A vision based method for humping detection in high-speed laser welding

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Abstract. In this paper a vision based detection method for humping in high-speed laser welding is proposed. A high-speed imaging system is used to capture the images of melt pool in the near-infrared range and the unaffected melt pool region is extracted as the ROI (region of interest) according to the structure of images. The occurrence of humping and positions of humps are determined according to the geometric characteristics of the melt pool in the ROI. Experimental results indicate that the proposed method can detect positions of humps when humping occurs and can also avoid false detection when no humping occurs. The potential of the proposed method is demonstrated for humping control.

1. Introduction

Humping is a typical welding defect, during which periodic beadlike protuberances appear and make the surface of weld beads uneven, as shown in Figure 1. Humping phenomenon has been found in high-speed melting processes like laser welding [1, 2], laser additive processing [3], and arc welding [4]. At present some researches on humping monitoring have been reported. Zhang et al. [5] built a multiple-sensor system to obtain information for laser welding statuses monitoring and determined the defect type including humping. Fang et al. [6] proposed an acquisition system of melt pool images in GMAW (gas metal arc welding) and determined the occurrence of humping according to the truncation of the melt pool length. These monitoring methods can detect the occurrence of humping, but cannot determine the specific position of humps. Pei [7] found that dual-beam in tandem could reduce humping in high-speed laser welding and increase the limit speed of laser welding without humping. In addition, he also found that the position of the secondary beam could influence the effect of humping suppression obviously. When a new hump started to form, if the secondary beam could irradiate it with appropriate power, then the formation of this hump would be suppressed. Based on this result, if the positions of humps which are forming can be detected, the setting positions of the secondary beam can be determined. In this paper, a vision based detection method of humping position during high-speed laser welding is proposed. A high-speed imaging system is used to capture images of the melt pool, and image processing is performed to determine the specific position of humps which are forming. The method is tested on experiments and its validity is verified.
2. Experimental setup
The high-speed imaging experiment was conducted to capture the images of melt pools during high-speed laser welding. Workpieces were SUS304 austenitic stainless steel sheets with dimensions of 200 mm × 50 mm × 1 mm. A MAX MFSC 4000W single-mode fiber laser and a Precitec YC52 laser processing head were integrated to perform laser welding. The maximum power of the laser was 4 kW and the wavelength of the output laser was 1070 ± 10 nm. The diameter of the laser focal spot was 0.4 mm. The laser processing head was installed on a YASKAWA MH24 robot. Workpieces were cleaned with absolute ethyl alcohol before welding. A NAC Memrecam HX-6 high speed camera was used to record the images of melt pools during welding and its frame rate was set to 5 kHz. The axis of the camera and lens formed a 45° angle with the horizontal plane. A narrow bandpass filter with the central wavelength of 810 nm was attached on the lens. A Cavitar CAVIULX HF pulsed high power diode laser light source was used as an active light source for illumination and its central wavelength was 810 nm. The configuration of the experiment was shown in Figure 2.

3. Detection method
3.1. Image capture
Researchers have found that the combination of an active light source and a bandpass filter with a wavelength of 810 nm can help capture the images of melt pools with high quality during laser welding [8, 9]. Therefore, we also tried this method, and the captured image is shown in Figure 3(a). The melt pool can be observed clearly in the image, but grayscales of the melt pool and the workpiece surface are similar, so it’s difficult to extract the contour of the melt pool based on grayscales. If the extraction is performed by using other features like textures, the computational cost will increase notably.

In order to make the contour of the melt pool easy to be extracted, we captured the image of the melt pool without the illumination of the active light source. The captured image is shown in Figure 3(b). Because 810 nm belongs to the near-infrared range, the grayscale in the image mainly reflects the intensity of thermal radiation. According to Stefan-Boltzmann law, the intensity of thermal radiation
increases with the increase of the object temperature, so the melt pool region with high temperature is bright in the image, and thus it can be differentiated from the workpiece surface more easily in the image processing. So we performed the high-speed imaging without the illumination of the active light source.

![Image](a) ![Image](b)

**Figure 3.** Captured images of the melt pool: (a) With the illumination of the active light; (b) Without the illumination of the active light.

3.2. **Image processing**

In the captured image, regions with high grayscale mainly consist of the following parts: the laser irradiated region, the plasma and its reflection region (referred to as plasma region hereinafter), and the melt pool, as shown in Figure 4. In order to determine the occurrence of humping, it is necessary to segment the melt pool in the image. The grayscale of the laser irradiated region is near saturation (close to the maximum grayscale 255), so it is easy to determine this region by threshold segmentation. However, the grayscales of the plasma region and the melt pool are similar, so it is hard to differentiate them by threshold segmentation. By observing Figure 4 it can be found that the front part of the melt pool is affected by the plasma, while the rear part of the melt pool is unaffected, where the humps appear. So in our image processing algorithm, a region of interest (ROI) containing only the rear part of the melt pool can be extracted. During the humping formation process, the height of the melt pool where the hump occurs will increase, and the necking of the melt pool will happen in front of the hump, so the occurrence of humping and the position of humps can be determined according to this phenomenon. The detailed process is described below.

![Image](Structure of the image)

**Figure 4.** Structure of the image.

3.2.1. **Extraction of ROI.** The extraction process of the ROI containing only the rear part of the melt pool is shown in Figure 5. The binarization of the image is conducted with a high threshold to extract the laser irradiated region, and its centroid C is then extracted. Then the binarization is conducted again with a small threshold, and close operation is performed to remove small holes. The extracted region mainly includes the plasma region and the melt pool region.

Next, the maximally connected domain is searched, and its contour is extracted. A polar coordinate CL with the pole at C is set up. The $\theta - r$ curve of the contour is then calculated. However, a $\theta$ value may correspond to several $r$ values on the contour. Thus, the following method is adopted:

Suppose the statistics range of $\theta$ is $[\theta_{\text{min}}, \theta_{\text{max}}]$, and divide this range into $n$ sub-ranges. The span of each sub-range is $\Delta \theta$. Then build an array $\{\theta_n\}$:

$$\theta_k = \theta_{\text{min}} + (k - 1)\Delta \theta, \quad k = 1, 2, ..., n$$  \hspace{1cm} (1)
Next, build another array \( \{ r_n \} \). For every point \( P(\theta_p, r_p) \) on the contour of the maximally connected domain, if

\[
\theta_p \in [\theta_{\text{min}} + (k - 1)\Delta \theta, \theta_{\text{min}} + k\Delta \theta)
\]

and

\[
r_k = \text{null or } r_p < r_k
\]

then let

\[
r_k = r_p
\]

Finally, plot the \( \{ \theta_k \} - \{ r_k \} \) curve and regard it as the \( \theta - r \) curve.

The statistics range of \( \theta \) is \([\pi/4, 3\pi/4]\) and \( n \) is 90 here. In order to avoid the influence of noise, the \( \theta - r \) curve is smoothed. In the \( \theta - r \) curve, two minimum points, \( J_1 \) and \( J_2 \), exist near the maximum point. In the original image, these two points correspond to the junction points of the melt pool and the plasma region. Finally, two rays \( CJ_1 \) and \( CJ_2 \) are built. The region which is between \( CJ_1 \) and \( CJ_2 \) and on the left of both \( J_1 \) and \( J_2 \) is segmented as the ROI.

3.2.2. Determination of the humps positions. Each column in the ROI is scanned, and the height of the melt pool, \( h \), is counted. The \( x - h \) curve is plotted, as shown in Figure 6. The melt pool is cut off where \( h(x) = 0 \), which indicates the occurrence of humping. For the melt pool which has not been cut off on the right of the image, the peaks and valleys of \( h(x) \) are searched. For a peak position \( x_1 \), and a valley position \( x_2 \) next to \( x_1 \) and on the right, if

\[
h(x_1) > th(x_2)
\]

Figure 5. The extraction process of the ROI.
then it can be speculated that a hump is forming at $x_1$, like position B and C in Figure 6. The value of $t$ is set to 1.2 here. As for the isolated melt pool which has been cut off on the left of the image, it represents that a hump has formed here, like position A in Figure 6.

![Figure 6. Determination of the humps positions.](image)

4. Results and Discussion

When the laser power is 3 kW and the welding speed is 24 m/min, humping occurs and the detection results are shown in Figure 7(a). Yellow marks represent humps which are forming, and red marks represent humps which have formed. It can be found that positions of humps are detected accurately. When the laser power is 2 kW and the welding speed is 16 m/min, humping does not occur and the detection results are shown in Figure 7(b). It can be found that no false detection happens. Thus the validity of the proposed detection method is verified.

![Figure 7. Detection results of humping.](image)
5. Conclusions
A vision based method was proposed to detect the humping in high-speed laser welding in this paper. Images of the melt pool in the near-infrared range are captured, and the unaffected region of the melt pool in the image is extracted according to the structure of images. The occurrence of humping and positions of humps are determined according to the geometric characteristics of the melt pool. Experimental results indicate that the proposed method not only can detect the occurrence of humping, but also can detect the positions of humps, and can also avoid false detection when no humping occurs. This study can provide a reference for the humping detection and control.

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