Analysis of Laser-Induced Plume During Disk Laser Welding at Different Speeds*

WANG Teng (王腾)1,2, GAO Xiangdong (高向东)1, Katayama SEIJI3

1School of Electromechanical Engineering, Guangdong University of Technology, Guangzhou 510006, China
2School of Computer, South China Normal University, Guangzhou 510631, China
3Joining and Welding Research Institute, Osaka University, Osaka 567-0047, Japan

Abstract During high power disk laser welding, the high-speed photography was used to measure the dynamic images of the laser-induced plume at different laser welding speeds. Various plume features (area, height and brightness) were extracted from the images by the color space clustering algorithm. Combined with observation on the surface and the cross sections of welding samples, the effect of welding speed on welding stability was analyzed. From the experimental results, it was found that these features of plume could reflect the welding state. Thus changes of the plume features corresponded to different welding speeds, which was helpful for monitoring the laser welding stability.

Keywords: disk laser welding, laser-induced plume, stability, high-speed photography, different welding speeds

PACS: 52.50.Jm, 81.20.Vj, 89.20.Kk

DOI: 10.1088/1009-0630/15/8/20

1 Introduction

The disk laser technology has received a lot of attention lately [1–4]. Since extraction of characteristic signals during laser welding is possible, many quality-sensitive welding processes are monitored. A common signal for monitoring the laser welding process is the characters of the plasma, which contains abundant information about the stability of welding process and correlates with the quality of the produced weld seam. Several online monitoring methods have been proposed to provide real-time information about the welding process with analysis of plasma characters, such as using electric signals [5], acoustic emission [6], optical signals [7–9] and image processing [10–12].

Nowadays, for the disk laser welding, researches on signal extraction and analysis of the plasma dynamic image are relatively few. It is necessary to clarify the features of dynamic image more deeply, which can directly reflect the plasma behavior. High-speed photography is a direct and effective type of measurement [13], which can take a series of photographs at a high sampling frequency.

The relationship between the plume features (area, height) and the characteristics of welded seam have been analyzed [14]. In order to further study the relationship between the plume signal and the stability of welding process, we focused here on the effect of welding speed on welding stability combined with the surface and the cross sections of welding samples.

2 Experimental details

The experimental setup for disk laser bead-on-plate welding without illumination diode is schematically illustrated in Fig. 1. In this study, bead-on-plate welding at different speeds of 3 m/min, 4.5 m/min and 6 m/min was performed on the austenitic stainless steel Type 304 specimens using a high-power disk laser (TruDisk-10003) with a constant laser power of 10 kW. Table 1 lists the welding conditions. A NAC’s high-speed camera system (Memrecam fx RX6) was mounted to monitor the plume and molten pool in the welding process. The optical filter was placed in front of RX6 to reduce the effect of multiple reflections between the filter and the lens. The shielding gas was argon to protect the molten pool from oxidation.

Fig.1 Schematic diagram of the experimental system (color online)

*supported by National Natural Science Foundation of China (No. 51175095), the Guangdong Provincial Natural Science Foundation of China (Nos. 10251009001000001, 9151000001000020) and the Specialized Research Fund for the Doctoral Program of Higher Education of China (No. 20104420110001)
Table 1. High power disk laser welding conditions

<table>
<thead>
<tr>
<th>Items</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam diameter</td>
<td>480 µm</td>
</tr>
<tr>
<td>Laser wavelength</td>
<td>1030 nm</td>
</tr>
<tr>
<td>Specimen</td>
<td>Stainless steel (Type 304)</td>
</tr>
<tr>
<td></td>
<td>with the dimensions</td>
</tr>
<tr>
<td></td>
<td>((L \times W \times D) mm) of 119 \times 51 \times 20</td>
</tr>
<tr>
<td>Nozzle angle</td>
<td>45°</td>
</tr>
<tr>
<td>High speed camera</td>
<td>Frame rate 2000 f/s,</td>
</tr>
<tr>
<td></td>
<td>(pixel \times pixel = 512 \times 500)</td>
</tr>
</tbody>
</table>

3 Results and discussion

The image processing was accomplished by using the Matlab platform. The processing steps included image acquisition, image segmentation, and features extraction. The plume area, plume height, and mean brightness of image were extracted from the processed plume color image by color space clustering algorithm [14,15]. After a color image was segmented, the pixel number of the effective plume image was set equal to plume area, the vertical distance between the lowest point and the highest point was set equal to plume height. The mean brightness of the plume image was the average intensity of the pixels in effective plume region.

3.1 Features of dynamic plume image

Fig. 2 was the calculated results of the area for the plume region at different welding speeds (color online).

3.2 Features of the welding sample

Fig. 3 was the surface appearance of sample welded at different welding speeds. As shown in Fig. 3, four different cross sections of the workpieces were selected for observation. At slower welding speed, the welded seam width became even, the number of spatters on the sample surface was decreased, and the welding process tended to be stable.

Fig. 4 shows the bead width and weld penetration made at different welding speed of the cross section 1. As shown in Fig. 4 and Table 2, the depth-to-width ratio (DWR) at 6 m/min was the largest, but its welding process was the most unstable, and the quality of its underfilled surface was the worst. Although the DWRs at 4.5 m/min and 3 m/min were a bit smaller, the welding process was more stable, and the quality of the welded seam surface was better. Observing the cross sections through metallurgical microscope, more pores were easily formed at the welding speed of 3 m/min, while few pores were formed at the welding speed of 6 m/min. When the welding speed decreased, the line energy input of welding process improved, and the laser energy could penetrate into the melting pool more effectively and more deeply. More energy obtained by the molten pool made the evaporation more intense, which caused the keyhole fluctuated violently. Thus, many bubbles are formed in the molten pool, and most of them were trapped by the solidifying metal, leading to the formation of pores [10].
Table 2. Depth and the depth-to-width ratio at different welding speeds

<table>
<thead>
<tr>
<th>Welding speed (m/min)</th>
<th>Depth (mm)</th>
<th>DWR</th>
<th>Depth (mm)</th>
<th>DWR</th>
<th>Depth (mm)</th>
<th>DWR</th>
<th>Depth (mm)</th>
<th>DWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>9.5</td>
<td>4.63</td>
<td>9.4</td>
<td>3.97</td>
<td>9.6</td>
<td>4.80</td>
<td>9.55</td>
<td>4.97</td>
</tr>
<tr>
<td>4.5</td>
<td>8</td>
<td>4.49</td>
<td>8.05</td>
<td>4.85</td>
<td>8.3</td>
<td>5.80</td>
<td>8.4</td>
<td>5.06</td>
</tr>
<tr>
<td>6</td>
<td>7.1</td>
<td>6.34</td>
<td>7.05</td>
<td>6.47</td>
<td>7.3</td>
<td>7.09</td>
<td>7.3</td>
<td>6.95</td>
</tr>
</tbody>
</table>

These results show that the keyhole behavior well corresponds to the welding speed. Therefore, high welding speed easily led to large depth-to-width ratio, but might affect the stability of the welding process. We should not blindly pursue a large depth-to-width ratio, but select an appropriate welding speed to take account of both the welding state and the depth-to-width ratio.

3.3 Effect of welding speed on welding stability

The average areas, height and mean brightness of plume region at different speeds were given in Table 3. The relative errors, the $e_{\text{MSE}}$ and the $e_{\text{MSRE}}$ of the average areas, height and mean brightness were calculated by using Eqs. (1) and (2).

$$e_{\text{MSE}} = \sqrt{\frac{\sum_{i=1}^{N} (V_{\text{calc},i} - V_{\text{mean}})^2}{N}},$$

$$e_{\text{MSRE}} = \sqrt{\frac{\sum_{i=1}^{N} \left(\frac{V_{\text{calc},i} - V_{\text{mean}}}{N}\right)^2}{N}},$$

where $e_{\text{MSE}}$ is the mean squared errors, $e_{\text{MSRE}}$ is the mean squared relative errors, $V_{\text{calc}}$ is calculated value, $V_{\text{mean}}$ is mean measured value, and $N$ is the number of samples. Corresponding calculated results were also given in Table 3.

As seen from Table 3, with the increase in welding speed, the mean square error of the plume area and height became larger correspondingly. It meant that, with increasing welding speed, the stability of dynamic plume became worse, and it further reflected that the stability of the welding process also became worse. Meanwhile, the average plume area, height and brightness became larger with increasing welding speed. When the welding speed decreased, the line energy input of welding process improved, the welding process became stable, and the laser energy could penetrate deeper and more effectively into the area below the welding surface of the workpiece, rather than accumulate around the surface of the workpiece, and thus made the size of melting region decrease. Thus, the metal vapor from the surface of the workpiece reduced, resulting in the decrease of the area and height of the plume in the surface region of workpiece. And the decrease of the plume area and height reduced the laser energy loss in the transmission process, which fed back a beneficial effect on the welding process. Therefore, it was believed that the decrease of welding speed could improve the stability of the welding process and welding quality.

4 Conclusions

The high-speed photography was used to diagnose the dynamic changes of the plume region during high power disk laser welding process at different welding speeds and a constant laser power of 10 kW. Useful plume images features such as the plume area, plume height, and mean brightness of image were extracted from the processed plume color image. Major conclusions obtained in this study are as follows.

a. High welding speed easily led to large depth-to-width ratio, but may affect the stability of the welding process. Appropriate decrease of welding speed could improve the stability of the welding process and welding quality under certain conditions.

b. More pores were easily formed when the welding speed was low. We did not discuss the problem here because the formation and evolution mechanism of the pores involved complex process of physics, mechanics and metal material science.

c. With increasing welding speed, the mean square error of the plume area and height became larger correspondingly, and the average plume area, height and brightness also became larger. Therefore, the change of the plume area can correspond to change of welding speeds, and provide useful information for monitoring the welding states.

Table 3. Average area and height of plume at different welding speeds

<table>
<thead>
<tr>
<th>Welding speed (m/min)</th>
<th>Average area (pixel)</th>
<th>$e_{\text{MSE}}$</th>
<th>$e_{\text{MSRE}}$</th>
<th>Average height (pixel)</th>
<th>$e_{\text{MSE}}$</th>
<th>$e_{\text{MSRE}}$</th>
<th>Average brightness</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 m/min</td>
<td>2497.6</td>
<td>1006.0</td>
<td>0.2812</td>
<td>68.85</td>
<td>23.82</td>
<td>0.0067</td>
<td>228.73</td>
</tr>
<tr>
<td>4.5 m/min</td>
<td>2924.6</td>
<td>1078.1</td>
<td>0.4503</td>
<td>80.51</td>
<td>25.57</td>
<td>0.0107</td>
<td>220.50</td>
</tr>
<tr>
<td>6 m/min</td>
<td>3550.3</td>
<td>1255.2</td>
<td>0.6996</td>
<td>124.10</td>
<td>28.69</td>
<td>0.0160</td>
<td>229.91</td>
</tr>
</tbody>
</table>
Acknowledgements

Many thanks are given to Mr. Shimpei OIWA and Mr. Terumasa OHNISHI, former graduate students of Osaka University.

References


(Manuscript received 7 March 2012)
(Manuscript accepted 30 October 2012)
E-mail address of corresponding author
GAO Xiangdong: gaoxd@gdut.edu.cn