Numerical Simulation and Analysis of Metal Fused Coating Forming

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Abstract. 3D printing has been widely used for the forming of functional parts, and electron beam and laser are used as the heat source mostly, which is expensive and energy consuming [1]. Metal Fused coating process is a developing additive manufacturing technology, the high power heat source is eliminated and the material is not confined to powder and wire [2]. In this paper, computational fluid dynamics method [3] combined with fluid volume method are used to study the influence of process parameters on coating and morphology. Considering the material’s thermal physical properties change with temperature, the temperature history of feature positions and three-dimensional morphology are analysed. It is found that the differences of the melt spreading temperature histories of three key positions increase with the printing speed. The influence rules of different layer thickness and ratios of feeding speed to nozzle moving speed on bonding width, single-layer width and the ratio of bonding width to single-lane width are gained, which provides guidance to select the parameters in given process conditions.

1. Introduction
Metal Fused coating is a process by using pressure to extrude the molten metal, spread on the substrate and solidifies into a single-lane, then forming a three-dimensional solid part by the accumulation of layer by layer. As the basic unit, the single-lane is the foundation of the whole process of forming, the molten metal spread out on the substrate constantly, with heat transfer and solidification into a single-lane coating layer. The coating process is affected by the temperature, the speed of the substrate, the thickness of the layer and the diameter of the nozzle. In this paper, volume of fluid method is used to calculate the coating process, and the influence of process parameters on the shape and size of the coating is analyzed. The platform for numerical calculation is Flow-3D [4].

2. Calculation method and theory

2.1 Volume of fluid method
Volume of fluid (VOF) method is used to simulate the process of metal melt flow in coating process. VOF method is based on volume function, the basic principle is to determine the free surface by calculating the fluid and mesh volume ratio function in the grid cell, tracking the change of the fluid, instead of tracking the motion of the particle on the free surface, the relationship between the fluid volume fraction and the free liquid surface of the grid is shown in equation 2-1. The VOF method can
deal with strong nonlinear phenomena such as free surface reentry, which has the advantages of short calculation time and less storage [5].

Suppose any grid cell in the flow field, defines the function as:

\[ f(x, y, z, t) = \begin{cases} 0, \text{nonfluid element} \\ 1, \text{fluid element} \end{cases} \]  

(1)

2.2 Reynolds number calculation

\[ R_e = \frac{\rho v d}{\eta_0} \]  

(2)

d-outlet diameter of nozzle/mm, 0.3–0.5 mm; v-Melt flow rate/mm·s, 1,0–40 mm/s; \( \eta_0 \)-zero shear viscosity/ Pa·s, 0.0013 Pa·s.

The Reynolds number is far less than 2100, so the melt flow belongs to laminar flow. Therefore, laminar flow model is selected and non-slip wall surface is adopted.

2.3 Heat transfer analysis

The process of metal fused coating is accompanied by the flow and heat transfer of molten metal, it has important influence on solidification process.

The basic law of fluid mechanics and heat transfer is followed in the process of coating. In the numerical simulation of the deposition process, metal liquid can be considered as an incompressible fluid. It can be regarded as the two-dimensional unsteady flow of viscous incompressible fluid with free surface, obeys the law of conservation of momentum and mass conservation. The state of the fluid can be described by the navier-stokes equation (N-S equation) and the continuity equation [6].

N-S equation:

\[ \rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = -\frac{\partial p}{\partial x} + \rho \alpha_x + \eta \nabla^2 u \]  

(3)

\[ \rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = -\frac{\partial p}{\partial v} + \rho \alpha_y + \eta \nabla^2 v \]  

(4)

\[ \rho \left( \frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = -\frac{\partial p}{\partial z} + \rho \alpha_z + \eta \nabla^2 w \]  

Mass conservation equation:

\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \]  

(5)

By using the volume function method to track the movement of free surface, we also use the volume function equation:

\[ \frac{\partial F}{\partial t} + u \frac{\partial F}{\partial x} + v \frac{\partial F}{\partial y} + w \frac{\partial F}{\partial z} = 0 \]  

(6)

In formula (2-3) -- (2-5): u, v, w -- the velocity component of the velocity at X, Y and Z respectively; \( \eta \)-Kinematic viscosity; T – time; F - volume function; P - pressure of (x, y, z) in flow field.

The coating process involves the conduction between the melt and the substrate, the conduction between the surface of the melt and the air, convective heat transfer and radiation heat transfer.

Heat conduction equation:

\[ \rho c = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + Q \]  

(6)

In this formula: \( \rho \)–the density of the melting body; C-specific heat capacity; T-temperature; t-time; \( \lambda \) - thermal conductivity; Q -- heat source.

Convective heat transfer equation:

\[ q = \alpha \left( T_f - T_w \right) \]  

(7)

In this formula: \( \alpha \) -convective heat transfer coefficient; \( T_f \) - temperature of the fluid; \( T_w \)– temperature of substrate.

The radiation heat transfer equation:

\[ q = \varepsilon \sigma_0 T_s^4 \]  

(8)
In this formula: $T_s$ - the adiabatic temperature of the surface; $\varepsilon$ - radiation darkness; $\sigma_0$ - Stefan-Boltzmann constant.

3. Model Construction and Parameters Setting

In this chapter, numerical simulation is used in the process of metal fused coating. Firstly, theoretical modeling is carried out, and the model is set up reasonably. Then we can solve for a finite volume. At last, simulation results are compared with the experimental data to verify its correctness [7]. The effects of different parameters on the process of deformation and solidification were studied by optimizing the parameters. This paper only considers the solidification process of metal melt flow and does not pay attention to the stage of metal melting in crucible. The diameter of nozzle is 0.4 mm, the Angle alpha is 45 °. Due to the coating nozzle is too longer, we only take 4 mm up to coating head as the inlet boundary to save calculation time.

The process of coating is simplified to the model shown in Fig. 1. The substrate remains stationary and the coated nozzle is moving at a constant speed along the positive direction of the x axis, the molten metal outflow, spread, cool and solidify on the substrate.

![Fig. 1 numerical calculation model of the forming process in two-dimensional.](image)

The main physical parameters used in the numerical calculation model of metal fused coating process are listed in table 1.

| Parameter           | Symbol | Reference (SI) |
|---------------------|--------|----------------|
| Density             | $\rho$ | 8320           |
| Surface tension     | $\sigma$ | 0.48         |
| Kinematic viscosity | $\eta$ | 0.0013        |
| Melting point       | $T_m$ | 183            |
| Specific heat       | $c$   | 212.9          |
| Heat transfer coeff  | $\lambda$ | 31.9     |
| Latent heat of fusion | $\Delta H$ | 47560 |

Model and boundary conditions are set as shown in Fig. 2, coating head diameter is 0.4 mm, length is 4 mm, Angle theta is 45 °, the distance from the substrate is 1.2 mm. The boundary conditions of $X_{max}$, $X_{min}$ and $Y_{max}$ are set as Continuative [8].

In order to improve the calculation speed, Symmetry is adopted, the symmetry plane is the xoz plane, and the boundary condition of $Y_{min}$ is set as Symmetric. $Z_{max}$ is set as Specified Pressure, and $Z_{min}$ is set as wall. The direction of gravity is -z direction. In order to achieve a good combination effect of the coating layer and the substrate, the substrate material also uses Sn63Pb37, which is used as the forming substrate as well as the paving layer.
4. Model Experimental Verification
The process parameters used in the numerical simulation of single-channel coating are shown in table 2.

Table 2 numerical simulation process parameters of single channel coating.

| Parameters     | Melt temperature | Substrate temperature | Printing speed | Crucible pressure | Distance |
|----------------|------------------|------------------------|----------------|-------------------|----------|
| Numerical      | 250°C            | 120°C                  | 12 mm/s        | 10 KPa            | 1.2 mm   |

4.1 Temperature Field Validation of the Spreading Road
The temperature and velocity field at different time of coating process were simulated:

Fig.3 numerical simulation of temperature field and velocity field at different time.
As shown in Fig.3 (a), when \( t = 0.15 \) s metal liquid outflow the nozzle under the action of gravity and pressure, then contact with the substrate, the heat of the melt passes to the substrate, molten pool is formed in contact with the substrate. After solidification, the coating layer is combined with the substrate. In the horizontal direction of the coating layer, the molten metal is spread on both sides to make the coating layer have a certain width. As the substrate continues to move, when \( t=0.50 \) s, the coating layer is combined with the base plate to achieve metallurgy, and the coating layer is moved along the substrate with the effect of metallurgical binding force, gradually form a single coating layer. And Fig.3(c) and Fig.3(d) show that the metal melt on the unsolidified coating layer rises to the side wall of the coating nozzle, this is due to the wettability of the metal melt and the end face of the coating, spread the melt along the end of the coating, and infiltrate along the side wall, the liquid level of the area is higher than that of other areas of the coating. Because of the temperature gradient between the molten metal and the substrate, the heat is diffused from the melt to the substrate, when \( t=0.92 \) s, the velocity field at the front of the coated layer shows that there is no relative drag between the molten metal and the substrate. With the movement of the substrate and the solidification of the coating layer, a single coating layer is gradually formed.

4.2 Morphology Validation of Single Channel Cross Section

Appearance of transverse section of forming surface have a very important influence on the surface roughness and bonding strength of the forming part. The size of the single cross section is observed under the NIKON ma-200 microscope (shown in Fig.4).

![Fig.4 NIKON MA-200 microscope.](image)

In Fig.5, the left part is numerical simulation of single cross section and on the right side is the single channel experiment (the single-channel layer thickness is 1.2 mm, substrate movement speed of 12 mm/s, the melt temperature of 260 °C, the substrate temperature is 100 °C, diameter of coated nozzle is 0.4 mm).

![Fig.5 numerical simulation of single-channel coating and the contour of the section of the experimental section.](image)
The main morphological dimension of the coating was compared with the calculated value. The comparison results are shown in table 3, for single-lane section profile size, the experimental value and the calculated value are basically consistent, the main dimension error is basically controlled within 5%. The model can predict the shape of coating layer well.

Table 3 comparison of experimental value and calculation value of main size of single channel coating layer.

|            | Single-lane width /mm | Single-lane height /mm |
|------------|-----------------------|------------------------|
| Experimental value | 2.743                 | 1.828                  |
| Calculated value   | 2.686                 | 1.768                  |
| Relative error /%  | 2.08                  | 3.28                   |

5. Conclusions
For the process of coating, a 3D melt flow spreading model was established. The temperature field distribution and the shape of the pavement were analysed and calculated. In the determination of model parameters, on the one hand, by looking up the relevant manuals, on the other hand, the boundary conditions of the melt temperature, the substrate temperature and the surface temperature of the spreading layer are determined by the experimental data.

The experimental results compared with the temperature variation process calculation results is less than 10°C. The numerical calculation results and experimental data error are small, and the main dimension error is less than 5%.

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