Process simulation of Multi-layer and Multi-channel Selective Laser Melt of Al₂O₃ Ceramics Based on Temperature Field

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Abstract. Based on the temperature field theory and ANSYS software, the simulation model of Al₂O₃ ceramics selective laser melting (SLM) temperature field of multi-layer and multi-channel was established, and the analysis process of SLM temperature field simulation was designed. The temperature distribution of Al₂O₃ ceramics SLM temperature field and molten pool forming characteristics were researched. When the laser power is 105W, the scanning speed is 50mm/s and the thickness of powder layer is 0.25m, there is no remelting in adjacent molten channels in the same layer and multiple layers. Laser power and scanning speed are the main factors that whether remelting occurs in adjacent molten channels and multiple layers.

1. Introduction

Ceramic materials have high melting point, high hardness, wear resistance, oxidation resistance and good chemical stability [1]. Traditional processing technology is difficult to process complex and high-precision ceramic parts, which seriously restricts the application of ceramic materials in industrial production. Laser selective melting (SLM) technology can directly form complex parts, which is a potential manufacturing technology for processing ceramic parts with high efficiency and low cost. At present, the development of SLM in printing materials, forming process and post-processing is not mature, and its forming mechanism needs further study. Convection in molten pool is one of the important factors affecting SLM forming process. Because of the influence of flow on heat and mass transfer, it drives bubbles to move in molten pool, affects the morphology of molten pool, and further affects the surface quality of specimens [2-3].

2. Selective Melting Temperature Field Model

2.1. Heat Transfer Control Equation

Selective laser melting is a typical non-linear transient heat conduction process, which is described by the Control equation (Fourier equation) [4]:

$$\rho \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q$$

In formula

- $\rho$ —— material density (kg/m³);
- $k$ —— thermal conductivity (W/mK);
- $Q$ —— heat source density (W/m³);
- $T$ —— temperature (K).

The temperature field simulation model of SLM was established, and the analysis process of SLM temperature field simulation was designed. The temperature distribution and molten pool forming characteristics were researched. When the laser power is 105W, the scanning speed is 50mm/s and the thickness of powder layer is 0.25m, there is no remelting in adjacent molten channels in the same layer and multiple layers. Laser power and scanning speed are the main factors that whether remelting occurs in adjacent molten channels and multiple layers.
c ——— specific heat capacity (J / (kg · K));
T ——— powder temperature (K);
t ——— laser scanning time (s);
Q ——— heat source density (W / m³);
$k_{xx}, k_{yy}, k_{zz}$ ——— heat conductivity (W / (m · K));

To solve the differential equation (1), it is necessary to determine the initial conditions and various boundary conditions of powder and substrate.

Assuming that the temperature at any point of the powder layer is $T_0$, the powder layer at $t=0$:

$$ T(x, y, z, t) \big|_{t=0} = T_0(x, y, z) $$

The boundary conditions refer to the heat exchange between the outer surface of the bed and the surrounding medium. The second, third and fourth type of boundary condition are used to simulate the temperature field [4].

2.2. Effective thermal conductivity

Gusarov [5] considered that there was extrusion deformation between powders. There was not only radiation heat conduction but also heat conduction between powders. The effect of heat conduction was far greater than that of radiation. Therefore, the effective thermal conductivity of powders was as follows:

$$ k_e = k \left(1 - \varphi \right) \frac{n}{\pi} \frac{a}{R} \quad (3) $$

In formula

- K—— thermal conductivity (W/ (m².K))
- $\varphi$—— porosity of powder bed;
- $n$—— general coordination Number;
- $a, R$—— the average contact radius of powder particles and the average radius of powder

Latent heat of phase transformation exists in the process of solid-liquid transformation, which has an important influence on the morphology of molten pool. The latent heat of phase change was treated by isothermal method in this paper.

2.3. Heat Source Model

In the process of simulating the temperature field of selective laser melting, the width and depth of the melt channel on the scanning path need to be simulated, and the laser has certain penetration ability to the powder layer, so the Gauss body heat source [6] is more suitable for selective laser melting. If the $x$-$z$ plane is taken as the powder plane, then the Gauss body heat source can be expressed as follows:

$$ q = \frac{2AP}{\pi \omega^2 h} \exp \left(-2 \left(\frac{x - (x_0 + V_t)}{\omega}\right)^2 + \left(\frac{z - (z_0 + \left(j - 1\right)d)}{\omega}\right)^2 \right) \quad (4) $$

In the formula, $x_0$ and $z_0$ are the coordinates (m) of the initial X and Z of the heat source; $t$ is the laser scanning time (s); $V$ is the laser scanning speed (m/s); $J$ is the number of laser scanning paths; and $D$ is the scanning distance (m).

3. Temperature field simulation of 3-layer multi-channel selective laser melting

3.1. Simulation analysis process

In order to simulate the temperature field in SLM forming process, a three-layer and three-channel scanning path is planned, as shown in Figure 1. The ANSYS software is used to establish the temperature field analysis model and carry out the finite element analysis.
3.2. Temperature Field Simulation
The whole model is divided into two parts: powder layer and substrate layer. The powder and substrate materials are the same, as shown in Figure 3. The size of powder layer is 5 mm × 0.20 mm × 0.45 mm, cell size is 0.1 mm × 0.07 mm × 0.05 mm, and three layers are constructed. The laser radius is 0.15 mm, and substrate size is 5 mm × 2 mm × 2.5 mm. The displacement of each load step is 0.001 mm. Solid70 thermal analysis unit is used for mesh generation, and the life and death element method are used for simulation.

In ANSYS software, the movement of heat source is controlled by triple loop statement. The whole powder layer is divided into three layers, and there are three channels in each layer. Zig-zag scanning strategy is adopted, and the influence between the same layer and the adjacent layer is researched by analyzing the temperature at the midpoint of each channel.
4. Analysis of simulation results

According to the established temperature field analysis process, the finite element analysis of SLM process temperature field for Al$_2$O$_3$ powder was carried out. According to the simulation results, the temperature distribution and forming characteristics of the temperature field were analyzed. The simulation parameters are: laser power 105W, scanning speed 50mm/s, powder layer thickness 0.25mm. Mark 1-9 in Fig. 2 is corresponding to node number: 4875, 4876, 4877, 4904, 4905, 4906, 2670, 2669 and 2668, respectively. It takes 16.66 seconds to complete the single channel scanning, and 159 seconds to complete the whole scanning.

Fig. 3 (a), (b), (c) is the temperature curve of the marker points 1, 4 and 7, respectively. The melting point of Al$_2$O$_3$ is 2000 °C. It can be seen from Fig. 4 that:

- (a) mark 1 (node 4875)  
- (b) mark 4 (node 4904)  
- (c) mark 7 (node 2670)

Fig.4 temperature curve of the node

1. The heat flux density makes the powder temperature reach 3200°C, which fully meets the requirement of powder melting to produce melting pool. In the whole laser melting process, the peak temperature of mark points 1, 4 and 7 when at 8.3s, 61s and 114.3s respectively, exceeds 3200°C, which exceeds the melting point of powder.

2. The simulation results show that the average temperature of the whole scanning area is lower than the melting point temperature, and the average temperature of the whole scanning process is gradually rising.

3. There is no remelting between layers. Taking node 4904 as an example, when the heat source scans at the third layer and reaches 2670 position, the temperature of node 4904 only reaches 1500 °C, which can not produce remelting.

4. There is no remelting between the molten channels. Taking node 4875 as an example, the temperatures of point 1, 2 and 3 are 3200, 600 and 400 degrees respectively. Obviously, the influence of the latter two channels to mark point 1 is not enough to make it reach the melting temperature, and the effect of heat effect decreases.

Fig. 4 is the temperature cloud of node 2670. It can be seen from Fig. 5 (a) that in the Z-axis direction, the heat-affected zone of the heat source center has no effect on the remelting of the powder in the adjacent molten channel, only making the temperature of a small amount of powder reach 1493 C. The size of the molten pool is 0.23mm in X direction and 0.15mm in Z direction. It can be seen from Fig. 4 (b) that in the direction of Y axis, the depth of molten pool produced by heat source is about 0.03mm. There is no remelting between layers, and the bonding between layers is loose, which seriously affects the density and forming effect of the final part.
5. Conclusion
In this paper, the finite element simulation of temperature field of Al₂O₃ ceramic SLM forming process is carried out. The relationship between temperature and time at several key points between layers was obtained, and the effects of laser power, scanning speed and powder layer thickness on molten pool size were analyzed. When laser power is 105W, scanning speed is 50mm/s, and thickness of powder layer is 0.25 mm, there is no remelting between adjacent melting channels and multiple layers in the same layer. The effect of remelting on the adjacent channel and the front layer depends mainly on the laser power and scanning speed.

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