Evaluation of welding process stability and weld formation during laser-MIG hybrid welding

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Abstract. In laser-MIG hybrid welding, the visual information can be used to monitor the stability of the process and estimate the weld formation. Taking the hybrid welding of ER308 stainless steel as an example, a high-speed camera is used to simultaneously obtain visual information of top and bottom of the weldment during the welding process. Combined with the visual characteristics of arc light, molten hump and spatter at the bottom, the influence of various welding state characteristics on weld formation was analyzed. The comparison between the welding process of good weld and root humps illustrated that the time series curves of the area and centroid coordinates of the molten hump at the bottom can reflect the formation process of the root humps. The main cause of root humps is the lack of heat input. The results support a basis for monitoring and controlling the laser–MIG hybrid welding process status.

1. Introduction

Laser-arc hybrid welding technology has the advantages of high laser energy density, fast welding speed, large depth-to-width ratio of the weld, and small welding thermal deformation; the joining of the arc increases the bridging ability, reduces the reflection and refraction of the laser, improving the utilization rate of the laser. It has received extensive attention and applications especially in industrial manufacturing fields such as automobile manufacturing, oil and gas pipelines, high-speed trains, aerospace engineering, shipbuilding. In laser-arc hybrid welding, due to the numerous adjustable parameters and stricter requirements for welding torch position, fiber spacing and other parameters, once the various parameters are not well matched, the welding process may become unstable. The interaction mechanism between laser and arc is complex, making the process quality inspection and control of laser-arc hybrid welding more difficult. The instability of the welding process will lead to welding quality problems, such as weld humps, cracks, pores, unfilled, undercuts. Therefore, real-time monitoring and
quality assessment for laser-arc hybrid welding are the key to researching the process mechanism and ensuring high-quality welding.

In view of the complex physical characteristics of laser-arc hybrid welding, scholars have used various types of sensors for research, such as vision sensors, sound sensors, X-ray imaging systems, photoelectric sensors, spectrometer and multi-sensor integration technology. The most effective technology for condition monitoring is visual sensing [1]. High-speed cameras were used by Jan Frostevarg to reveal the influence of laser-wire distance and arc parameter on the melt flow as well as the penetration depth. Lei et al. [2] used a high-speed camera system to observe the droplet transfer in laser-cold arc welding (CMT) hybrid welding. The research results showed that the process parameter that has the greatest influence on the droplet transfer frequency is the welding current. The thermal effect of the laser will affect the droplet transfer process. Gao [3] applied two high-speed cameras to observe the effect of droplet transfer on the of keyhole bottom. Root hump of the weldment is the most common defect form in laser-arc hybrid welding [4]. Jan comprehensively analyzed the formation mechanism of root welding and avoiding methods [5].

In this paper, a high-speed camera is used to simultaneously collect the welding status information of the top and bottom of the weldment during the laser arc hybrid welding process. The visual features in the welding process are extracted by image processing algorithms, and the influence of different welding process features on the weld formation is analyzed. The welding process of weldments with root humps is compared with that of good weldments, for exploring the formation process and influencing factors of root hump. Experiments show that the characteristic parameters of arc area, bottom spatter, and bottom molten hump are closely related to the welding state and weld formation, which provides basis for real-time state monitoring of the hybrid welding process.

2. Experimental setup
As shown in Figure 1, the high-power laser-MIG hybrid welding system consists of a high-power fiber laser system (YPG YLS-4000), a pulsed MIG welding system (YM-500GL4), and a high-speed imaging system. The laser head was perpendicular to the worktable. The angle between the laser head and the MIG torch was 45°, and the distance between the laser and torch was 2 mm. The defocus distance of the laser was 0 mm in the high-power fiber laser system, the shielding gas (2% CO₂ + 98% Ar) flow in the MIG torch was 30L/min. And welding speed was 1.4 m/min. The experimental weldment and filler wire used in this study were stainless steel plates of 200 mm × 60 mm × 4 mm and stainless wire (ER308) of 1 mm-diameter. The high-speed camera was used to capture video of the laser-MIG hybrid welding process. It was placed in a horizontal position flush with the weldment and perpendicular to the welding direction, observing the top and bottom of weldment simultaneously. A narrowband filter with a wavelength of 950 nm was configured in front of the lens.
The fundamental mechanism of the fiber laser-MIG hybrid welding process is illustrated. Firstly, the base metal is preheated by arc, and droplet transfer occurs in the MIG welding system. Then, the base metal is heated up by high-density laser beam to a high temperature, liquefying and vaporizing of metal at heat source shooting place. Secondly, the gaseous metal produces a high steam pressure, blowing the molten metal around to produce a keyhole. With the overflow of metal vapor, abundant plasma is formed above the workpiece and inside the keyhole. Thirdly, when the amount of metal vapor exceeds the critical value, a greater impulse is produced which brings about spatters formed. Finally, under the action of keyhole, some melt will be released from the bottom of the molten pool.

3. IMAGE PROCESSING AND FEATURE EXTRACTION

3.1. Feature extraction of top surface during welding
The visual information of top surface reveals the real-time status of welding process. In this work, the significant visual features are chosen to extract the feature parameters. Images captured from the high-speed cameras are in RGB format. In order to explore the welding status information from images of arc with strong light, the HSI (Hue-Saturation-Intensity) color model is applied to analyze the relationship between the feature of arc light and the welding quality.

From the above analysis, it can be seen that the arc shapes of different states need to be treated with different HSI characteristics. However, at the beginning, we do not know which type it is, so the H feature is always processed first, and then the pixels of the region in the arc root can be judged for the next steps. If the number of white pixels is less than a certain threshold, it is the projected transfer, and the I feature is used for processing. The captured RGB image is converted to HSI space, and then the arc region of H-component image is obtained. After processing the image by black-and-white inversion and Otsu segmentation, the area near the arc root $S_{\text{root}}$ could be calculated for judgement. If $S_{\text{root}}$ is less than 5, it is in the state of projected transfer, thus the I-component image is processed instead. With the arc region of I-component image is obtained, the arc area could be calculated by binarization. If the $S_{\text{root}}$ is greater than 5, it is in the state of arcing, short circuit transition or spray transfer, and the arc area $S_{\text{arc}}$ could be preliminarily calculated. If $S_{\text{init}}$ is greater than 1500, it is in the state of arc discharge, which is accompanied by a strong arc light. So morphological operations will be carried out. At this time, the maximum area in the welding process is the arc area, so the largest-area searching method is adopted. If $S_{\text{init}}$ is less than 1500, it is in the state of spray transfer or short-circuiting transfer, and the area of arc light $S_{\text{arc}}$ can be calculated directly.
3.2. Feature extraction of bottom surface during welding

During laser arc hybrid welding, the visual signal at the bottom of the weldment contains a lot of information, which can also help us to understand the stability of the welding state. The key visual signals include the state of keyhole bottom, the bottom molten pool, the bottom spatter and so on. The extracted features include arc light area at the bottom $S_{AB}$, the area of the bottom molten pool $S_{MB}$, the centroid coordinates of the bottom molten pool $(x_c, y_c)$, the area of the bottom spatter $S_{SB}$ and brightness of the bottom spatter $B_{SB}$. $S_{AB}$ reflects the open state of the keyhole bottom. When calculating the $S_{AB}$ and $S_{SB}$, the methods including ROI selection, threshold segmentation based on bimodal method are used. And the area is obtained by calculating the number of white pixels. In order to obtain the bottom spatter area, the root pool area should be removed first. In some cases, the root molten pool will gradually accumulate to form a melting hump, which is also the embryonic form of humping at the bottom of the weldment. The feature extraction of root molten pool also requires ROI selection and threshold segmentation for preprocessing. In the feature extraction process of root molten pool, owing to the ROI is relatively large and there is a lot of interference in this region, it is necessary to use morphological operation and the largest-area searching method to eliminate interference, obtaining the $S_{MB}$. The center coordinates of the root pool are measured as follows:

$$x_c = \frac{\sum_{x,y \in S_{MB}} f(x,y)x}{\sum_{x,y \in S_{MB}} f(x,y)} \quad (1)$$

$$y_c = \frac{\sum_{x,y \in S_{MB}} f(x,y)y}{\sum_{x,y \in S_{MB}} f(x,y)} \quad (2)$$

where $f(x, y)$ is the value of the image pixel at position $(x_c, y_c)$. The brightness of the spatter can also reflect the intensity of the welding process. The luminance channel signal $Y$ of the original image in RGB format is extracted as follows:

$$Y = 0.2989R + 0.5870G + 0.1140B \quad (3)$$

After the spatter region is selected from the luminance picture, the average value of luminance pixels in the region is calculated as characteristic parameter of a frame.

4. Analyze the relationship between the visual features of welding process and the weld formation

The welding parameters involved in this paper are shown in Table 1. In order to analyze the relationship between welding process state and weld formation, the welding images and seven signal features extracted from the image are used as analysis objects: the area of arc light $S_{arc}$, arc light area at the bottom $S_{AB}$, the area of the bottom molten hump $S_{MB}$, the centroid coordinates of the bottom molten hump $(x_c, y_c)$, the area of the bottom spatter $S_{SB}$ and brightness of the bottom spatter $B_{SB}$. The weld lengths are 150mm respectively. Judging from the time series curves of the entire welding process with root humps, the curves of $S_{MB}$, $x_c$, $y_c$ show a series of regular peaks and troughs, as shown in Figure 2. The number and position of wave peaks and troughs correspond to those of the root humps. On the contrary, there is no evident changing regularity for the welding process of good weld, as shown in Figure 3. Compared with the welding process of the weldment with root hump, the open area of the bottom keyhole in the welding process of the good weld is larger and the frequency is higher; at the same time, the area and brightness of the bottom spatter become larger.

| Table 1 | Experimental conditions of laser-MIG hybrid welding. |
|---------|-----------------------------------------------------|
| Welding parameters | Laser power/kW | Arc current/A | Arc voltage/V |
| No.1 (root hump) | 2 | 130 | 20 |
| No.2 (good weld) | 2.5 | 180 | 25 |
Intercept a piece of data for detailed analysis. As shown in the partial image of Figure 2, for a specific bottom molten hump, the change trend of its area is to increase first and decrease later, while the abscissa and ordinate of the centroid increase gradually. Among the data intercepted during the welding process with root humps (experiment No.1), $t + 4.5\text{ms}$, $t + 149\text{ms}$, $t + 273\text{ms}$, and $t + 381\text{ms}$ are the moments of arcing, and the arc area $S_{\text{Arc}}$ reaches the local maximum. While $t + 48.5\text{ms}$, $t + 149\text{ms}$, and $t + 378.5\text{ms}$ are the moments when the bottom keyhole is opened, so the $S_{\text{AB}}$ reaches the local maximum. The period from $t \text{ms}$ to $t + 7.5\text{ms}$ is the process of arcing and droplet transfer. From the series of pictures from $t$ to $t + 381\text{ms}$, it can be seen that the bottom molten hump is getting away from the heat source area. In the pictures at $t + 378.5\text{ms}$, a new molten hump is generating. When two molten humps appear at the same time, root humps are bound to form.

Figure 2 Visual features of welding process with root hump.
Droplet transfer affects the melt flow by increasing the momentum of the melt flowing to the root. All the melt flowing to the keyhole outlet needs to be diverted and redirected by surface tension, otherwise it will be ejected in the form of spatter. When the surface tension at the bottom of the molten pool reaches a balance with the gravity of the melt, a molten hump will form. With the melt accumulating in the bottom, the volume of the molten hump will gradually increase. The shielding gas has the low oxygen content, so the surface tension behind the bottom molten pool increases with the decrease of temperature, which promotes the formation of molten hump, and the molten pool is pulled toward the hump. The formation process of root hump can be divided into the aggregation phase of root melt, the augmentation stage of root melt and the resolidification stage.

![Visual features of welding process](image_url)

Figure 3  Visual features of welding process of good weld.
The dropping down of the droplets will have an effect on the state of the keyhole bottom. Under the experimental condition No.2, the keyhole bottom will open in 0.05 - 0.6 ms after the droplet falls into the molten pool. The delay may due to the time difference caused by heat conduction and molten pool flow. As shown in Figure 3, although there are spikes in the characteristic curve $S_{MB}$, $x_c$, $y_c$ of experiment No.2, they quickly flatten out, and there is no steady increase like the welding process of experiment No.1. The welding process of experiment No.2 did not emerge regular molten humps. When there are micro-protrusions at the bottom of the molten pool, the keyhole bottom could be opened under the combined effect of laser and droplet transfer, afterward, the molten material could be released from the bottom. Consequently, a larger molten hump cannot be further formed, and the root hump can be avoided.

5. CONCLUSION
(1) The visual features of the top and bottom of the weldment have been analyzed simultaneously. The timing curves of $S_{MB}$, $x_c$, $y_c$ can reflect the formation process of root humps, and they can be used as a basis for judging whether the root hump has occurred.

(2) Compared with the welding process with root humps, the open area of the keyhole bottom in the welding process of good weld is larger, which could be reflected by $S_{MB}$. In the welding process of good weld, the opening frequency of keyhole bottom is higher and more stably; at the same time, the area and brightness of bottom spatter become larger. Under the combined effect of the laser and the droplet transfer, the melt could be released from the keyhole bottom, which can avoid the formation of root hump.

(3) In the experiments of this article, root humps will generate when the laser power is 2kW, the arc current is 130A and the arc voltage is 20V. The welding state of root humps is between penetration and incomplete penetration. Therefore, the main reason for the root hump is the lack of heat input. When increasing the energy input of the laser or arc, the root humps can be avoided.

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