Feedforward control of droplet transition in electron beam freeform fabrication based on dual beam spot method

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Abstract. In this paper, a feedforward control method of droplet transition based on dual beam spot in electron beam freeform fabrication is proposed. A deflection coil is used to form two beam spots on the surface of the workpiece. Images containing the prepositive spot are taken, the height information of the workpiece surface is obtained through image processing method, and feedforward control is performed accordingly. The experiment result shows that the proposed method has excellent detection accuracy. It can keep the droplet transition distance and state stable when the height of the surface to be deposited fluctuates, and achieve uniform and stable deposition morphology.

1. Introduction
Electron beam freeform fabrication (EBF3) is developing rapidly in recent years, and has attracted the attention of many researchers. Compared with other metal additive manufacturing methods, EBF3 can achieve higher manufacturing efficiency and internal quality. The performance of manufactured parts is close to that of forgings [1, 2]. However, in the manufacturing process, changes in heat dissipation conditions at different positions of complex structural parts and random disturbance both lead to geometric errors. Even if the geometric error of each layer is slight, the upper surface of the workpiece will fluctuate significantly after the accumulation of multiple layers [3-5]. Since the wire feeder is generally fixed during the EBF3 process, when the upper surface of the workpiece is higher than the target plane, the droplet transition distance is reduced, and the wire is likely to stick to the workpiece, resulting in interruption of the manufacturing process and reduction of manufacturing efficiency. Conversely, when the upper surface of the workpiece is lower than the target plane, the droplet transition distance increases, and the molten wire falls into the molten pool in the form of large droplets, instead of an ideal liquid bridge, which aggravates forming quality. At the same time, unstable droplets are prone to splashing, which reduces the amount of material deposited to the workpiece and continuously amplifies this kind of error [6]. Therefore, there is an urgent need for a method to maintain a constant distance between the wire and the upper surface of the workpiece to ensure that the transfer state of the droplet remains stable liquid bridge state.

Optical images are rich in information and are often used for real-time control. Heralic et al. [7] used optical methods to measure the height of the workpiece surface in laser metal wire deposition, but did not achieve droplet transition control. Chang et al. [8] realized the three-dimensional reconstruction of the workpiece based on electron beam structured light during EBF3 process, but it can only work during the deposition interval, which limits the manufacturing efficiency. Taminger et
al. [5] proposed a method for monitoring the height of workpiece surface in EBF3 process with a lateral optical camera, and adjusted the height of the substrate to stabilize the droplet transition. However, this patent only gives a system structure without reporting specific image processing algorithms and control effects.

A feedforward control method for the droplet transition in EBF3 process based on the dual beam spot method is proposed in this paper, which uses the high-speed deflection characteristic of the electron beam to produce a prepositive spot in front of the molten pool. The surface height at the prepositive spot is obtained by the image processing method. According to this, height adjust to the substrate is made in real time, and the stability control of the droplet transition distance and state is realized.

2. Influence of the droplet transition distance

2.1. Definition of droplet transition distance

In the EBF3 process, the wire is melted in an area irradiated by the electron beam, rather than a certain point. The wire diameter and electron beam scanning range are both in the same order of magnitude as the droplet transition distance, so it is difficult to define the droplet transition distance precisely. For the convenience of research and discussion, the droplet transition distance is defined as follows in this paper. Suppose the wire axis is L1, the electron beam axis is L2. The intersection of L1 and L2 is defined as the theoretical wire melting point P1, and the intersection of L2 and the surface of the workpiece is the deposition target point P2. The distance between the points P1 and P2 is defined as the droplet transition distance Td, as shown in Figure 1.

Using this definition, even if the theoretical droplet transition distance remains the same, different wire diameters and electron beam diameters will result in different actual droplet transition modes. Therefore, in all experiments, the wire diameter is fixed at 2mm, and the electron beam focus point is fixed at a certain position above the wire and substrate as well.

![Figure 1. Definition of droplet transition distance (Td).](image)

2.2. Transition state and deposition morphology with different droplet transition distances

A single-pass deposition experiment was carried out at droplet transition distance of 0-5mm, and the process parameters are shown in Table 1. The state of the droplet transition during the deposition process is shown in Figure 2. It can be seen from the experimental results that when the droplet transition distance is 0mm, the wire is in contact with the leading edge of the molten pool. The wire is prone to stick and cause interruption of forming. When the droplet transition distance is 1mm, the droplet transition is a stable liquid bridge form. When the droplet transition distance is greater than 3mm, the liquid bridge state gradually changes to the large droplet transition, the size of the droplet gradually increases, and the randomness of the deposition position on the substrate increases.
Table 1. Parameters used in forming process.

| Parameter                                    | Value | Unit     |
|----------------------------------------------|-------|----------|
| Acceleration voltage                         | 60    | kV       |
| Electron beam current                        | 40    | mA       |
| Deposition speed                             | 400   | mm/min   |
| Wire feed speed                              | 1500  | mm/min   |
| Droplet transition distance (Td)             | 0~5   | mm       |
| Deposition length                            | 50    | mm       |

Figure 2. State of droplet transition with different droplet transition distances.

The single-pass deposition results obtained with the parameters in Table 1 are shown in Figure 3. It can be seen that a continuous and stable deposition pass can be obtained when the droplet transition distance is about 1 mm, which corresponds to the liquid bridge state. When the droplet transition distance gradually increases from 3 mm, the liquid bridge gradually changes to the large droplet transition, the continuity of the deposition pass gradually deteriorates, and the forming quality decreases. Therefore, the target of closed-loop control of the droplet transition distance should be between 0-2 mm.

Figure 3. Morphology of deposition passes under different droplet transition distances.

3. Real-time measurement of workpiece surface height based on dual electron beam spots
A droplet transition feedforward control system based on dual electron beam spots is designed in this paper, and its structure is shown in Figure 4. Deflection coil is used to split the beam spot to a main spot used to form molten pool and a prepositive spot used to measure the height of the position where
the molten pool is about to reach. An industrial camera captures the image containing the prepositive spot, and the image processing program is running on the industrial computer to calculate the height of workpiece surface according to the position of the spot in the image, and output the height difference at that point relative to the deposition starting point. As the deposition process goes on, when the molten pool moves to the position of the prepositive spot, the height difference of the previously extracted point is compensated by adjusting the height of the substrate, and the feedforward control of the droplet transition is realized.

Figure 4. The structure of droplet transition feedforward control system.

3.1. Generation of dual electron beam spot
The electrons are emitted from the cathode of electron gun, accelerated to about half the speed of light, deflected by the deflection coil, and then move in a straight line to the surface of the workpiece, collides with the metal atoms of the workpiece, and convert the kinetic energy into the heat. The current of the deflection coil is set to square wave, as shown in Figure 5. In the time period T1, the current of the deflection coil is 0, the electron beam is not deflected, and the main spot is formed. The energy is used to melt the wire and the substrate to form a molten pool for additive manufacturing. In the time period T2, the current of the deflection coil is I_d, the electron beam is deflected to the forward direction of deposition to form a prepositive spot, and the energy is used to form a local high-temperature high-brightness area on the upper surface of the workpiece. Since the time cycle of the current in the deflection coil is much shorter than the time constant of thermal effect of the electron beam on the workpiece, the thermal effect of the periodically deflected electron beam is the same as that of two electron beams. It can be ensured that the power of the main spot is suitable for forming, while the prepositive spot has proper brightness and does not melt materials by adjusting the relationship between T1 and T2 and the power of the electron beam properly.

Figure 5. Current waveform of deflection coil.
The electrons are emitted from the cathode of the electron gun, became high-speed electrons through the accelerating electric field. Their velocity $v_x$ meets the following relationship:

\[ m_0c^2 + eU = mc^2 = \frac{m_0c^2}{\sqrt{1 - \left(\frac{v_x}{c}\right)^2}} \]  \hspace{1cm} (1)

where $m_0c^2$ is the static mass of electrons, $e$ is the electric quantity of electrons, $U$ is the accelerating voltage of electron gun, $m$ is the dynamic mass of high-speed electrons, and $c$ is the speed of light in vacuum. With the effect of the magnetic field generated by the deflection coil, the direction of movement of the high-speed electrons is deflected. The deflection angle $\theta$ can be calculated by the Equations (2) - (3):

\[ \theta = \arcsin \frac{P_x}{mv_x} \]  \hspace{1cm} (2)

\[ P_x = \int F_x dt = \int B(z)e\frac{v_z}{v(z)}d\frac{x}{v(z)} = e \int B(z)dz \]  \hspace{1cm} (3)

where $P_x$ is the horizontal momentum of an electron after deflection, $F_x$ is the horizontal deflection force acting on the electron, $B(z)$ is the deflection coil magnetic field distribution function, and $v_z$ is the vertical velocity component of the electron at the height of $z$. The integral of the magnetic field distribution of the deflection coil satisfies the following relationship:

\[ \int B(z)dz = KI_d \]  \hspace{1cm} (4)

where $K$ is a coefficient related only to the geometric size and position of the deflection coil. For a specific electron gun, it is constant and can be measured through experiments. $I_d$ is the current in the deflection coil. From the geometric relationship, the distance $d_f$ between the prepositive spot and the main spot satisfies:

\[ d_f = H \cdot \tan \theta \]  \hspace{1cm} (5)

where $H$ is the height of the deflection coil to the surface of the workpiece. When the deflection angle $\theta$ is small, using approximation $\tan \theta \approx \sin \theta \approx \theta$ and Equations (1) - (5), $d_f$ can be calculated by Equation (6):

\[ d_f = H \cdot \frac{eKId}{mv_x} = \frac{HeKId}{\sqrt{eU(2m_0c^2+eU)}} \]  \hspace{1cm} (6)

$H$ and $K$ are constant geometric parameters, $e$, $m_0$, and $c$ are constants. Therefore, the distance $d_f$ between the prepositive spot and the main spot is only related to the deflection coil current $I_d$ and the electron gun acceleration voltage $U$. In the additive manufacturing process, in order to ensure the stability of penetration depth and deposition morphology, $U$ is generally a constant value, and $d_f$ can be adjusted only by changing $I_d$.

3.2. Real-time measurement of workpiece surface height

As shown in Figure 6, the electron beam is incident on the surface of the workpiece along a straight line, intersects the workpiece at point A1, and forms a light spot there. The light spot is focused to point B1 on the CMOS of the camera after passing through the lens. When the height of the workpiece surface changes and rises to the plane 2, the intersection of the electron beam and the workpiece changes to A2, and a light spot is formed there. The light spot is focused to point B2 on the CMOS after passing through the lens. The height of the workpiece when the light spot is imaged at the center of the CMOS is defined as $h_1$. The height difference between other positions and the zero position is defined as $\Delta h$. The CMOS center point B1 is defined as the CMOS zero point. The distance between other points on the CMOS and the zero point is defined as $h'$. The angle between the imaging optical axis and the horizontal plane is $\alpha$, the object distance when the workpiece is at the zero position is $u$, the
and the image distance is $v$. The corresponding relationship between the position of the light spot on the CMOS and the height of the workpiece can be obtained by geometric calculation:

$$\Delta h \cdot \cos \alpha \cdot v = h' \cdot u \tag{7}$$

![Image of measurement setup](image)

**Figure 6.** Measurement of workpiece surface height.

It is proposed in Literature [7] that when $\Delta h$ is large enough, the image of the prepositive spot cannot be well focused on the CMOS because this measurement system does not meet the requirements of the Scheimpflug Principle, resulting in nonlinear errors. After calculating and eliminating this error through optical analysis, the accuracy of the system has been improved, but the residual error after correction still has a certain distribution. Since the optical axis of the lens is not parallel to the measured $\Delta h$, a larger $\Delta h$ will not only cause the image of the prepositive spot to be defocused and enlarged, but also cause a certain change in the object distance during imaging. At this time, the object distance should be corrected to $u - \Delta h \cdot \sin \alpha$. After this correction, the relationship between $\Delta h$ and $h'$ is no longer linear, as shown in Equation (8).

$$\Delta h = \frac{h' \cdot u}{v \cdot \cos \alpha + h' \cdot \sin \alpha} \tag{8}$$

### 3.3. Image processing method

In order to calculate the height of the workpiece surface, it is necessary to extract the image position of the prepositive spot in the CMOS. The images captured by the CMOS are usually noisy, and the splashes generated during the deposition process will also affect the calculation of prepositive spot position. The image processing method is needed to quickly and stably extract the position of the prepositive spot center. The entire image processing flow is shown in Figure 7. The original image captured by the camera is shown in Figure 7(a). First, binarize the original image as shown in Figure 7(b). It can be seen from the figure that after binarization, some surrounding noises with lower gray values have been eliminated. The cathode of the electron gun is burnt during use, the manufacturing error of the focus coil, the texture of the workpiece surface, etc. will make the beam spot contour irregular. Smoothing can be performed through the morphological opening operation of first erosion and then dilation, as shown in Figure 7(c). The connected domain is then extracted from the processed image as shown in Figure 7(d). Because the electron beam travels in a straight line in space, the image of prepositive spot on the CMOS should be located in a straight area, so the region of interest (ROI) filtering can be used to remove the molten pool and surrounding noise. The prepositive spot image after ROI limitation is shown in Figure 7(e). Then the center of the connected domain of prepositive spot is extract, its pixel coordinate $Y$ is calculated, and $h'$ is then calculated according to the CMOS pixel size.
3.4. System calibration

After calculating the pixel coordinate $Y$ of the prepositive spot in the image, in order to get the actual height $h$ of the workpiece surface based on the Equation (8), the geometric parameters in the equation need to be determined. Since it is difficult to measure the angle $\alpha$ between the optical axis and the horizontal plane, the object distance $u$, and the image distance $v$ in space with high precision, it will introduce large errors to the system. Therefore, the fitting method is used to estimate these geometric parameters. The model shown in Equation (9) is used in fitting, where $c_1$, $c_2$, $c_3$ are undetermined parameters. The negative sign before $Y$ is because the camera has inverted the image once.

$$h = c_1 + \frac{c_2 \cdot Y}{c_2 - Y}$$ (9)

When calibrating, first adjust the prepositive spot exactly in the middle of the camera's field of view. When the height of the workpiece changes, the relationship between actual height of the workpiece surface and the pixel coordinate of prepositive spot image center is shown in Figure 8.

![Figure 8. Relationship between workpiece height $h$ and spot pixel coordinate $Y$.](image)

![Figure 9. Residual distribution of fitting result.](image)

Use Matlab's nonlinear fitting function to fit the parameters, and the results are as follows:

$c_1=3.46\text{mm}$, $c_2=8872\text{Pixel}$, $c_3 =836.5\text{mm/ Pixel}$

Comparing the calibration data and the fitting results, the residual distribution is shown in Figure 9. Almost all errors are distributed in the range of $\pm0.01\text{mm}$, and the standard deviation is $5.6 \times 10^{-3}\text{mm}$. The measurement accuracy of workpiece surface height can reach 0.02mm, which meets the need of real-time control. It can be seen that the residual has no obvious distribution, indicating that this model can better describe the error source of the measurement system, and the residual is random error.
4. Results and discussion

4.1. Static control accuracy
In order to test the control accuracy and stability of the feedforward control system, a static control experiment was carried out. In the experiment, an electron beam was emitted without wire feed. It was only used to form a molten pool and a prepositive spot. With the action of the controller, the surface height of the workpiece is shown in Figure 10, and the control error is within ±0.03mm.

![Figure 10. Static control accuracy.](image)

4.2. Deposition results on slope
Experiments are carried out on a substrate placed obliquely to verify the effect of the droplet transition feedforward control system based on dual beam spot method. On the substrate tilted at the same angle, the feedforward controller is turned on and off respectively, and the deposition result is shown in Figure 11. It can be seen that without control, the droplet transition distance gradually increases from 0mm to 5mm, and the droplet transition form changes from continuous liquid bridge to large droplet transition, and the deposition quality deteriorates. When the feedforward control is used, the droplet transition form has been maintained as a continuous liquid bridge, and the forming quality is satisfying.

![Figure 11. Feedforward control effect on slope.](image)

4.3. Deposition results on step
Experiments were carried out on substrate with steps on surface to verify the effect of the feedforward control system based on dual beam spot method. The geometric dimensions of the substrate surface are shown in Figure 12. The feedforward controller is turned on and off respectively for deposition on this substrate, and the result is shown in Figure 13. It can be seen that without control, the distance between the patterns increases significantly as the step decreases, and different deposition morphologies are generated with three different droplet transition distances. When the feedforward control is used, the droplet transition distance is stable and the deposition morphology is uniform.

![Figure 12. Geometric dimensions of the substrate with steps.](image)
5. Conclusions
A feedforward control system and method for droplet transition based on dual beam spots for electron beam freeform fabrication is proposed in this paper. The system can form two electron beam spots on the surface of the workpiece, and measure the height of the workpiece surface by taking the image of the prepositive spot and performing image processing. Thereby the feedforward control of droplet transition is realized. Through calibration and error correction, the measurement accuracy of workpiece surface height can reach 0.02mm, and the static error of feedforward control is within ±0.03mm. Experiments on substrates with slope and steps show that the proposed control system can stabilize the droplet transition distance, keep the droplet transition form in a liquid bridge state, and achieve uniform deposition morphology.

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