Research on width control of Metal Fused-coating Additive Manufacturing based on active control

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Abstract. Given the stability of the shape of the forming layer is one of the key problems that affect the final quality of the sample morphology, taking a study on the forming process and the control method of morphology make a significant difference to metal fused-coating additive manufacturing (MFCAM) in achieving the efficient and stable forming. To improve the quality and precision of the samples of single-layer single pass, a control method of morphology based on active control was established by this paper. The real-time acquisition of image was realized by CCD and the characteristics of morphology of the forming process were simultaneously extracted. Making analysis of the characteristics of the width during the process, the relationship between the relative difference of different frames and moving speed was given. A large number of experiments are used to verify the response speed and accuracy of the system. The results show that the active system can improve the morphology of the sample and the smoothness of the width of the single channel, and increase the uniformity of width by 55.16%.

1. Introduction

Additive manufacturing (AM) technology can break through the limits of parts in complexity of shape and form three-dimensional solid parts directly, which has several inimitable advantages over other traditional manufacturing technology [1]. Metal Fused-coating Additive Manufacturing (MFCAM) has been proposed as a commercial manufacturing that is a prospective additive manufacturing (AM) technology for fabricating 3D metal functional parts. Making a comparison with other metal additive manufacturing technologies, it possesses the obvious advantage of the lower cost of equipment. However, the poor shaping precision and surface quality have seriously restricted the application of MFCAM. In order to overcome these shortcomings and expand the application prospects of technology, monitoring the forming process is of great significance. As far as we know, process monitoring is widely used in the field of welding rather than MFCAM in quality control. Pinto-Lopera et al. presented a novel technique for real-time measuring of the width and height of weld beads in gas metal arc welding (GMAW) using a single high-speed camera and a long-pass optical filter in a passive vision system [2]. Cruz J G et al. presented a methodology to perform the modeling, optimization and control of the weld bead width, enabling the adjustment of process parameters in real time. [3]. A common method to monitor geometric variables in GMAW processes is the indirect mode, by using a mathematical model to relate the geometric parameters to another process variable that is easier to measure, such as current or voltage [4-5]. Hu Xiao dong from Xi'an Jiao tong University, who used CCD to monitor the metal forming process and designed a fuzzy PID controller that was
adjusted by capturing the image information of the weld pool, which made welding samples obtain better processing accuracy [6]. Heralic et al. designed a system for directly observing the height of the molten pool and structured photo-detection based on CCD and established a dual-input-output closed-loop control system adjustment system through adjusting the wire feed speed to control the width of the weld and the laser power, which ensured a high degree of stability [7-8]. Liu Xiao Yan et al from Hunan University, proposed the control algorithm of material state by using the principle of image feedback and designed the real-time control system of the motion state of the rotating drum, which can realize real-time monitoring of the movement state of the rotating cylinder realize the real-time monitoring of the rotary cylinder motion state [9]. Huang Jin et al. from Northwestern Polytechnic University, proposed an automatic target recognition algorithm based on sequence images, and the results of the simulation for various posture aircraft images show that the algorithm can effectively and accurately identify the aircraft types [10].

2. Experimental procedure
Molten metal is transported from the channel of the fused-coating nozzle to the region between the horizontal moving substrate and the thermal capillary flow. The melt encounters the relatively cold substrate or pre-solidified layers, cooling and solidification begin at the interface of the melt and substrate or pre-solidified layers. The solidified layers will be subjected to the same forming motion along with the substrate. The strong shear stress generated at the solidification front will be consequent ancillary products as the rapidly moving and advancing solidification front encounter cooling conditions. What’s more, the newly formed dendrites might shed to a certain extent due to the interfacial shear stress. What is important is that the new forming process can significantly enhance metal forming efficiency. The conclusion can be drew that if the forming accuracy and surface quality got be further improved, MFCAM will have a great prospect in the field of national defense industry, automobile industry and so on.

2.1. Experimental System
The schematic diagram of MFCAM and forming platform are illustrated in detail in Fig. 1 (a). The main subsystems of experimental system consist of a pressure control system, an inert gas (argon) protection system, and a machine control system based on a three-dimensional motion platform. In most actual conditions, the specimens were successfully manufactured through the effective combination and mutual cooperation of each module according to model’s information. Under the combined action of gas pressure, hydrostatic pressure, and surface tension, the molten metal flows through the channel in the fused-coating head, as shown detailed in Fig. 1 (b).

![Figure 1. (a) Molten metal micro-coating equipment schematic diagram. (b) Forming principle diagram](image)

2.2. Arrangement of the Experiments
The raw material of Single-layer single pass specimens in the experiment is the long block of Sn63Pb37 alloy. Taking the thermal properties of material into comprehensive consideration, the crucible temperature was heated to 270 °C, the initial distance between the micro-coating nozzle and
the substrate was set to 1.6 mm, the substrate temperature was set to 90 °C, and the argon mass flowmeter pressure was set to 100KPa. Single-layer single pass (SLSP) experimental conditions are shown in Table 1.

| Parameter                        | Value                   |
|----------------------------------|-------------------------|
| Coating Head Temperature         | 270 °C                  |
| Argon Mass Flow Rate             | 10~80 mm³/s             |
| Deposition Velocity              | 9~27 mm/s               |
| Initial Distance                 | 1.6 mm                  |
| Coating Nozzle                   | 0.3 mm                  |
| Pressure                         | 100 KPa                 |
| Glove Box                        | Ar (99.999%) (20 ppm)   |
| Size of Copper-clad Substrate    | 300*200*10 mm           |
| Single-track Deposited Length    | 130 mm                  |

3. Problems and solutions

It is found that there is an inconsistency in the width of the single-layer single pass alloy specimens under normal forming process, through visual direct observation. The width of the middle section is in the smaller fluctuations with a high consistency, however, there are more fluctuations in the start and stop segments. Given the above phenomena, the first width sampling point is set at 5mm from the start position, and the length of the model is more than 100 mm. To reflect the variation of the width of the sample, the single-layer single pass sample is segmented by the sampling as Fig. 2 (b). Where L represents the total length of the single-layer single pass sample, ΔL (ΔL for different samples is different) represents the sampling segment spacing, the number 1-20 represents the number of sampling points, and the length related in Fig. 2 (b) satisfies L = (ΔL + 20 * 5+10) mm. With reference to the sampling model, the width of the sample point is measured using the software of Halcon after the necessary calibration and the value of width retains four decimal places as shown in Fig. 2(a). The statistical curves of 6 groups of samples’ width have been drew according to the measured results, which could be found in Fig. 2(c).

Figure 2. (a) Width measurement practicality picture. (b) Width sampling model. (c) Width variation curves of single-layer single pass in 6 group
In order to quantify the changes of the width of the single-layer single pass alloy samples and obtain the necessary information which comprises maximum width, minimum width, mean width and width standard deviation, the measured width of the above six groups was analyzed statistically. More details could be found in Table 2. The standard deviations of the B and C samples in Table 2 are 1.30929 and 1.23926, respectively, which are shown in Fig. 2 (c) with large fluctuation. The standard deviations of E and F samples in Table 2 are 0.41369 and 0.36477, respectively, reflected in Fig. 2 (c) shows a small range of width fluctuation. Analysis found that the standard deviation can better reflect the width of single-layer single pass specimen changes. Taking the above into consideration, the paper uses the standard deviation to measure the uniformity of the sample width.

**TABLE 2.** statistics of width information of single-layer single-pass samples.

| Sample | Mean (mm) | Minimum (mm) | Maximum (mm) | Standard Deviation |
|--------|-----------|--------------|--------------|-------------------|
| A      | 3.88      | 3.32         | 5.54         | 0.57109           |
| B      | 6.54      | 5.02         | 9.6          | 1.30929           |
| C      | 6.65      | 4.44         | 8.42         | 1.23936           |
| D      | 4.24      | 3.56         | 7.02         | 0.86077           |
| E      | 3.08      | 2.88         | 4.68         | 0.41369           |
| F      | 3.56      | 3.18         | 4.72         | 0.36447           |

There are many factors affect the sample width, such as the physical properties of the raw material, the system pressure and substrate speed. The phenomenon found by experiment was that among these factors, the substrate velocity had a great influence on the sample width and it had faster response than other factors. The paper proposes the solution that the speed of the substrate can be adjusted automatically by the width change, and thus the control of sample width can be realized to a certain extent. Therefore, the sample shape and the width consistency can be improved greatly.

4. **Image capture system**

In order to verify the proposed ideas, the vision sensor of CCD was added to current MFCAM system. The camera used in system has a USB2.0 data transfer interface and the camera can be used for a maximum resolution of 2048 * 1536 pixels. It is worth emphasizing that the camera has a frame rate range of 12-114 PFS related to the resolutions. The relative position of the camera, nozzle and substrate is shown in Fig. 3 (a).
The CCD in the equipment was calibrated to minimize the effect of optical distortion to the maximum extent. Camera calibration is the process of solving the camera internal and external parameters through a certain number of different spatial position images. In the practical application, we need to recalibrate the CCD camera, if we need to adjust the camera position. The process of camera calibration is completed in the Halcon software platform by capturing the images of the calibration plate at different positions. The calibration process and related images are shown in Fig. 3 (b), which is characterized by the follows: the number of marked points and rows of $7 \times 7$, the distance of the neighbor marker points is 3mm, the diameter of the mark point is 1.5mm, and the width of the black frame is 0.75mm. 20 calibration images were used in Polynomial model of traditional calibration method. The calibration process is completed in the Halcon calibration assistant, and the camera internal and external parameters are obtained as follow:

\[
\text{SatrtCamPar} := [f, k, S_x, S_y, C_x, C_y, \text{Width, Height}]
\]

1) Where \( f \) is the focal length, \( k \) is the distortion coefficient, initialized to 0, \( S_x \) is the horizontal distance of the adjacent pixels of the, \( S_y \) is the vertical distance of two adjacent pixels, \( \text{Width} \) is the image width, \( \text{Height} \) is the image height. \( C_x, C_y \) is the center of projection in the vertical projection imaging plane.

5. Automatic control algorithms
Dynamic monitoring the width of single-layer single pass is a prerequisite for automatic control. In the forming process, the crucible nozzle is relatively stationary and 3D platform follow the predetermined trajectory. It is possible to obtain the increment of single channel width and the width of the last node, as for the length of samples on different time nodes is different. Considering that the system depends on the motion of the substrate, the image captured by CCD is the relative displacement at the actual condition. The automatic control algorithm of width based on active control is proposed for the MFCAM process, which mainly includes the method of automatic detection and control of the motion state of the substrate based on the image width. The block diagram of single-layer single specimen’s width control system can be found in Figure 4 in detail.

![Figure 4. Block diagram of single-layer single specimen’s width control system.](image-url)
The relative difference between the two adjacent widths $\Delta W$ could be calculated on the basis of the obtained width of single-layer single pass, and the update velocity of substrate is determined by the dynamic change of $\Delta W$. Many experiments show that when $|\Delta W| < 0.05$, the current substrate speed shouldn’t be changed, and when $|\Delta W| > 0.05$, the substrate speed needs to be changed according to empirical Formula 2.

$$
\Delta V = \begin{cases} 
-\frac{\Delta W}{a} \cdot V_0, & (\Delta W \geq 0.05) \\
0, & (|\Delta W| \leq 0.05) \\
+\frac{\Delta W}{a} \cdot V_0, & (\Delta W \geq 0.05)
\end{cases}
$$

The $\Delta V$ that can be converted into the velocity of motor could be calculated quantitatively by $\Delta W$. IPC uses the pulse increment which is transformed from $\Delta V$ to achieve the control of substrate velocity. As far as we know that the pressure at the beginning is unstable, so the automatic control program of width delays 20ms after the implementation. In the actual forming process, the CCD acquisition speed is 8 frames per second, and the width increment is dynamic refreshed to actualize real-time control.

### 6. Experiment and result analysis

The hardware and software of system combined effectively to take the forming process in single direction for verification. The width data of single-layer single pass specimens were made into statistics in Fig. 6 (b) according to the Fig. 2 (b) sampling model. The trend of width change is weakened than before and the subsequent forming process is stable respectively like Fig. 6 (a). The standard deviation of the sample width (Table 3) is found to be reduced, and the sample has better consistency than ever. The experimental results show that the control system based on image feedback can meet the requirements of real-time response, and improve the forming accuracy of the sample to some extent.
### TABLE 3. statistics of width information of single-layer single-pass samples based on active control.

| Sample | Mean (mm) | Minimum (mm) | Maximum (mm) | Standard Deviation |
|--------|-----------|--------------|--------------|--------------------|
| A      | 4.212     | 3.92         | 5.68         | 0.44568            |
| B      | 3.39      | 5.28         | 3.98         | 0.15252            |
| C      | 4.926     | 4.62         | 6.56         | 0.52114            |
| D      | 5.808     | 5.52         | 7.22         | 0.37721            |
| E      | 2.588     | 2.46         | 3.78         | 0.28153            |

(a) A test sample of control in track width;
(b) Statistical curves of 5 different samples with control in track width)

7. Conclusions
To conclude, the method based on active control was carried out in micro-coating metal additive manufacturing (MCMAM). The forming morphologies of the width of single layer single pass specimens were analyzed in detail, and the main findings are summarized as follows:
After automatic width automatic control algorithm is used, the accuracy has been greatly improved, and the average increase of sample width uniformity reaches 55.16% than before.
In Metal Fused-coating Additive Manufacturing (MFCAM), the monitoring data and process parameters are closely combined to obtain the better specimens. The developed algorithm based on active control has great universality and versatility to improve the quality of specimens in MFCAM. Although the method could improves the surface quality and forming accuracy of the forming parts, to a certain extent, there is still a long way to go from the precise industrialization application. In the further work, we will pay attention to further improve the response speed of the method to improve its efficiency.

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