Simulation on Molten Pool Characteristics of Al2O3 Laser Selective Melting Based on Energy Input Model

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Abstract. In order to obtain the formation rule of molten pool characteristics in SLM process of ceramics, an energy input model for SLM process of Al2O3 ceramics is established. The model is related to laser power P, scanning speed v, scanning spacing s and thickness h of powder layer. The influence of process parameters in the energy model on molten pool characteristics is analyzed by simulation of temperature field of multi-layer and multi-channel SLM process. The simulation results show that when the laser power P is 105W, the scanning speed v is 50mm/s, the initial temperature of powder is 330℃ and the thickness of powder layer is 0.20mm, the molten pool formed is easy to form Al2O3 ceramic specimens.

1. Introduction

The process of selective laser melting (SLM) is very complicated. Foreign researchers have summarized up to 130 factors influencing the quality of SLM. The technological parameters that affect the quality of parts are: laser power, scanning speed, scanning distance, powder composition and particle size. R.organ [3] et al. discussed the relationship between energy input and density, and believed that energy input varies with laser power, scanning speed, scanning spacing and other process parameters, but ignored the influence of the thickness of the powder layer on energy input. A. semimchi [4] deeply studied the relationship between energy input and density, and believed that within a certain range of technological parameters, the density of molded parts increased with the increase of energy input. Molten pool convection is one of the important factors affecting SLM forming process. Due to the influence of flow on heat and mass transfer, molten pool convection drives bubbles to move in the molten pool, affects the morphology of the molten pool, and further affects the density of specimens [1-2]. Based on the establishment of SLM energy input model, the influence of energy model parameters on the formation of molten pool is analyzed by ANSYS software simulation.

2. SLM energy input model

SLM forming process mainly includes: material melting and solidification, molten pool morphology and flow, other physical and chemical changes of materials, etc. [5-6]. The input and output of energy in the molding process will directly lead to the change of the physical state of the powder. In the interaction between laser and powder materials, energy is transferred from laser to powder, which complies with the conservation of energy. Energy transfer can be divided into three parts: part of laser energy is reflected by the surface of powder, and dissipates to the air above by convection; The other
part of laser energy is transferred to ceramic powder by heat conduction, making the powder melt. The rest of the laser energy is transferred to the material in the region near the heat source, heating up the surrounding powder and melting layer. Figure 1 is a model of energy transfer involved in SLM processing, in which laser input energy is \( Q_1 \), energy transferred to powder layer and substrate is \( Q_2 \), and energy escaping from powder in the form of radiation and convection is \( Q_3 \). The red area represents the molten pool, and the red dotted line represents the gaussian distributed laser heat source.

![Fig. 1 energy transfer model of SLM process](image)

The amount of energy input directly determines whether there is remelting between different melted channels and different powder layers, and thus affects the density of the molded parts. On the basis of Simchi energy input model, energy input is defined as a function of laser power, scanning speed, scanning interval and powder layer thickness. Its physical significance is the total energy input per unit volume of powder in unit time:

\[
\psi = \frac{P}{\nu s h}
\]

\( P \) is laser power, \( \nu \) is laser scanning speed, \( s \) is scanning interval, and \( h \) is powder layer thickness. These parameters are called energy model parameters.

3. Multi-layer and multi-channel SLM temperature field simulation

3.1 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)[7]:

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

In formula

- \( \rho \) —— material density \((\text{kg} / \text{m}^3)\);
- \( c \) —— specific heat capacity \((\text{J} / (\text{kg} \cdot \text{K}))\);
- \( T \) —— powder temperature (K);
- \( t \) —— laser scanning time (s);
- \( Q \) —— heat source density \((\text{W} / \text{m}^3)\);
- \( k_x, k_y, k_z \) —— heat conductivity \((\text{W} / (\text{m} \cdot \text{K}))\);

To solve the differential equation (2), 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 \( t=0 \):
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[7].

3.2 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 2. The ANSYS software is used to establish the temperature field analysis model and carry out the finite element analysis. 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.

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 is used for simulation. The thermal physical parameters of alumina are shown in Table 1.

| Temperature /K | Thermal conductivity/(W·m⁻¹·K⁻¹) | Specific heat capacity/(J·kg⁻¹·K⁻¹) |
|----------------|-----------------------------------|--------------------------------------|
| 300            | 35                                | 779                                  |
| 600            | 15.8                              | 838                                  |
| 1000           | 7.85                              | 1224                                 |
| 1700           | 5.54                              | 1320                                 |
| 2200           | 5.5                               | 1330                                 |
4. Characteristics of multilayer multichannel temperature pool

SLM simulation process parameters are: laser power $P=105W$, scanning speed $v=50mm/s$, powder layer thickness $h=0.25mm$, mark 1 ~ 9 in figure 2, corresponding node Numbers: 4875, 4876, 4877, 4904, 4905, 4906, 2670, 2669, 2668. It takes 16.66s to complete a single scan, and a total of 159 seconds to complete all the scans. The length, width and depth of the melted pool at node 2670 (point 7 in Fig.2) are 0.23mm, 0.15mm and 0.03mm respectively.

4.1. Influence of laser power on the characteristics of molten pool

When $P=80W$ and other processing parameters remain unchanged, the top view of temperature cloud at 2670 node is shown in Fig. 5(a). (1) Compared with the power of 105W, the maximum temperature in the whole process decreases with the decrease of laser power, and the maximum temperature drops from 3246℃ to 2273℃, resulting in melting of Al₂O₃ powder. (2) The length of the molten pool is 0.13mm, which decreases. (3) The width of molten pool is 0.14mm, which reduce slightly. Figure 5(b) is the left view of temperature field of 2670 node. (4) The molten pool depth is 0.025mm, which decreases a little. The powder layer is only slightly melted and most of the powder is at 1174℃.

4.2. Influence of scanning speed on the characteristics of molten pool

When the speed is doubled, $v=100mm/s$, and other process parameters remain unchanged, the simulation results are shown in Fig. 6. (1) The melting pool width is 0.14mm, which reduced slightly. (2) The melting pool depth is 0.014mm, reducing 54%, and only a small part of the powder melted. Under the same material, the depth of molten pool is affected by the laser power and velocity, and velocity has a great influence.
4.3. influence of initial powder temperature on the characteristics of molten bath

$P=80\text{W}$, $v=50\text{mm/s}$, $h=0.25\text{mm}$, and the initial temperature of the powder is increased to 330℃. The simulation results are shown in Fig. 7. (1) Remelting begins between layers, as shown in figure 7(a). When the heat source is scanned to 2670 node, the temperature of node 4904 can still reach 2100℃. (2) There is no remelting between the channels. Taking node 4875 as an example, the temperature when scanning to the mark points 1, 2 and 3 is 2100℃, 800℃ and 500℃, respectively. Obviously, the influence of the latter two melting channels on mark point 1 is not enough to reach the melting temperature. (3) As shown in Fig. 7(b)(c), the length and width of the molten pool change little, and the depth of the molten pool reaches 0.036mm. It can be seen that increasing the initial powder temperature has a great impact on the depth of the molten pool.

4.4. Influence of powder layer thickness on molten pool characteristics

$P=105\text{W}$, $v=50\text{mm/s}$, the initial temperature of the powder is 330℃, and the thickness of the powder layer is set to 0.20mm. The simulation results are shown in Fig. 8. (1) Remelting begins between layers, as shown in figure 8(a) below. When the heat source scans to the 2670 node, the temperature of node 4904 can still reach 3000℃, meeting the remelting condition. (2) There is no remelting between the channels, as shown in Fig. 8(b). The width of the molten pool is 0.15mm, which did not change. (3) As shown in Fig. 8(c), the molten pool depth reaches 0.068mm, and the powder layer thickness has a great influence on the molten pool depth.
5. Conclusion
The powder thickness, initial temperature, scanning speed and laser power of the energy model have great influence on the depth of the molten pool. The influence of scanning speed and laser power on the length of molten pool is the second. These parameters have a little influence on the width of molten pool, among which the laser powder has greater influence on the width of molten pool. Appropriate energy model parameters are required to determine whether remelting occurs between different layers. When the simulation process parameters $P=105\text{W}$, $v=50\text{mm/s}$, the initial temperature of the powder is $330^\circ\text{C}$, and the thickness of the powder layer is $0.20\text{mm}$, the characteristics of the molten pool that is easy to be formed can be obtained.

References
[1] Chen Q, Guillemot G, Gandin C A, et al. Numerical modelling of the impact of energy distribution and Marangoni surface tension on track shape in selective laser melting of ceramic material[J]. Additive Manufacturing, 2018:713-723.
[2] Panwisawas C, Qiu C L, Sovani Y, et al. On the role of thermal fluid dynamics into the evolution of porosity during selective laser melting[J]. Scripta Materialia, 2015, 105:14-17.
[3] Morgan R-H, Papworth A-J, Sutcliffe C, et al. High density net shape components by direct laser re-melting of single-phase powders[J]. Journal of Materials Science, 2002, 37(15):3093-3100.
[4] Simchi A, Petzoldt F, Pohl H. On the development of direct metal laser sintering for rapid tooling[J]. Journal of Materials Processing Tech, 2003, 141(3):319-328.
[5] Bertol L-S, Júnior W-K, Silva F-P-D, et al. Medical design: Direct metal laser sintering of Ti–6Al–4V[J]. Materials & Design, 2010, 31(8):3982-3988.
[6] Vandenbroucke B, Kruth J. Selective laser melting of biocompatible metals for rapid manufacturing of medical parts[J]. Rapid Prototyping Journal, 2013, 13(4):196-203.
[7] Duley W-W. Laser processing & analysis of materials.N.Y.Plenum Pr,1983.1-459.