which makes it have narrower range of applicable process parameters for good weld quality [7]. The temperature profile around the keyhole and weld pool has great influence on the formation and stability of keyhole. Although modeling and simulation have been performed to understand the thermo-physical phenomena in keyhole mode welding processes, simplified assumptions have to be made because of the complexity of the problem. Some models focused on only thermal conduction phenomena, and fluid flow in the weld pool was not taken into account [8,9]. Keanini and Rubinsky assumed the keyhole shape according to experimental results, and neglected the electromagnetic forces [10]. Fan and Kovacevic developed a two-dimensional model to demonstrate the heat transfer and fluid flow in stationary keyhole PAW, which is different from the moving keyhole PAW [11]. Dong et al. dealt with a gas tungsten arc weld pool where no keyhole exists [12]. Wei's group proposed algorithms to predict the fusion zone shape, but the keyhole was absent in the molten pool because only the case of low power-density beam was considered [13,14]. Generally, the available models are oversimplified. In-process sensing of weld pool and keyhole status is able to provide more direct and useful information [15,16]. Through experimental measurement of the temperature field and the keyhole behavior in keyhole PAW process, the underlying physical dynamics of the keyhole and weld pool can be understood, and the process parameters can be optimized for obtaining high quality of weld structure.

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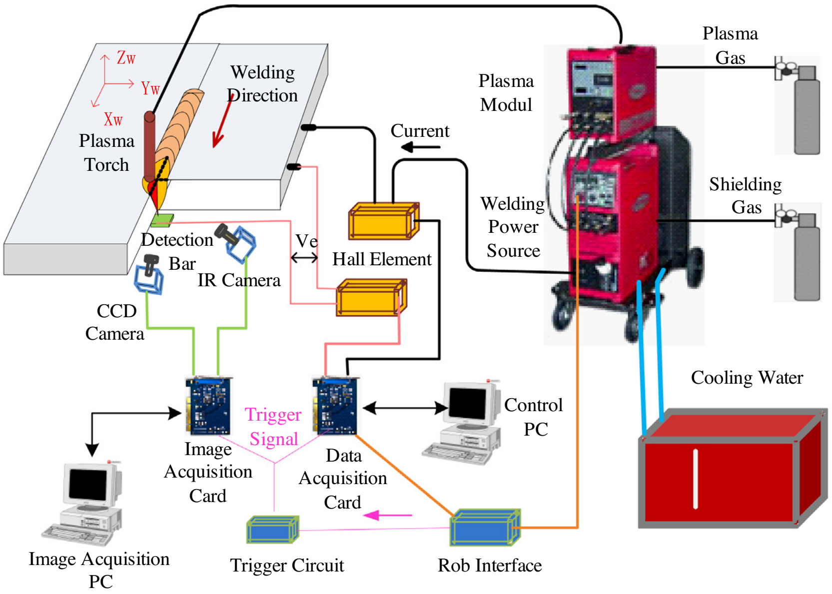

Fig. 1. Schematic of experimental system for keyhole plasma arc welding.

Therefore, it is of great significance to sense and monitor the temperature distribution and keyhole geometry in keyhole PAW process.

Some indirect signals have been measured to characterize the keyhole condition in the PAW process, such as the electrical potential induced from the efflux plasma exiting through the keyhole [17,18], the plasma arc sound or light signals identifying the no-keyhole and keyhole modes [19–21], the amount of the reflected plasma from the keyhole wall [22,23], etc. However, all these detecting approaches provide only indirect information and just indicate if an open keyhole (completely penetrated keyhole) is formed or not, but do not provide quantitative information on the shape and size of an open keyhole. Vision-based sensing could give more direct and complete information, and thus have been used to observe the weld pool in arc welding processes [24,25] and the keyhole/weld pool in laser welding process [16,26]. Matsunawa et al. [27] used high-speed optical and X-ray transmission methods to conduct real-time observation of keyhole in the pulsed and continuous-wave laser welding, but the special chamber and protection means related to X-ray makes such a system inconvenience in practical application. Bicknell et al. developed an infrared sensor for top face monitoring of weld pools during tungsten inert gas welding [28]. Song and Zhang [29] developed a reconstruction scheme to derive the three-dimensional shape of the weld pool surface based on the reflected image of low power continuous structured laser pattern, and the process is also tungsten inert gas welding (gas tungsten arc welding). However, because the PAW torch is usually much larger in volume than those of tungsten

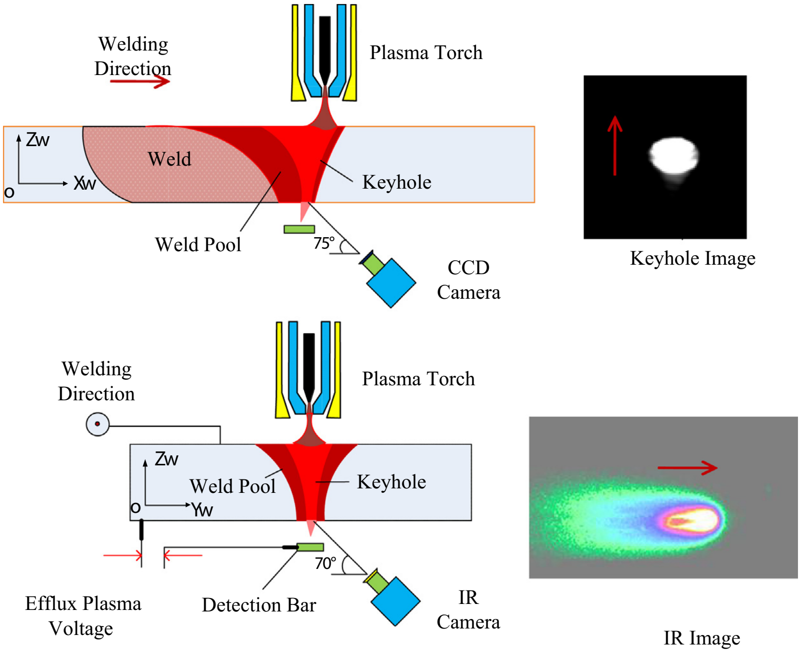

Fig. 2. Schematic of the sensors set-up.