Analysis of characteristics of process parameters in CMT additive manufacturing

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Abstract. To have a further study on the dynamic response characteristics of process parameters in cold metal transfer wire plus arc additive manufacturing (CMT-WAAM), the paper selects aluminium alloy 2319 as experimental material. On the basis of previous experiments, step response experiments were carried out for the forming parameters, welding speed (WS), wire feeding speed (WFS), arc length correction and pulse correction included. After WEDM, the width and height of the single layer single pass (SLSP) were captured respectively, and then the image processing algorithm was used in Halcon12.0 software for edge extraction and static extraction of sample contour’s morphology features. In this paper, different feature extraction algorithms were proposed for the layer height and the pass width, and the characteristics of process parameters were given.

1. Introduction
Additive manufacturing (AM) is a promising technology with unique advantages, such as low consumption, high efficiency, economic and can significantly shorten the development time of the product, therefore the domestic and foreign scholars have launched a wide range of research for this field. However, when it comes to specific AM processes, different processes have their special occasions in manufacturing. The forming precision of selective laser melting (SLM) and electron beam powder manufacturing (EBM) is higher, but lower deposition efficiency was a huge cost in consequence. In addition, due to the confinement of its airtight space in atmosphere protection, the SLM and EBM may have limits to form large and medium-sized parts. At meanwhile, the majority of key components on domestic AM equipment rely on importation was still a urgent need to change [1].

Compared with the traditional manufacturing, WAAM has a higher flying ratio and no limits in the size of forming dimension theoretically [2]. Make a comprehensive comparison with SLM and EBM, WAAM has a great advantage in economy, due to its inexpensive raw materials and general equipment [3]. Aluminum alloys in high strength are widely used in aerospace and national defense because of their outstanding strength-to-weight ratio, excellent comprehensive mechanical properties and corrosion resistance [4]. Among those AM processes, WAAM has already been proved to be more suitable for medium and large components requiring high forming efficiency and low cost [5]. Welding technology CMT (Cold metal transfer, CMT) integrates wire motion control technology, which can realize the digital coordination between wire feeding motion and droplet process through
mechanical structure. The surfacing process is more stable in CMT, making it a new process without spatter, welding slag, low heat input, good bridge ability for additive manufacturing [6], and it has been proved that CMT was suitable for forming aluminum alloy materials.

The control method is known to all that the current and voltage of FRONIUS-CMT welding machine changes with wire feeding speed. In order to obtain the dynamic response characteristics of process parameters of 2319 aluminum alloy in CMT-WAAM, step response experiments were carried out on the selected process parameters, such as welding speed (TS), wire feeding speed (WFS), arc length correction and pulse correction.

2. Experiments

2.1. Experimental equipment

The hardware of CMT-WAAM equipment mainly includes arc heat source system, motion platform, wire feeding mechanism, turntable and inert gas protection unit. The FRONIUS-CMT Advanced 4000R welder is used as the system heat source, which roughly consists of CMT welding power source, RCU5000I remote controller and cooling water tank FK4000R. To achieve good droplet transfer during the forming process, the FRONIUS-VR7000-CMT is equipped with a complete wire feeding mechanism, CMT wire buffer and filler drawing mechanism. The maximum wire filling speed can be up to 22m/min. KUKA KR16 six-degree-of-freedom robot was adopted as kinematic mechanism, which including control system, mechanical system and hand-held operation programmer. The movement mechanism is matched with turntable which diameter is 1.5 m. Compared with the ordinary three-dimensional motion platform, the robot has the advantages in mobility, flexibility and sufficient space. The physical objects are shown in Figure 1.

![Figure 1. The hardware of CMT-WAAM forming system.](image)

Table 1. The content elements of 2319 filler.

| Composition | Content(%) |
|-------------|------------|
| Si          | 0.20       |
| Fe          | 0.30       |
| Cu          | 5.80-6.80  |
| Mn          | 0.20-0.40  |
| Be          | 0.0003     |
| Zn          | 0.10       |
| Ti          | 0.10-0.20  |
| Zr          | 0.10-0.25  |
| Al          | balance    |

2.2. Experimental filler

An aluminum alloy wire with a diameter of 1.2 mm and grade of 2319 is used as a filler in this research. The alloy is widely used in the aerospace, automotive and military industry for high better hardness and corrosion resistance.

Firstly, EDS element analysis and X-ray characteristic composition analysis were carried out on the raw filler. The composition of the raw filler could meet the national standard. The detailed composition was shown in Table 1 and the experiment was carried out in C+P mode.
2.3. Experiments design
WAAM-CMT is a complex nonlinear forming process with multi-factor coupling effect. In the univariate model experiment process, to guarantee the accuracy of the experimental data to a extent, and to avoid the interference of accidental factors, the design of the process parameters need to meet the following conditions:
1. The variation of process parameters should be strictly controlled within a better forming interval, and defects should be avoided.
2. The sampling frequency should completely reflect the change of macroscopic appearance and ensure enough data for analysis.
3. Minimize gross errors and ensure repeatability of experiments.
There are two mainstream approaches to extract the morphological features of WAAM-CMT forming samples. Line laser profiler or vision sensors are used to monitor and extract the macroscopic topographical features during the forming process [7-10]. The visual sensor or scanner will be affected by the strong arc light during the forming process, the shape extraction accuracy fluctuates apparently, and the online equipment will consume much capital. Taking all aspects into consideration, the offline extraction method is adopted in this paper which has the advantages of high image quality and high accuracy of data features. Combine the previously process parameter range, screen the process parameters and give the experimental interval, as shown in Table 2.

| Parameters          | Range value |
|---------------------|-------------|
| WS / m·min⁻¹        | 0.3-0.7-0.3 |
| WFS / m·min⁻¹       | 5-7-5       |
| Argon               | 99.99       |
| Flow rates / °      | 25          |
| Arc length / °      | 0-30%-0     |
| Pulse correction    | 0-5-0       |
| Dry elongation /     | 10-18-10    |
| Substrate           | 400*400*20  |
| Sample length /     | 200         |

Figure 2. The figure of pass width.

3. Processing and results
3.1. Experiments and image capture
According to the process parameters in Table 2, the welding speed, the wire feeding speed, the arc length correction, the pulse correction and the dry elongation were carried out respectively in experiments. The substrate for forming was pre-treated with an alcohol and a copper brush before the experiment to remove the partial oxide film and other contamination on the surface. The single control variable mode was adopted, and the remaining process parameters remain unchanged (normal standard) in the forming process.

The overall length of the sample is 200 mm. Two sets of experiments are carried out for each process parameter, which can be used as a comparison reference and can be used to eliminate the coarse errors that occur during the experiment. In order to achieve the change of special parameters.
during the experiments, different JOB numbers inside the welder or different positions in KUKA were used.

![Figure 3. The figure of layer weight.](image)

![Figure 4. The edge extraction algorithm diagrammatic sketch.](image)

3.2. Edge extraction
The captured images were processed by cropping, horizontal correction and exposure compensation, and then imported into Halcon software for processing, and the data of layer height and pass width were extracted by edge extraction. Although the image was pre-processed, it is impossible to ensure that the sample is in the horizontal position in the image area. Therefore, direct selection of the fixed-point pixel coordinates as the layer height extraction feature point would bring a large error to some extent. The contact points A and B at the bottom were determined firstly, and then the two-point method was used to fit the contour line equation, the formula was as follows.

\[
\frac{Y - Y_B}{Y_A - Y_B} = \frac{X - X_B}{X_A - X_B}
\]  

(1)

In order to reflect the variation law of the layer height in detail, the measurement interval was 10 pixel units, and the measurement line L1 in Figure 4 was established. The measurement line is perpendicular to the central axis of the image, and the coordinate of C was obtained by the edge recognition method. D is the intersection of the extension line of the measurement line and the fitting line segment Y. Through the coordinates of C and D and the pixel equivalent, the height difference H between the intersections of the lines could be extracted and calculated, and then the layer height h could be calculated indirectly by the pixel equivalent PD. The calculation formulas are as follows:

\[
H = \sqrt{(X_C - X_D)^2 + (Y_C - Y_D)^2}
\]

(2)

\[
h = H \ast PD
\]

(3)

Pass width measurements could use edge pairs or double edge recognition. The former uses only one measuring line, and the measuring line will intersect with the two contour edges of the sample image. The pixel space distance can be calculated by the position coordinates between the intersection points, and the actual space distance can be obtained by using the pixel equivalent. See Figure 5(3) for details of W1 measurement. The latter uses two lines to identify each side edge of the contour separately. The comparison shows that the W1 process is more concise and suitable for high-quality and clear-cut images; the W process is relatively complex, and it can realize separate control of edge
extraction parameters, reduce the error of unified control, and improve the recognition accuracy. Given this, the double edge recognition algorithm was adopted to extract the pass width.

### 3.3. Results

In order to adequately reflect the variation of the macroscopic features of the sample and clearly express the influence of the parameter mutation on the morphology, the sampling point was set at 450 or more. The welding speed step response curve is shown in Figure 5. The wire feed speed step response curve is shown in Figures 6. It could be draw the conclusion from Figure 2 and Figure 3 that the dry elongation produces convex hulls at the abrupt nodes, and the layer height and the pass width have a little change in dimension. The arc length correction step response curve is shown in Figures 7. The pulse correction step response curve is shown in Figures 8.

According to the obtained curve of deposition with process parameters, the conclusions could be draw that the welding speed and the wire feeding speed both have significant influence on the layer height and pass width, and the arc length correction and the pulse correction have some influence on the pass width but not significance on layer height. The above analysis was validated by statistical analysis of 25 groups of data in different stable stages and their average value was used for analysis. Detailed data is shown in the table 3.

![Figure 5. Transient response of layer height and pass width to welding speed.](image)
Figure 6. Transient response of layer height and pass width to wire feeding speed.

Figure 7. Transient response of layer height and pass width to arc length correction.
Figure 8. Transient response of layer height and pass width to pulse correction.

Table 3. Layer height and pass width statistics

| Parameters       | Initial Segment | End Segment | Change Value | Percent(%) |
|------------------|-----------------|-------------|--------------|------------|
| P-WS / m-min⁻¹   | 0.3             | 0.7         | -0.4         |            |
| Height-Avr       | 4.23            | 2.21        | 2.02         | 47.75%     |
| Width-Avr        | 8.58            | 6.15        | 2.43         | 28.32%     |
| N-WS / m-min⁻¹   | 0.7             | 0.3         | 0.4          |            |
| Height-Avr       | 2.78            | 4.02        | -1.24        | -44.60%    |
| Width-Avr        | 5.51            | 8.03        | -2.52        | -45.74%    |
| P-WFS / m-min⁻¹  | 5               | 7           | -2           |            |
| Height-Avr       | 2.76            | 2.73        | 0.03         | 1.09%      |
| Width-Avr        | 4.32            | 6.72        | -2.4         | -55.56%    |
| N-WFS / m-min⁻¹  | 7               | 5           | 2            |            |
| Height-Avr       | 2.78            | 2.86        | -0.08        | -2.88%     |
| Width-Avr        | 6.62            | 5.68        | 0.94         | 14.20%     |
| P-ALC/%          | 0%              | 30%         | -0.3         |            |
| Height-Avr       | 3.75            | 3.71        | 0.04         | 1.07%      |
| Width-Avr        | 6.31            | 5.62        | 0.69         | 10.94%     |
| N-ALC/%          | 30%             | 0           | 0.3          |            |
| Height-Avr       | 3.68            | 3.49        | 0.19         | 5.16%      |
| Width-Avr        | 6.08            | 7.04        | -0.96        | -15.79%    |
| P-PC             | 0               | 5           | -5           |            |
| Height-Avr       | 3.18            | 3.16        | 0.02         | 0.63%      |
| Width-Avr        | 6.02            | 7.26        | -1.24        | -20.60%    |
| N-PC             | 5               | 0           | 5            |            |
| Height-Avr       | 3.16            | 3.20        | -0.04        | -1.27%     |
| Width-Avr        | 7.46            | 6.62        | 0.84         | 11.26%     |
4. Conclusions
The image processing technology was used to obtain the width and height of the 2319 Aluminum alloy in the process parameter mutation process, and the curve of the curve was analysed in detail. The characteristics of the process parameters were compared. This paper could draw the conclusions as follow.

- For the extraction of layer height geometry data, a method of single edge contour line fitting is proposed;
- For the extraction of pass width geometry data, the method of collinear double edge recognition had been proposed, which could improve the recognition accuracy and facilitates the regulation of single edge parameters;
- The variation curve of process parameters was analysed, and the influence of process parameters on the morphology was obtained, which would provide a basis for the realization of closed-loop feedback control.

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