A Comprehensive Prediction Model of Bead Geometry in Wire and Arc Additive Manufacturing

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Abstract. To explore the effect of process parameters on the bead geometry in cold metal transfer wire arc additive manufacturing (CMT-WAAM), the response surface optimization method was adopted in this paper. According to previous experiments, some process parameters were selected as independent variables. They are wire feed speed (WF), traveling speed (TS) and substrate temperature (ST). Some geometric parameters of the welding bead were selected as dependent variables. They are the track width (w), layer height (h), penetration (p), accumulated area (A2), penetration area (A1), aspect ratio (B) and dilution ratio (D). In the given parameter interval, the prediction model behaves good. The relative error of bead size between actual value and predicted value are all within 5%. And five sets of verification experiment were carried out to prove that the accuracy of the developed model.

Keywords: Additive manufacturing; Bead size prediction; Response surface optimization; Aluminium alloy; CMT-WAAM.

1. Introduction

In the past few decades, Additive Manufacturing has become more and more popular in the manufacturing industry. So far, it has formed a three-legged situation with subtractive manufacturing and equal-material manufacturing. Due to its low-volume production and high degree of customization, metal additive manufacturing is useful to aerospace and biomedical industry. According to the F2792-12[1] standard metal additive manufacturing terminology which is proposed by American Society for Materials and Experiments Committee (ASTM), the main methods of metal additive manufacturing involve Powder Bed Fusion (PBF) and Directed Energy Deposition (DED). As one of the processes of DED, efficient and low-cost wire arc additive manufacturing (WAAM) has unique advantages for rapid prototyping of medium-complexity, large-size components for aerospace[2],[3]. High strength aluminum alloy for its excellent strength to weight ratio, excellent corrosion resistance and mechanical properties and widely used in aerospace and defense[4]-[6]. The materials currently used for the launch vehicle structure are mainly 2 series and 7 series high-strength aluminum alloys. CMT-WAAM can produce high-quality, spatter-free welded structures with low heat input[7], thus it has attracted widespread attention and recognition. The biggest feature of CMT is that the heat input in the welding process can be controlled, and the cold metal transition is to control the reciprocating movement of the wire feeding process through digital control and mechanical withdrawal. CMT-WAAM has been proved to be suitable for forming aluminum alloys.
Neural network was used to explore the relationship between TIG welding process parameters and welding bead size by Zhang Guangyun[8]. Bai Jiuyang[9] of Harbin Institute of Technology used a quadratic regression model to explore the relationship between TIG welding process parameters and the width of the multi-layer bead stabilization zone. Based on the pulsed PAW process, Xu Fujia[10] used BP neural network based on genetic neural algorithm to predict the weld bead size. The test sample melt width error reached 5.5%, and the maximum error of the residual height reached 13.9%. However, ST was not considered as a key factor in these researches and there is a few research on CMT-WAAM welding bead size prediction.

2. Experiments

2.1. Experimental Equipment

The hardware composition of CMT-WAAM system is shown in Fig. 1. The FRONIUS-CMT Advanced 4000R welding machine is used as the heat source of the forming system, and the FRONIUS-VR-1550 wire feeding device is used as a supporting device. The motion actuator uses a German KUKA-KR16 six-degree-of-freedom robot that can flexibly match various application requirements. The robot arm and joints are driven by servo motors, with high repeatability (0.05 mm), fast running speed, and small walking error of reciprocating path. In the process of conducting experiments, it is necessary to build a high-precision temperature control system to control and measure ST. The controller realizes DC-controlled AC through the thyristor output, thereby heating the substrate through the resistance wire. A K-type thermocouple with high temperature resistance was used to heat the substrate and the Simens TC1231 module was used to do the temperature calibration.

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

**Table 1.** The chemical composition of welding wire and substrate.

| Composition | Content [%] |
|-------------|-------------|
| Al          | balance     |
| Cu          | 5.80-6.80   |
| Fe          | 0.30        |
| Si          | 0.20        |
| Mn          | 0.20-0.40   |
| Zn          | 0.10        |
| Ti          | 0.10-0.20   |
| Zr          | 0.10-0.25   |
| Be          | 0.0003      |
2.2. Experimental Filler

For the experiment, ER2319 aluminum alloy welding wire produced by Fushun Donggong was used as the deposition raw material. The diameter of the welding wire was 1.2 mm. The substrate with the same composition as the welding wire is used. Its size is 500 mm × 500 mm × 30 mm. The composition of welding wire and substrate is shown in Table 1. Before the experiment, the surface of the substrate was polished with a grinder and wiped with anhydrous alcohol before drying.

2.3. Experiments Design

In order to reflect the influence of process parameters on the output variables and their interactions in a small number of experiments, the Box-Behnken method in the response surface optimization was used to design the test samples[11]. The process parameter range was determined based on experience. The working ranges were decided upon by inspecting the welding process for smooth appearance without spatters and other visible defects such as porosity and undercut. The chosen important factors with their units and notations are shown in Table 2.

Table 2. Process control and their levels.

| Parameters | Units | Notation | Factor levels |
|------------|-------|----------|---------------|
| WFS        | m/min | v        | -1 0 1        |
| TS         | m/min | \( v_s \) | 6 7.5 9       |
| ST         | °C    | T        | 50 125 200    |

As shown in Table 3, the development of the design matrix in software design experts in 8.0.6. The total number of experiments is determined by formula (1)[12].

\[
N = 2q(q - 1) + C_0
\]  

Wherein \( q \) is a number of experimental factors for reducing the number of the center point \( C_0 \) of experimental error due to environmental and human factors. In this article, the number of experimental factors are 3, \( C_0 \) is set to 3. In addition, to avoid the unstable section of the start position in the single weld bead and the coarse error due to the too short forming section, each forming path was set to 150 mm under different process parameters.

Table 3. Design matrix and response variables.

| Experimental runs | Design matrix | Response variables |
|-------------------|---------------|--------------------|
| \( v \) | \( v_s \) | \( T \) | \( w \) (mm) | \( h \) (mm) | \( p \) (mm) | \( A1 \) (mm²) | \( A2 \) (mm²) | \( B \) (%) |
| 1 | -1 | 0 | -1 | 4.55 | 2.84 | 0.81 | 9.90 | 1.88 | 1.60 | 15.94 |
| 2 | -1 | -1 | 0 | 6.02 | 3.10 | 1.38 | 14.75 | 3.60 | 1.94 | 19.62 |
| 3 | 0 | 0 | 0 | 7.32 | 2.49 | 2.26 | 13.15 | 8.60 | 2.94 | 39.54 |
| 4 | 0 | 0 | 0 | 7.40 | 2.45 | 2.00 | 12.97 | 7.21 | 1.94 | 35.71 |
| 5 | -1 | 1 | 0 | 4.48 | 2.25 | 1.17 | 7.50 | 2.81 | 1.99 | 27.26 |
| 6 | 0 | 0 | 0 | 7.28 | 2.55 | 2.14 | 13.70 | 7.67 | 2.85 | 35.90 |
| 7 | -1 | 0 | 1 | 6.38 | 2.25 | 1.62 | 12.01 | 6.80 | 2.84 | 36.14 |
| 8 | 0 | 1 | 1 | 7.88 | 1.83 | 2.29 | 11.19 | 10.17 | 4.31 | 47.62 |
| 9 | 1 | 0 | 1 | 10.11 | 2.36 | 3.58 | 18.11 | 19.25 | 4.28 | 51.52 |
| 10 | 0 | -1 | 1 | 10.37 | 2.71 | 2.44 | 22.76 | 14.39 | 3.83 | 38.73 |
| 11 | 1 | 1 | 0 | 7.70 | 2.31 | 2.83 | 11.83 | 11.53 | 3.33 | 49.35 |
| 12 | 0 | 1 | -1 | 6.77 | 2.01 | 1.54 | 10.45 | 5.27 | 3.37 | 33.52 |
| 13 | 1 | 0 | -1 | 8.55 | 2.70 | 2.44 | 15.89 | 10.24 | 3.17 | 39.19 |
| 14 | 1 | -1 | 0 | 9.70 | 3.33 | 3.34 | 26.35 | 17.26 | 2.91 | 39.58 |
| 15 | 0 | -1 | -1 | 7.56 | 3.27 | 1.51 | 21.08 | 5.51 | 2.31 | 20.72 |
In order to avoid the unstable section of the start position in the welding bead and the coarse error due to the too short forming section, each forming path was set to 150 mm under different process parameters. The section feature of welding bead includes track width \((w)\), layer height \((h)\), penetration \((p)\), accumulated area \((A2)\), penetration area \((A1)\), aspect ratio \((B=w/h)\) and dilution ratio \((D=A1/(A1+A2))\).

Dilution ratio is used to describe the shape of the welding bead. The larger the dilution is, the flatter the welding bead is. The definition of other parameters was shown in Fig. 2.

Figure 2. Single welding bead geometry.

Figure 3. The Figure of the deposition and the corresponding process parameters.

2.4. The Regression Model

Fig. 3 shows the figure of welding bead and the corresponding process parameters. Using the Keyence laser profile scanner to measure the height and width of SLSP, the unstable segment at the start position should be avoided, which can effectively reduce the coarse error and ensure the measurement accuracy. The number of measurements of each welding bead is 2000 and the average value was taken. A schematic diagram of the measurement principle was shown in Fig. 4.

Then the regression equations are founded in the software design-expert 8.0.6. The adequacy of the models was verified using analysis of variance (ANOVA), and the results were presented in Table 4. From the analysis, all developed models were adequate since F ratios were larger than the tabulated values at 95 % confidence level and p values less than 5% of significance. The values of R2 and Adj. R2 were over 90%. These values indicated that the developed models were quite adequate.

Table 4. ANOVA for developed models.

| Response          | F ratio | P value  | R² (%) | Adj. R² (%) |
|-------------------|---------|----------|--------|-------------|
| Bead width        | 205.75  | <0.0001  | 99.52  | 99.03       |
| Bead height       | 42.66   | <0.0001  | 96.97  | 97.70       |
| Penetration       | 112.25  | <0.0001  | 96.84  | 95.97       |
| Penetration area  | 142.53  | <0.0001  | 99.48  | 98.78       |
| Accumulated area  | 161.03  | <0.0001  | 99.18  | 98.56       |
| Ratio of width to height | 22.18   | <0.0001  | 97.56  | 93.16       |
| Dilution ratio    | 116.14  | <0.0001  | 98.47  | 97.63       |

After verifying the adequacy of the model, a T-test was used to eliminate the unimportant factor to avoid the accuracy of the developed model. Finally, the mathematical models of the forming process parameters and the geometric parameters of the welding bead were established. They were described in the equation (2) – (8):

\[
w = -12.179 + 4.6669v - 7.3708v_\delta + 0.0032019T - 0.028333v_\delta T - 0.2313v^2 + 5.6771v_\delta^2 + 0.0001039T^2
\] (2)
\[ h = 8.3499 - 1.0463v - 3.2979v_g - 0.000070299T + 0.0063333v_g \cdot T + 0.071197v_g^2 - 0.000223521T^2 \]  \quad (3)

\[ p = -2.8481 + 0.60036v - 0.53125v_g - 0.0060375 \]  \quad (4)

\[ A1 = -12.614 - 0.58594v + 32.287v_g - 0.020644T - 4.1158v \cdot v_g + 0.0090773 \cdot T - 0.066215v_g \cdot T + 0.36793v_g^2 + 0.00015393T^2 \]  \quad (5)

\[ A2 = 5.4377 + 5.9661v - 46.101v_g - 0.033492T - 6.05242v \cdot v_g + 53.343v_g^2 + 0.00017902T^2 \]  \quad (6)

\[ B = -11.506 + 3.2833v + 1.3255v_g - 0.012088T - 0.18994v^2 + 0.000080373T^2 \]  \quad (7)

\[ D = -74.235 + 8.9107v + 76.270v_g + 0.23902T - 0.017504v \cdot T - 43.186v_g^2 \]  \quad (8)

Figure 5. Results of the conducting experiments.

Table 5. Results of verification experiments.

| Item No. | 1     | 2     | 3     | 4     | 5     |
|---------|-------|-------|-------|-------|-------|
| WFS (m/min) | 7     | 7     | 6.5   | 8     | 8.5   |
| TS (m/min)   | 0.5   | 0.7   | 0.45  | 0.6   | 0.55  |
| ST (℃)       | 80    | 80    | 100   | 140   | 140   |
| W-Prediction (mm) | 6.67 | 6.11  | 6.30  | 8.08  | 8.74  |
| W-Actual (mm) | 6.76 | 6.34  | 6.42  | 8.03  | 8.78  |
| W-R-Er (%)    | 1.26  | 3.67  | 1.89  | 0.57  | 0.43  |
| H-Prediction (mm) | 2.91 | 2.35  | 3.05  | 2.53  | 2.71  |
| H-Actual (mm) | 2.90 | 2.37  | 3.02  | 2.45  | 2.69  |
| H-R-Er (%)    | 0.42  | 0.68  | 1.07  | 3.26  | 0.92  |

2.5. Verification Experiment

Five randomized trials conducted to validate the model development. Input variables should be different variables used in the design matrix. The relative errors of the track width and layer height of verification experiments were also within 5%, which indicates that the regression model is suitable for the prediction of the welding bead size in CMT-WAAM. The results were shown in Table 5.

3. Results and Analysis

Based on the developed models, the direct effect of input parameters on feature size (track width, layer height and penetration are included), feature area (accumulated area and penetration area are included) and feature ratio (aspect ratio and dilution ratio are included) were calculated and have been presented in Fig. 6, 7, 8. One factor which is achieved by changing the while keeping the remaining factors at zero level. Important information about the course of the discussion are analyzed as follows.
3.1. The Effect of WFS on Welding Bead Morphology

Fig. 6 shows the effect of WFS on feature size, feature area and feature ratio. The track width and layer height are the focus of discussion. WFS has a positive effect on the track width and has a complicated effect on the layer height. To be specific, when WFS is less than 7.35 m/min, the layer height decreases as it increases; while the WFS is greater than 7.35 m/min, the layer increases as it increases.

3.2. The Effect of TS on Welding Bead Morphology

Fig. 7 presents the effect of TS on feature size, feature area and feature ratio. TS has a negative effect on both track width and layer height. This may be caused the wire feed length per unit bead length decreases as TS increase. Furthermore, due to the process characteristics of CMT and the influence of the droplet's own gravity, the changing rate of track width with TS is reduced.

3.3. The Effect of ST on Welding Bead Morphology

Fig. 8 depicts the effect of TS on feature size, feature area and feature ratio. The fluidity of the droplet behaves better at a high temperature. As the substrate temperature rises, the weld bead width increases gradually under the influence of the droplet's own gravity. By the law of conservation of weight, the layer height will decrease with the increase of the track width.
3.4. Direct Effect of Process Parameters on Feature Size

Fig. 9 shows that WFS has the greatest effect on track width and penetration, which TS has the greatest effect on layer height. These effects may be due to the following reasons: the heat input increases as WFS increases, which result in the increase of track width and penetration.

4. Conclusion

A high precision laser scanner was used to measure the track width and layer height of the welding bead and the Box-Behnken method has been applied to investigate the prediction model from the data. On this basis, the relationship between the welding bead size and process parameters was further analyzed. The major conclusions are generalized as follow.

- The relative error of the track width and layer height, which are the most important feature size, are within 5%.
- The track width first increases and then decreases when WFS increase in CMT-WAAM, and the turning point of WFS within the parameter interval is 7.35 m/min.
- WFS has the greatest influence on track width, the degree of influence on layer height is TS>ST>WFS, the degree of influence on penetration is WFS>ST>TS.
- The reverse model about the welding bead size and process parameters would be found through the influence of process parameters on the welding bead morphology from the regression model in the future. Multi-layer single pass forming would be guided by the regression model as well.

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