Study on Human Welder Behavior by Measuring Local Flow Pattern of Weld Pool and Torch Posture

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Abstract. To study human welder behavior by sensing the welding torch posture and weld pool flow pattern, so as to provide a way to realize intelligent robot welding, a synchronous experiment system is setup with laser vision and a dynamic tilt sensor to precisely obtain the three-dimensional information of weld pool and torch posture. In the downward welding experiment, the data of reflected laser striped image of weld metal fluid flow and the change of torch posture are obtained. The algorithm for extracting weld metal fluid flow characteristic parameters is also written to obtain the weld pool flow pattern. Through the experiment analysis, it is found that the change of weld pool flow characteristic parameters and the change of torch posture have obvious coherence. The change of torch posture reflects the reaction and control ability of the human welder. The change of the weld pool flow characteristic parameters reflects that the welder maintains specific weld metal fluid flow pattern and obtains good weld forming ability.

Keywords: GTAW · Human welder behavior · Laser vision · Local flow pattern · Weld pool · Torch posture

1 Introduction

It is found that through observing the surface of weld pool, skilled welders can adjust the welding torch posture correctly to control certain penetration status, and to control the weld defects so as to obtain homogeneous weld as much as possible [1]. However, it needs a long-term to train human welders for getting skills and experience. Welders' experience is the interaction behavior between people and weld pool. In order to realize intelligent robot welding [2], many scholars of home and abroad have studied the interaction behavior between human welder and weld pool. Liu Yukang, Zhang Yuming [3–6] made some researches on human welder behavior relating to welding current and welding speed, they proposed an adaptive neuro-fuzzy inference system (ANFIS) to correlate the human welder's response to the 3D weld pool surface as characterized by its width, length and convexity. Japan's Aoyama Gakuin University [7] made a research on welder behaviors with four cameras to record the positions of tungsten electrode tips in the TIG welding with filler wire process. British M.S. Erden [8] identified the difference between skilled welder and unskilled welder by analyzing the data of welding torch tip's position which was obtained from a three-dimensional motion capture system, and the result showed that

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skilled welders can control the welding torch tip and limit the torch speed to vary in a small range. Liu Yukang, Zhang Yuming [9] also established a virtual welding system, which successfully finished the welding on a pipeline, and they obtained a good weld formation. They established a predictive control algorithm, made the automated GTAW pipeline welding experiment with different welding current and speed. The result showed that the algorithm has a good robustness. However, these studies are all focused on the control or regulation of the energy index of the weld pool. On the one hand, the regulation of energy is easy to make the temperature gradient change relatively, which makes the weld pool unstable. On the other hand, the regulation of energy is easy to make the property of welded joint change greatly, which influences the follow-up service of welds. Therefore, this paper proposes a new experimental scheme that intends to control welding torch posture to change the weld metal flow pattern of weld pool and adjust local heat input of the thermodynamic coupling process. At present, direct measurement of the weld metal flow pattern is very difficult. Although some researchers have investigated the measurements of molten pool fluid flow in metallic melts [10, 11], those processes are not associated with actual welding conditions.

This paper focuses on qualitatively studying the correlation of the welding torch posture and the local flow pattern of the weld pool, which in turn reflects the human welder's responses on the varying weld pool surface, and verifies the proposed scheme to investigate the interactive behavior of welder. To this end, a synchronous acquisition test system, including a five-line-mode-structure laser vision to measure the flow pattern of weld pool and a dynamic angle sensor sensing the data of welding torch posture were established, and the verified experiment was performed.

2 Experimental Principle and System

2.1 Experimental Principle

During TIG welding process, the surface of liquid weld pool carries important welding physical information. However, during the welding process, the change of the weld metal fluid flow cannot be measured directly. Therefore, this paper presents the measuring method of using the striped laser vision to measure the local flow pattern of weld pool. The laser stripes produced by low-power structured laser are projected, covering on the surface of weld pool. The changes of the laser stripes reflected on the surface of the weld pool are observed and recorded by the CCD camera and stored in the computer. Because the laser stripe pattern, which is projected onto the surface of weld pool with a certain geometric parameter and imaged after specular reflection, has a strict optical correspondence with the change of the flow pattern of weld pool on the surface, so the spatial geometrical mapping optical model established between the weld pool and the projected laser stripes can realize the dynamic measurement of the weld metal fluid flow. The principle is shown in Fig. 1.

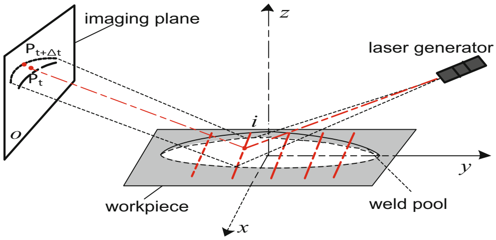

Fig. 1. Experimental principle

2.2 Experimental System

According to the principle of measuring the flow pattern of weld pool by laser vision in Fig. 1, the experimental system of synchronous acquisition in Fig. 2 is established. The experimental system of synchronous acquisition uses the MPU6050 sensor to sense the welding torch posture. In the system, a structured laser with wavelengths of 658 nm, 37.5 mW is placed in plane *OYZ*, and it was about 90 mm from the weld pool, and about 30° from the work-piece. In the plane *OXZ*, an imaging screen is vertically or obliquely placed about 53 mm from the weld pool to intercept the striped lacer reflected by the weld pool surface. The system uses the high-speed CCD camera to record the reflected laser image. In order to further reduce the impact of the arc exerts on the image quality, CCD camera lens is equipped with a 660 ± 10 nm band-pass filter. It uses AC-DC inverter welding machine TIG315AC/DC as a welding power source. During the welding process, the torch is supported by the universal joint and adjusts the direction and speed of welding trolley by the stepper motor combined with an inverter.

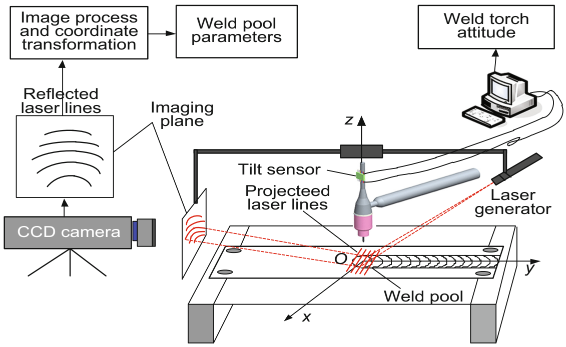

Fig. 2. Experimental system

3 Experimental Procedure and Discussion

3.1 Image Processing Algorithm

In order to extract the laser stripes' curvature radius from the collected laser stripe image, the image should be preprocessed at first. In order to remove the noise signal in the reflected laser stripe image, image filter method was adopted. Through the binarization of image processing, the laser stripe is separated from the image and to study. The edge of the laser stripe contains a wealth of intrinsic information, which is a basis to make a distinction between a laser stripes and another one. In order to facilitate the curve fitting of the laser stripes, it is necessary to perform the image edge detection on the edge of the laser stripe image, and then extract the edge value of the laser stripes, using the least squares fitting method to fit the midpoint between the upper and lower edges of the laser stripes. The fitting steps are as follows.

Fitting Laser Stripe Function
Assuming the general expression of the image fitting function is:

$$y = a_0X^n + a_1X^{n-1} + a_2X^{n-2} + \ldots + a_iX^{n-i} \ldots + a_{n-1}X + a_n \tag{1}$$

where $a_i(i = 1, 2, 3 \ldots n)$ are constants.

Midpoint value should be fitted at first, and each midpoint value should be go on through, and then a_iX^{n-i} can be constructed, and finally the fitting function of the midpoint value in the laser stripe was obtained. Figure 3 shows the laser stripes' midpoint detection, and the detected mid-points were fitted by the above function. The fitted curve can be seen in Fig. 3 red line.

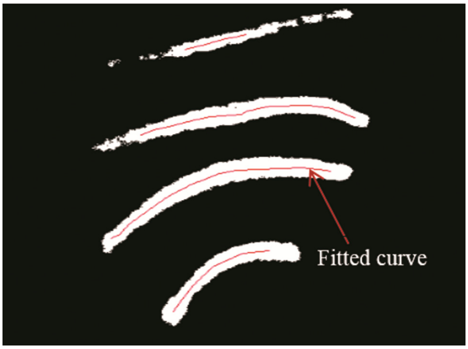

Fig. 3. Midpoint detection of laser stripe (Color figure online)

Solving the Laser Stripes' Curvature Radius. After the function expression that can expresses the laser stripe image is obtained, each a_iX^{n-i} should be goon through and to find the first derivative $(n - \mathrm{i})a_iX^{n-i-1}$. And then each $(n - i)a_iX^{n-i-1}$ should be goon through to find the second derivative $(n - i - 1)a_i X^{n-i-2}$, finally the first derivative function expression y' of the function, and the second derivative function expression y'' can be obtained.

Then according to the expression of curvature K:

$$K = \frac{|y''|}{(1 + y'^2)^{3/2}} \tag{2}$$

Therefore, the curvature radius:

$$R = \frac{1}{K} \tag{3}$$

Thus the solution of the laser stripes' curvature radius function expression is obtained, which is shown in Fig. 4.

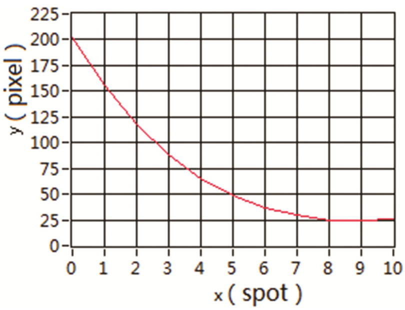

Fig. 4. The curvature radius of the laser stripe

Representation of Local Flow Pattern of the Weld Pool. As shown in Fig. 1, the ith laser stripe reflected by the surface of the weld pool is taken as an example. After an interval time Δt, point $P(t)$ moved to point $P(t + \Delta t)$. Taking a small part of the liquid metal on the surface of weld pool as an example, a micro displacement Δs occurred in the pool. Taking the laser stripe on the imaging screen as the object of study, the reflected laser stripes' curvature radius is changed from $R(t)$ to $R\ (t + \Delta t)$, so the flow rate of the weld pool is:

$$V = \frac{\Delta S}{\Delta t} \tag{4}$$

Because $\Delta t \to 0$, so $\Delta s \to 0$, simply:

$$\Delta S = f\left(R_{t+\Delta t} - R_t\right) \approx c\left(R_{t+\Delta t} - R_t\right) \tag{5}$$

where c is a constant.

So:

$$V = c\frac{\Delta R}{\Delta t} \tag{6}$$

After the laser stripes curvature radius of function expression is obtained, the curvature radius of each laser stripe. Since the length of the video time is T, the total number of the pictures which obtained after framing is N, the flow rate is expressed as a function between the change of curvature radius and time:

$$V = c\frac{\Delta R}{\Delta t} = c\frac{\Delta R}{\frac{T}{N}} \tag{7}$$

3.2 Experimental Results and Discussion

In order to extract characteristic parameters which reflect the change of flow pattern of weld pool from the changing laser stripes, a program to extract the laser stripes' curvature radius is written in Lab VIEW by using the program flow chart shown in Fig. 5.

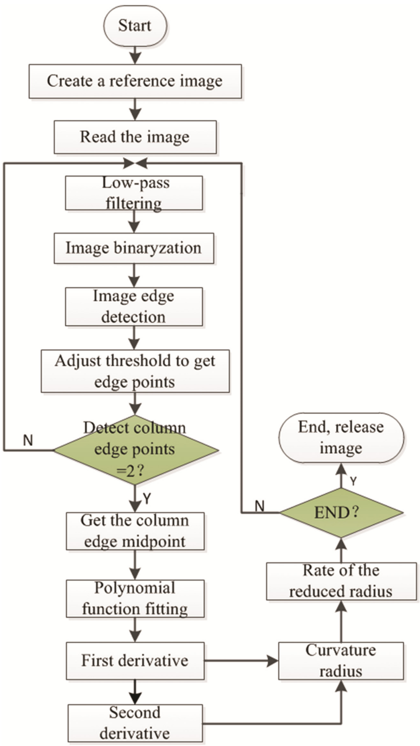

Fig. 5. The program flow chart of laser stripe image processing

The established experimental platform was used to make a bead-on-plate welding experiment with 304 stainless steel, and the experimental parameters are shown in Table 1. When the laser stripes completely covered the surface of the weld pool, the laser stripe images captured on the imaging screen were shown in Fig. 6. In order to study the welders' behavior of adjusting flow pattern of weld pool by adjusting the weld torch posture, the program which was written by the program flow chart shown in Fig. 5 was used to process the laser stripe image.

Table 1. Experimental parameters

Name	Material	Plate thickness H/(mm)	Current I/(A)	Arclength l/(mm)	Welding speed v/(mm/s)	Gas flow Q/(L/min)
Parameters	304 Stainless steel	3	60	3	1.5	8

Figure 6 shows laser stripe images which reflected by the weld pool surface during the welding process, and the image was formed under the DC current which was obtained every 3 s in the video shot by the high-speed camera with the sampling frequency of 200 Hz. In Fig. 6, during the whole welding process, the shape of the laser stripe image is changing constantly. There are 3 points selected in the second laser stripe image: the point near the center of the weld pool, the point near the edge of the weld pool and the point between the center and the edge of the weld pool. And the Fig. 7 shows the dynamic changing curve of torch posture. Figure 7 shows the weld pool characteristic parameters of local flow pattern, which is obtained from Eq. (7). From the change trend of the whole curve, we can receive the information that closer to the center of the weld pool, the greater of curvature radius change rate will be, indicating that when the position is closer

Fig. 6. The typical reflection of the laser stripe (the time interval of images: 3 s)

to the center of the weld pool, the liquid metal's flow rate will be greater. The comparative analysis between Figs. 7 and 8, it shows that in Fig. 7, weld pool characteristic parameters of local flow pattern change greatly at 30 s–34 s while the angle of torch posture also changes greatly at 30 s–34 s. Correspondingly, weld pool characteristic parameters of local flow pattern at 47 s–51 s in Fig. 7 changed dramatically, while the posture angle at the 47 s–51 s in Fig. 8 changed greatly, and then weld pool characteristic parameters of local flow pattern reaches a steady state again. The results show that when the welding process unstable state is caused by the change of weld pool local flow pattern, welder can adjust the welding torch posture to bring the weld pool to another steady state again. The change relationship between the rate of laser stripe's curvature radius changes and time also reflects the liquid metal's flow state in the plane *XOZ* to a certain extent. When the position is closer to the center of the weld pool, the liquid metal flow rate will be greater. This result agrees well with that by simulation [12].

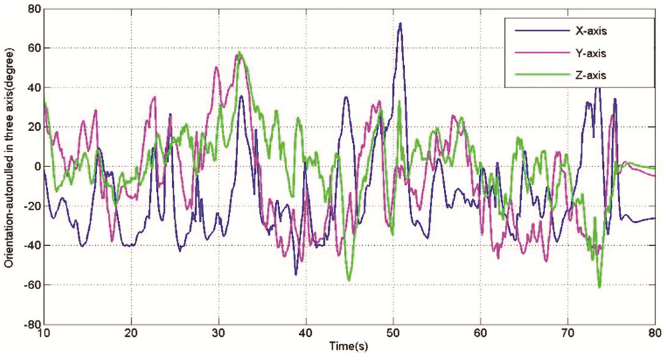

Fig. 7. The posture curve of welding torch

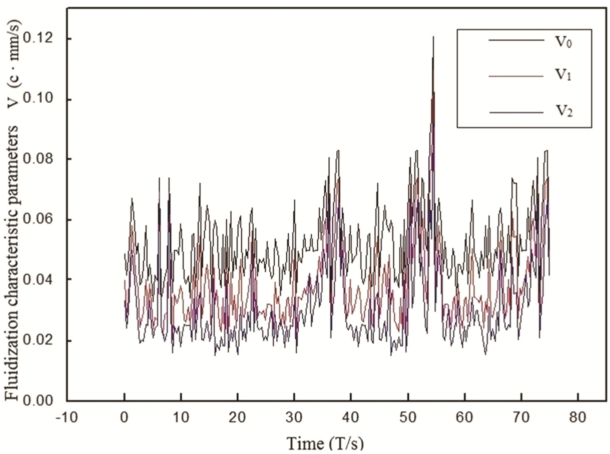

Fig. 8. The fluidization characteristic parameters (v_0 represent central area of weld pool; v_1 represent between central and edge area of weld pool; v_2 represent edge area of weld pool)

4 Conclusions

A new method is proposed in this paper to characterize the local flow pattern of weld pool by mean of measuring the dynamic change rate of the curvature radius of weld pool surface during welding process. The change of weld pool characteristic parameters of local flow pattern and the change of welding torch posture have obvious coherence, therefore it can characterize the human welder behavior in welding operation. The weld pool characteristic parameters of local flow pattern show that liquid metal flow rate at the center of weld pool is greater than that at the weld pool edge. This result agrees well with that by similation.

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