Additive manufacturing of Sn63Pb37 component by micro-coating

Guangxi Zhao*, Zhengying Wei, Jun Du, Wei Liu, Xin Wang, Yunfei Yao

* Corresponding author. Tel.: +8613484627265; fax: +8602982660114.
E-mail address: zgx6464946@gmail.com

Abstract

Micro-coating is a novel technology to build near-net component layer by layer, which uses a crucible and nozzle instead of a weld head and wire feeder to supply material compared with shaped metal deposition. A pneumatic system is adopted to adjust liquid metal flow rate and the layer height is controlled by the distance between nozzle and substrate. Height and width of a single channel are measured by confocal microscopy, it is found that the error between numerical results and experiment are 5.5% and 1.1%. Tensile stress vertically to the deposition layers reaches to 40.89Mpa, while tensile stress parallel to the deposition layers gives a value of 43.14Mpa. Yield stress of vertically and parallel to the layer are respectively 34.28Mpa and 35.23Mpa. Specimens exhibit better mechanical properties than casting component, whose tensile stress and yield stress are respectively 36.51Mpa and 29.25Mpa.

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Keywords: micro-coating; shaped metal deposition; mechanical properties; near-net forming; 3D printing; Sn63Pb37

1. Introduction

Additive manufacturing (AM) builds up components through the deposition of materials layer-by-layer, including selective laser sintering (SLS) [1], laser-engineered net shaping (LENS) [2], directed light fabrication (DLF) [3] and direct metal deposition (DMD) [4], et al. These methods enable the fabrication of custom objects with metal materials directly from computer data of CAD/CAM system without using molds or dies. However, technologies mentioned above usually have expensive equipment and low efficiency. Significant reductions in manufacturing costs and time to market production as well as savings of energy and materials are expected [5].

Micro-coating is a novel technology to build near-net component layer by layer in a simple and rapid way. The idea came from slot die coating [6-8]. Micro-coating mainly includes a crucible, one three-dimensional translation

* Corresponding author. Tel.: +8613484627265; fax: +8602982660114.
E-mail address: zgx6464946@gmail.com
platform, a chamber, a nozzle, a pneumatic system and a corresponding software. Metals inside the crucible are heated to melt by electromagnetic induction, and then the molten metals flow out through the nozzle under effects of gravity and pneumatic system. Simultaneously, the three-dimensional translation platform moves according to the preset trajectory. Consequently, liquid metal forms a specific shape on the platform, and after one layer finished, the platform moves downwards a certain distance until the whole model is finished. Schematic diagram is shown in figure 1:

![Schematic diagram of micro-coating process](image)

**Fig. 1. Schematic diagram of micro-coating process**

### Nomenclature

| Symbol | Definition |
|--------|------------|
| F      | fluid fraction |
| V      | velocity     |
| T      | temperature  |
| T_l    | melting point |
| T_s    | solidus temperature |
| \( \rho_s \) | solidus density |
| \( \rho_l \) | liquid density |
| t      | time         |
| \( \sigma \) | surface tension |
| h      | latent heat of fusion |
| \( \lambda \) | Thermal conductivity |
| \( \mu \) | viscosity    |
| P      | pressure     |
| H      | coating gap  |

2. **Analysis and modelling**

The micro-coating process involves melting, solidification, phase transformation and material properties are also temperature-dependent, therefore, it’s a typical non-linear transient heat transfer process. The flow is considered to be steady and incompressible and the liquid metal behaves as Newtonian liquid. The effect of the ambient airflow is neglected.

VOF method \(^{[9-11]}\) is used to track the phase interface. Governing equations for incompressible Newtonian fluid is given as below:

\[
\nabla \cdot \vec{V} = 0
\]

The conservation equation is based on fluid fraction (F) of grid cell volume, F=1 denotes that the grid cell is full of fluid, while F=0 represent the grid cell is full of solid, besides, 0<F<1 means it contains a free surface in the grid volume. The fluid fraction is governed by:
Accurate tracking of the fluid volume fraction within each cell is the basis to determine the free interface. The air above the free surface is defined as a uniform temperature and pressure, neglecting the flow of gas, and the momentum conservation equation of the viscosity is as follows:

\[
\frac{DV}{Dt} = -\frac{1}{\rho d} \nabla P + \mu \nabla^2 \vec{V} + \vec{G}_z \left[ 1 - \beta (T - T_m) \right]
\]  

The equation of conservation of energy:

\[
\frac{dh}{dt} + (\vec{V} \cdot \nabla) h = \frac{1}{\rho d} \nabla \cdot (K \nabla T)
\]

Phase change problem of substrate melting is processed according to the relationship of enthalpy (h) and temperature\(^{[12-14]}\). The calculation equation of h is given in formula (5):

\[
h = \begin{cases} 
\rho_s T_s C_s & T < T_s \\
\left(h(T_i) + \rho_s C_s (T - T_i)\right) & T > T_i
\end{cases}
\]

Latent heat of fusion refers to absorbed or released heat when the phase of material change from solid to liquid or from liquid to solid, which is very important for phase change analysis and can’t be neglected.

A symmetrical 3D finite difference model is developed to simulate the temperature and velocity field during micro-coating process by using the software Flow-3D. Flow 3D meshes the whole calculation space instead of every component, which is different from the usual modeling software. Top side of the mesh is set as a pressure boundary condition, and the value of relative pressure is 350Pa. While the bottom is set to be wall, and the symmetrical side boundary condition is symmetry, the remains are assumed continuative. Angle of the nozzle is 60°, diameter of the end surface is 2mm, and the orifice diameter is 0.5mm. This paper also adopt Sn63Pb37 as the substrate material for same material can be bonded more firmly. The velocity of substrate movement is 10mm/s and The coating gap is 0.5mm. Initial temperature of fluid, substrate and atmosphere are 540K, 400K, and 295K.

Sn63Pb37 is a eutectic alloy, its low melting point makes it suitable as experimental material. Its physical properties are shown in Table 1:

| Melting point (K) | Density (Kg/m³) | Viscosity (Pa’s) | Specific heat (J/Kg*K) | Latent heat of fusion (J/Kg) | Surface tension (N/m) | Thermal conductivity (W/m*K) |
|------------------|----------------|-----------------|------------------------|-----------------------------|----------------------|-----------------------------|
| 456.5            | 8420           | 0.014           | 150                    | 28470                       | 517                  | 50                          |

Surface tension is very sensitive to temperature changes, which will decrease as temperature increase, and the coefficient is:

\[
\frac{D\sigma}{DT} = -0.0049
\]

3. Results and discussion

Temperature and velocity field are calculated at different times. Figures 2a, 2b, and 2c are respectively cases at 0.04s, 0.08s and 0.12s.

Figure 2 illustrate that molten Sn63Pb37 spreads on the substrate before t =0.04s, and then under the effect of surface tension and thermal capillary, the molten metal begins to infiltrate along the left side of the nozzle and form a flow loop. The outside metal begins to solidify due to heat conduction, convection and radiation. Particularly the metal contacting with the substrate solidified first. Figure 2 also shows that there is some bubble occurred at the
interface between liquid metal and substrate. The generation of gas porosity is known mainly due to the air
entrainment \cite{15-16} in the liquid metal during the spreading stage. Under the compression of nozzle, part of the bubbles
is squeezed out. With the substrate moving and liquid metal solidifying, a single layer is formed on the substrate.

![Temperature and velocity field](image)

**Fig. 2.** Temperature and velocity field (a) t=0.04s; (b) t=0.08s; (c) t=0.12s.

Shape and size of numerical single channel is shown in figure 3(a), and its width and height are got by post
processing, which are 2.68mm and 1.02mm respectively.

![Shape and size of a single channel](image)

**Fig. 3.** Shape and size of a single channel (a) numerical results; (b) experimental results

Experimental results are measured by confocal microscopy in figure 3(b). Three different locations of the single
channel are measured and averaged, and the width and height are 2.71mm and 1.08mm. Consequently, the errors are
1.1% and 5.5%.

In order to study the impact of velocity, this paper also calculated when substrate velocity equals to 8mm/s,
12mm/s, 14mm/s with the other condition unchanged. Numerical and experimental results are shown in figure 4(a).
Figure 4(a) shows that with the velocity increasing, the width and height of single channel are both decreasing. The maximum error of width and height between numerical results and experimental one are 5.6% and 3.3%. Similarly, this paper also investigated the effect of coating gap, and the relationship between width, height and coating gap is shown in figure 4(b).

This paper finds that as the gap increases, and the width increases and gradually stabilizes, while the height increases obviously first and then becomes stable. The maximum error of width and height between numerical results and experimental one are 8.6% and 4.3%.

Different scanning methods are shown in figure 5, and it has great influences on component mechanical properties. In order to prove the necessity of micro-coating process, three kinds of micro-coating parts are processed into bone shape to test their tensile and yield properties as is shown in figure 6, they are respectively one-layer part parallel to the tensile direction (numbered 1), one-layer part perpendicular to the tensile direction (numbered 2) and two layers combined the two ways (numbered 3). Besides, a casting one (numbered 4) is also used for comparison.

Size and mechanical properties are listed in table 2, it is can be seen that yield stress of the four parts are respectively 35.23Mpa, 34.28Mpa, 36.48Mpa and 29.25Mpa, While the maximum tensile stress are 43.14Mpa, 40.89Mpa, 47.36Mpa and 36.51Mpa. As a result, the yield strength and tensile strength of micro-coating part are
higher than the casting one. Yield stress and maximum tensile stress of part whose processing direction parallel to tensile direction are higher than perpendicular one. Besides, the two layers’ combination has the best yield and tensile strength.

| Number | Width (mm) | Thickness (mm) | Maximum load (KN) | Yield stress (MPa) | Maximum tensile stress (MPa) |
|--------|------------|----------------|-------------------|-------------------|-----------------------------|
| 1      | 7.90       | 2.50           | 0.99              | 35.23             | 43.14                       |
| 2      | 7.90       | 2.56           | 0.83              | 34.28             | 40.89                       |
| 3      | 7.90       | 3.50           | 1.36              | 36.48             | 47.36                       |
| 4      | 7.90       | 3.68           | 1.06              | 29.25             | 36.51                       |

4. Conclusions

A novel additive manufacturing technology is proposed in this article, which has the advantage of high efficiency and low cost. Temperature and velocity field during micro-coating process is calculated out, and air entrainment is found near the substrate interface. Width and height of a single channel are compared between numerical results and experiment in different parameters. The numerical results are considered reliable to some extend because the maximum error is 8.6%. Tensile and yield properties of micro-coating parts are tested, and it is found that mechanical properties are better than cast process. Parameters such as initial temperature of the liquid metal and substrate, air pressure from the top, et al. are not studied. Furthermore, effects of oxidation cannot be ignored in the further study.

Acknowledgements

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