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Vision-based weld pool boundary extraction and width measurement during keyhole fiber laser welding

Masiyang Luo, Yung C. Shin *

Center for Laser-based Manufacturing, School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907, USA

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ABSTRACT

In keyhole fiber laser welding processes, the weld pool behavior is essential to determining welding quality. To better observe and control the welding process, the accurate extraction of the weld pool boundary as well as the width is required. This work presents a weld pool edge detection technique based on an off axial green illumination laser and a coaxial image capturing system that consists of a CMOS camera and optic filters. According to the difference of image quality, a complete developed edge detection algorithm is proposed based on the local maximum gradient of greyness searching approach and linear interpolation. The extracted weld pool geometry and the width are validated by the actual welding width measurement and predictions by a numerical multi-phase model.

1. Introduction

Laser welding has been a promising welding technique in industrial manufacturing owing to its high-density energy, low heat input, large depth-to-width ratio, small heat-affected zone (HAZ), high speed and so on [1]. Particularly, the keyhole laser welding or deep penetration welding is probably the most commonly used process. In keyhole welding, the laser beam is focused on a small spot to obtain a high power density at the surface of a workpiece. The temperature of fusion zone is rapidly elevated to the evaporating point where a vapor cavity, known as keyhole, is formed due to the influence from recoil pressures, vapor plume impacts and other forces [2].

While keyhole welding has been paid much attention and studied extensively, the instability of the keyhole and the weld pool still generates some defects during welding processes. Hence, to deeply understand the dynamics of keyhole welding and improve weldment quality, a variety of research has been carried out, such as the dynamic model analysis [3–7], the assisted shield gas application [8–10] and the weld pool monitoring [11,21]. Since the weld pool contains useful information related to welding quality, on-line weld pool monitoring techniques have been developed over the past few years. Li et al. [11] used the "acoustic mirror" to study the ultrasonic airborne acoustic emission of weld pool plasma and laser beam. Wang et al. [12] and Huang et al. [13] measured welding temperature distributions by an IR thermography system, which was calibrated by thermocouples.

At present, as a result of the continuous development of visual imaging techniques and high computational capability with a reduction of cost, a vision-based system has become a popular approach to monitoring the weld pool. Captured imaging signals are capable of providing more straightforward welding details, such as variations of weld pool geometry. Measurements have been conducted using a high speed camera and a dot matrix pattern laser so as to reconstruct the three dimensional weld pool surface in gas tungsten arc welding (GTAW) [14–16]. Moreover, a calibrated camera with structured lights was used to directly measure the weld pool depth in GTAW [17]. However, even if the structured light method has potential to detect the three dimensional shape of the weld pool, they are only limited to the GTAW since the weld pool is not that deep compared with keyhole laser welding. In keyhole welding, the structured light could hardly be reflected from the keyhole area.

On the other hand, to capture the two dimensional geometry of the weld pool in keyhole welding, a coaxial monitoring system was developed. With this type of system, Kim et al. [18] investigated the size of keyhole area by testing various optic filter combinations with a coaxial illumination laser and Qin et al. [19] extracted molten pool edges by taking advantage of the binarization algorithm. However, these methods are probably too simple to capture the dynamic details of the weld pool. Recently, Zhang et al. [20] built an on-line coaxial monitoring system with an auxiliary illuminant for the fiber laser welding of Zn-coated steel and proposed a region-growing method with the Canny algorithm to extract the boundary of weld pool. Even though their algorithm owned the computational efficiency and good accuracy, their

* Corresponding author. Tel.: +1 765 494 9775.
E-mail address: shin@purdue.edu (Y.C. Shin).

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image processing method may not be able to deal with the low quality images with more noises of welding on other materials. In terms of weld pool reflection features, a more complex edge detection algorithm was designed on the edge enhancement [21]. But the lack of illumination made a slow transient region occur between the image background and the weld pool area, which introduced some uncertainties into the weld pool edge detection. Additionally, the lack of comparisons between the actual welding width and the monitored one also brings up the unknown reliability of the image processing results.

The present work describes an efficient weld pool boundary extraction algorithm that aims at dealing with the noisy captured weld pool images in keyhole fiber laser welding based on a coaxial monitoring system with the green laser illumination. According to the different noise disturbance level, a searching technique for the local maximum gradient of grayness is developed for detecting clear weld pool edges (in the head and tail parts of the captured images). Although the boundary points can be defined straightforwardly as the ones with the maximum gradient of grayness [14], more advanced image processing procedures and initial point or start line selection methods are used to reduce the effects of noise and to improve the fidelity of weld pool width detection. The linear interpolation is adopted to reshape the blurred weld pool boundary (in the middle part). The width of the weld pool is then calculated via the acquired edge data in order to analyze the relationship between the different welding conditions and the corresponding weld pool geometries. Eventually, some unique methods are proposed to validate the image processing results.

The paper is organized as follows. Section 2 presents the experimental set-up of the coaxial monitoring system. Section 3 describes the image processing procedure and the proposed algorithms. Then the various experimental results and validations are covered in Section 4. Finally, the conclusions are made in Section 5.

2. Experimental setup

The keyhole welding process is performed by a photonics fiber laser (IPG YLS-1000) with a spot radius of 0.2 mm at the focal position. The laser beam is transmitted through the fiber to the laser head and its wavelength is 1070 nm. The laser details are shown in Table 1. The assisted gas Argon is blown into the weld pool to improve the weldment quality in the experiments. The 304 stainless steel with 2 mm of thickness is used as the substrate material. The chemical composition of the 304 stainless steel is listed in Table 2. The welding process is controlled by the three-axis Mazak Controller.

The coaxial monitoring system is composed of two dichroic mirrors, a complementary metal–oxide–semiconductor (CMOS) camera, an illumination resource and optic filters. The whole monitoring system and the laser head are all mounted on the Mazak CNC machine as shown in Fig. 1. The dichroic mirrors are arranged and aligned into the holders against two opposite sides in a parallelogram block so as to guarantee the output beam is perfectly focused, as schematically shown in Fig. 2. Both the dichroic mirrors completely reflect the laser beam around the wavelength of 1064 nm but transmit others, which make it realizable to capture the weld pool images through the illumination at different wavelengths. The CMOS camera selected in this study is DFK 42BUC03 USB 2.0 Color Industrial Camera. The preset resolution is 1280 × 720 pixel with the maximum frame speed of 33 frames/s. The sensitivity response of the camera is plotted in Fig. 3, which needs to be considered for determining the type of illumination for detection.

In the keyhole welding, the irradiation object is not only the light emission of the weld pool, but also ionized metal plasma, which is much weaker though. To efficiently reduce the impact of disturbing irradiations, a spectrometer is mounted horizontally above the workpiece to gather the wavelength distribution of the welding plasma prior to the actual weld pool measurement. The average result attained from the multiple experiments is shown in

Fig. 1. Photo of coaxial monitoring system and Mazak Controller.

Table 1
Description of IPG YLS-1000 fiber laser.

Available output power	≤ 1000 *W*
Emission wavelength	1070–1080 nm
Diameter of feed fiber	200 μm
Dope material	Ytterbium

Table 2
Chemical composition of 304 stainless steel.

Element	Carbon	Manganese	Phosphorus	Sulfur	Silicon	Chromium	Nickel	Nitrogen	Iron
Portion	0.08	2	0.045	0.03	0.75	19	10	0.1	68