Analysis of droplet transition features and weld formation in laser-MIG hybrid welding

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Abstract. The image of laser-MIG hybrid welding process was collected by high-speed camera, the arc area and the barycenter of droplet were extracted by image processing method, the weld width and weld height were extracted from the 3D point cloud of weldment surface, and the relationship between droplet transition features, droplet velocity and weld formation were analyzed. Results show that the extremum of arc area and droplet transition period have the same change trend. The change of droplet velocity can effectively reflect the change of weld width. The decrease of arc length can increase the droplet transition frequency, speed up the droplet velocity and increase the weld width. The abrupt increase of arc length will increase the ratio of height to width, which reduce the welding quality.

1. Introduction
Laser-arc hybrid welding is an advanced joint technology which combines laser and arc heat sources in a specific way and acts on the weldment together [1]. The laser increases the depth of fusion, the arc increases the weld width which can reduce assembly requirements as well as improve the weld bridging ability by filling the welding wire. The synergistic effect of laser and arc makes the welding process more stable and achieve complementary advantages [2, 3].

Based on the demand of enterprises for higher production capacity, higher safety and higher quality output, as well as the demand of product traceability, the application of welding monitoring is increasing. In the field of laser welding monitoring, optical sensors were used to monitor various signals emitted by the laser as it interacts with the material, including visible light, ultraviolet light, infrared light and laser reflection, which can effectively reflect the welding state [4, 5]. For laser-arc hybrid welding, due to the interference of arc light, it is not conducive for optical sensor to detect key hole, molten pool, metal vapor and splash, but the periodic fluctuation of arc and metal vapor also contains a lot of information, which can effectively reflect the state of droplet transition and coupling of arc and laser. It is directly
related to welding process stability, weld formation, splash size and so on, which finally affects the welding quality and production efficiency [6]. Therefore, the study of the relationship between droplet transition features and weld formation in laser-arc hybrid welding can provide a theoretical basis for the welding monitoring and prediction of weld formation in laser-arc hybrid welding.

2. Experimental Setup

The device diagram is shown in Fig.1 which consists of continuous fiber laser device (IPG YLS-4000-S2T), arc welding machine (Panasonic YD-350GL4), gas shielding device and image acquisition system (Keyence YW-6000). The laser head and welding torch were installed at the end of KUKA six-axis robot. The laser wavelength is 1.07μm, the focal length is 300mm, and the focus diameter is 0.468mm. A high-speed camera with a narrow band filter at 930nm was placed horizontally on the side of the weldment for observation. The image acquisition frame rate was 2000 fps and the image resolution was 640 pixel × 480 pixel. During the welding process, the robot and the high-speed camera remain stationary and the workbench moves in the opposite of the welding direction.

The surfacing welding material was 304 stainless steel which surface treatment was wiredrawing processing. The weldment size was 200mm×100mm×4mm. Before welding, wipe the weldment with alcohol to remove impurities and oil on the surface. The welding wire was ER308 which diameter was 1mm. The shielding gas was 98%Ar+2%CO2, which flow rate was 30L/min. During the welding process, the arc was in the front and the laser was in the back. The laser was directed perpendicular to the weldment surface, the inclination angle of the welding torch (α) was 41°, the distance between the laser and wire (DLA) was 2mm.

In order to study the droplet transition features (arc area, droplet transition period, droplet velocity) and their influence on the weld formation, the experimental group with dropwise transition was selected for analysis. The welding speed was 1.4m/min, arc voltage was 20V and current was 130A, and laser power range was 1.5-3.5kW.

3. Data Processing

3.1. Droplet Transition Feature Extraction

The image processing is shown in Fig.2. In the test with a laser power of 2.5kW, the image of frame 8653 was taken as an example.

The original image was transformed into a grayscale image, and gaussian blur was used to smooth and denoise the image. Cut the image to extract the arc ROI area, and bright objects such as arc and
droplet are extracted by threshold segmentation. It is found from the observation of the image that the droplet size fluctuates in a certain range under the constant welding process parameters. By selecting the appropriate threshold, the regions with too large and too small areas (arc, splash, wire) can be deleted, while the regions with medium areas (droplet) can be retained, and finally the binary image of the droplet can be extracted.

The geometric moment of the image can be used to calculate the contour area and the barycenter, the geometric moment of an M×N image (moment of order p+q) is

\[
m_{pq} = \sum_{i=1}^{M} \sum_{j=1}^{N} i^p j^q f(i, j)
\]  

Where, \(f(i, j)\) is the gray value of row \(i\) and column \(j\) of the binary image, the bright area is 1, and the dark area is 0. The area of the bright region (A) and the barycenter of the droplet (\(O_x, O_y\)) are calculated as (2) and (3).

\[
A = m_{00}
\]

\[
(O_x, O_y) = \left(\frac{m_{10}}{m_{00}}, \frac{m_{01}}{m_{00}}\right)
\]

After obtaining the barycenter coordinates of the droplet, the method of frame difference was used to calculate the velocity of the droplet passing through the pixel coordinate \(y=105\) of the image, as shown in Fig.3. Take frames 8650-8658 as an example, find two images before and after \(y=105\), that is frames 8654 and 8655, and calculate the droplet velocity approximately according to the barycenter of the droplet in these two images.
3.2. Weld Profile Extraction
Using computer assisted measurement system (measuring machine IN2.0/V4i scanning, measurement accuracy ± 0.065 mm) to extract weldment surface profile, convert "STL" format (grid surface data) to "ASCII" format (point data) by CloudCompare software. The weldment surface was parallel to the x0y surface by three-dimensional rotation, and the Z-axis coordinates of the 3D point cloud were rendered to get the image as shown in Fig. 4.

![Figure 4 3D point cloud image of weldment surface](image)

![Figure 5 Weld section drawing](image)

![Figure 6 Flowchart of calculation of weld width and height](image)

The 3D point cloud coordinates of weldment surface were imported into MATLAB software for processing, and the point cloud was fitted with a 0.01mm square grid by mesh function. The contour curve of the weldment section was extracted along the x axis, as shown in Fig. 5.
According to the weldment section, the weld width (B) and the weld height (a) were calculated, the flowchart is shown in Fig. 6. Where, B(j) and a(j) are respectively the weld width and weld height corresponding to the section in row j. Z(i,j), Y(i,j) and X(i,j) are respectively the coordinate values of z, y and x of the points in row i and column j.

4. Experimental Results And Analysis

4.1. Analysis of droplet transition features

After obtaining the arc area change curve, the fast fourier transform (FFT) was applied to the curve to get the spectrum, and the interval between the extreme points of the arc area was calculated as the droplet transition period, and the change curve and statistical chart of droplet transition period were drawn, as shown in Fig. 7.

By combining the K1 region in Fig. 7(a) for analysis, the extreme value of the arc area fluctuates about 26mm², droplet transition frequency fluctuates between 7 and 7.5ms, on the whole, arc area fluctuation and droplet transition frequency were stable, the droplet transition was in a stable state. The extreme value of the arc area showed slight elevation in the front segment, with an amplitude increase of about 6%, at the same time, droplet transition frequency was stable at 7.5ms, showing a local increase.

The extremum of arc area and droplet transition period have the same change trend. By combining the K2 region in Fig. 7(b) for analysis, to some extent, the larger arc area was, the larger droplet transition period will be, and the fluctuation range of arc area will be larger at this time. The spectrum diagram of arc area change curve can effectively reflect the overall stability of droplet transition [7]. When the harmonic frequency and transition period were narrow and dense, the droplet transition frequency fluctuates little, the arc combustion is in a stable state, and the droplet transition period is relatively stable on the whole, which also makes the weld formation more stable.

4.2. Weld formation analysis

In order to analyze the influence of droplet transition features on the weld formation under the condition of penetration and lack of penetration, the weld width, weld height, the ratio of height to width, droplet transition period and droplet velocity were analyzed, as shown in Fig. 8.

In general, when the extremum of arc area becomes larger, the arc length becomes longer, the droplet transition period becomes longer, and the droplet velocity decreases. However, the droplet velocity is
affected by many factors and has certain volatility and randomness. The interpolation curve of the droplet velocity was obtained by shape-preserving interpolation, and the influence of the droplet velocity on the weld formation was analyzed.

The droplet velocity has the same variation trend as the weld width and weld height roughly. On the one hand, the higher the droplet velocity, the longer the droplet transition frequency, which means that the arc plasma jet has a larger impact on the molten pool with a longer duration. The molten metal filling to the molten pool increases, the molten metal overflow to both sides of the molten pool increases, the welding toe spreads to both sides, making the weld width and height increase. On the other hand, the higher the droplet velocity, the shorter the arc length, the arc heat source is more concentrated, the melting area of base metal surface increases, and the weld width also increases. Due to the strong fluidity of the molten pool, the influence of a single droplet on the molten pool is negligible. Only under the joint action of multiple droplets, can the weld formation have an obvious influence. The weld height curve is relatively smooth, generally does not appear sharp changes. Compared with weld height, weld width is more closely related to the droplet velocity. It can also be seen from the fig.8 that when the droplet velocity increases locally, weld height does not change significantly, but weld width increases to a certain extent.

It is found from the M1 to M4 regions of Fig. 8 that the ratio of weld height to width will rise when the droplet transition period increases suddenly, which will result in weld stress concentration and reduce the welding quality. The abrupt increase of droplet transition period was caused by the sudden increase of arc length. On the one hand, the arc heat source was not concentrated, result in the solidification rate of the molten pool was accelerated and the fluidity was weakened. On the other hand, the impact of arc plasma jet and droplet on molten pool was weakened, which was reflected in the decrease of droplet velocity and transition frequency. Therefore, the degree of bulge of the weld will increase, which will increase the ratio of weld height to width. For the M5 region, the droplet transition period does not increase obviously, but the ratio of weld height to width shows an upward trend. After analysis, it is because there was a metal splash beside the weld in this region, which interferes with the extraction of weld width and make the extracted weld width wider than the actual weld width and decrease the ratio of weld height to width.

![Figure 8 Weld formation analysis.](a) Laser power 1.5kW, (b) Laser power 2.5kW]
5. Conclusion

(1) The increase of arc length will decrease the melting speed of welding wire and decrease the droplet transition frequency, the extremum of arc area and droplet transition period have the same change trend.

(2) Weld width and weld height is closely related to droplet velocity, and the increase of local average droplet velocity will increase the local weld width and weld height.

(3) Droplet transition period can reflect droplet velocity and arc plasma jet impact on molten pool to a certain extent. The shorter the droplet transition period, the higher the droplet velocity, which will decrease the ratio of weld height to width. The abrupt increase of arc length will increase the ratio of height to width, which will reduce the welding quality.

(4) The arc area, droplet transition period, droplet velocity and other features extracted from the welding process images can effectively reflect the weld formation, providing a theoretical basis for the realization of laser-arc hybrid welding monitoring and prediction of weld formation.

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