

Numerical Simulation of Marangoni flow field of Selective Laser Sintering of Polyamide 6 Powder

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Abstract. In this paper, we investigated polyamide 6 single layer laser sintering process. The temperature field distributions with different energy density were achieved using the finite element method. In addition, we investigated the Marangoni flow field and achieved the relationship between process parameters and Marangoni flow field. The results indicate that the Marangoni flow strongly influences the temperature field and the fluid flow: with the energy density increases, the convective heat transfer becomes intensely, so the heat in the pool center spreads faster, the high temperature area becomes relatively smaller, and the molten pool becomes wide and shallow. According to the relationship between energy density and Marangoni flow field, we can optimize the SLS process parameters and get the better parts.

1. Introduction

Selective laser sintering (SLS) constructs complex 3D parts by laser consolidating powder material layer by layer. Each layer is sintered according to its corresponding cross section from 3-D digital data [1]. In the microscopic point of view, SLS is a series of complex process of continuous formation, re-melting, and re-solidification of molten pool around the laser spot.

At the fluid surface, Marangoni flow arises from chemical capillary or thermal gradients, the direction of flow being from a position of low surface tension to one of high surface tension [2]. At present, many experts and scholars have studied the Marangoni flow, revealed that the final morphology of the weld pool is mainly affected by the Marangoni flow [3] [4]. In addition, Marangoni flow also has important effects including enhances particle rearrangement [5] and decreases the proportion of bubbles of the weld pool [6]. So the Marangoni flow directly determines the symmetry, regularity, the temperature and velocity fields of the weld pool, thus affects the properties of the final specimen such as density, microstructure and mechanical properties.

The magnitude of Marangoni flow is affected by so many factors such as tension gradient of the liquid surface, the free surface length, the dynamic viscosity and the kinematic viscosity. The surface tension gradient is mainly affected by the surface temperature gradient, and the dynamic viscosity and kinematic viscosity are mainly affected by the temperature. The process parameters of the laser sintering process, such as laser power, scanning speed, scanning mode, scanning distance and preheating temperature all affect the surface temperature gradient and temperature, and then affect the magnitude of the Marangoni flow.

In this work, according to the study of temperature field distribution with different process parameters, the distribution of Marangoni flow can be obtained. We can achieve the relationship between process parameters and Marangoni flow field, and we can also achieve the relationship



between velocity field and temperature gradient with different energy density. So as to optimize the SLS process parameters and get the better parts.

2. Theory

2.1. Physical model and assumptions.

As shown in Fig.1, the laser beam is defined as a Gaussian power distribution, which moves at a constant scan speed. As the laser beam irradiate on the powder, a molten pool is formed and the Marangoni flow is driven by surface tension gradient.

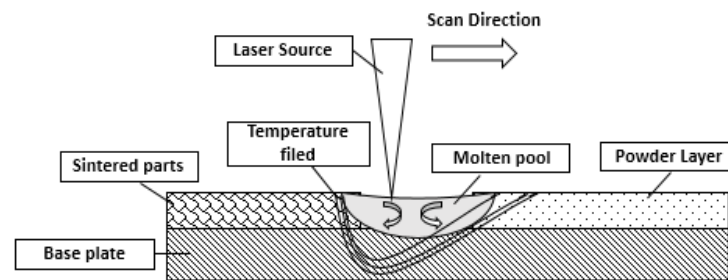


Figure 1 The schematic of SLM physical model

2.2. Governing equations of temperature field simulation

The SLS process is the regional transient effect of the laser applied on the powder material. It can be simplified that the moving Gaussian heat source. In order to establish the temperature field model of sintering process, the following simplifications and assumptions can be proposed [7]:

(1) The laser spot is so small and the applied time is short, and the value of the convective heat transfer between the spot area and the environment is small, so the convection heat transfer influences can be neglected. The laser irradiates vertically, ignoring the surface's reflection of energy. (2) Regardless of the latent heat of transformation during the sintering process, the thermal conduction in the powder material is considered as no internal heat source. (3) Assuming the powder is isotropic homogeneous material, its thermal properties will change with temperature. (4) Laser irradiate vertical to the zone, lift the temperature highly, forming a area of the large external radiation energy, so consider the impact of radiation. (5) The heat transfer form of the powder to the substrate is heat conduction and considers the contact thermal resistance.

Based on the first law of thermodynamics of heat conduction and Fourier law, the three-dimensional heat conduction equation can be expressed:

$$\rho c \frac{\partial T}{\partial t} = \lambda \left[\left(\frac{\partial^2 T}{\partial x^2} \right) + \left(\frac{\partial^2 T}{\partial y^2} \right) + \left(\frac{\partial^2 T}{\partial z^2} \right) \right] \quad (2.2.1)$$

Where ρ , c , T , t , λ are the density, specific heat, temperature, time and thermal conductivity respectively. X , y , z represent the source item of the momentum conservation equation in the X , Y and Z direction.

Based on the assumptions and simplified conditions, Equation (2.2.1) corresponding to the boundary conditions can be further expressed as the following equations:

(1) To the powder on the surface, only consider the heat radiation heat transfer, the heat flow can be expressed:

$$\Phi_R = A \sigma \epsilon_\alpha (T_s^4 - T_f^4) \quad (2.2.2)$$

(2) The lower surface of the powder is conducted with the substrate, so:

$$-\lambda' \frac{\partial T}{\partial n} = q(t) \quad (2.2.3)$$

Where: λ' is the thermal conductivity of copper, n is the normal vector of the boundary, $q(t)$ is the heat flux density function at the boundary.

(3) The rest surface of the laser irradiation zone's temperature changes have little effect, can be set to adiabatic surface, so:

$$-\lambda'' \frac{\partial T}{\partial n} = 0 \quad (2.2.4)$$

Here, λ'' represents the thermal conductivity of each surface.

(4) Initial conditions: The initial temperature of the powder and the substrate are ambient temperature or preheat temperature, so:

$$T|_{t=0} = T_0 = T_f \quad (2.2.5)$$

Here, T_f is ambient temperature or preheat temperature.

3. Simulation method

3.1. Materials

In Table 1[9], we listed the characteristics of the PA6 powder.

Table1. PA6 main characteristics

Parameters	Value	Parameters	Value
Powder size (mesh)	80	Dynamic viscosity (Pa*s)	0.003
Powder density (Kg/m3)	578.9	Temperature derivative of surface tension	0.065e-3
Material emissivity	0.95	Thermal conductivity (W/ (m*K))	0.3
Melting point (°C)	220	Heat capacity (J/(kg*K))	1400
Gasification point (°C)	500		
Porosity ratio (ε)	0.406		

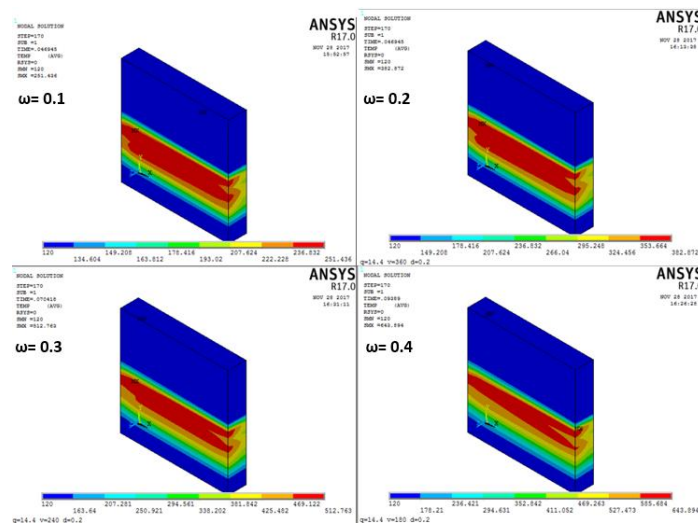
3.2. Experiment of temperature field simulation

When applied to SLS, the appropriate process parameters is one of the most important research points. We choose relatively appropriate parameters using the Energy density (ω), defined as the relative applied laser energy per unit area, can be calculated by Eq.3.2.1. ω was in the range from 0.1 to 0.4 J/mm². Therefore, we selected the laser sintering process for with same scan spacing (H) was 0.2mm, the powder layer thickness (D) was 0.5 mm, the preheating temperature was 120 °C, scan speed (V) range was 180 ~ 360 mm/s, and the laser power (P) range was 3.6 ~ 14.4 W, as shown in Table 2. We simulated temperature field of the laser sintering process, with different energy density, as shown in Fig.2. At the energy density of 0.1 J/mm² (P=7.2w, V=360mm/s, H=0.2mm), the temperature gradient Delta T=15 °C, When energy density comes up to 0.2 J/mm² (P=14.4w, V=360mm/s, H=0.2mm), the Delta T=30 °C, At the energy density of 0.3 J/mm² (P=14.4w, V=240mm/s, H=0.2mm), the Delta T=45 °C, Finally, When energy density comes up to 0.4 J/mm² (P=7.2w, V=360mm/s, H=0.2mm), the Delta T=60 °C.

$$\omega = \frac{P}{V \times H} \quad (3.2.1)$$

Table2. Process parameters of selective laser sintering

Parameters	Value
Energy density: ω (J/mm^2)	0.1, 0.2, 0.3, 0.4
Scan spacing: H (mm)	0.20
Layer thickness: D (mm)	0.50
Preheating temperature: T ($^{\circ}\text{C}$)	120
Laser power: P (w)	3.6, 7.2, 14.4
Scan speed: V (mm /s)	180, 360
Laser Scan direction	X-direction

**Figure2.** Five samples' pictures of a single-layer SLS simulation with the energy density of 0.1—0.4 J/mm^2

3.3. Experiment of Marangoni Flow simulation

Due to the laser spot is so small ($d=20\text{ }\mu\text{m}$), scanning speed is relative high, in this study, the unit volume model under the laser spot was simplified as a simple square model ($a=10\text{ mm}$), and the Marangoni flow in the model were simulated using Comsol software.

According to the temperature field simulation, we can bring the results to the Marangoni Flow simulation. In Fig.3, the Marangoni Flow were shown with different temperature field. The contour represents the excess temperature in model domain, and the arrow surface represents the velocity field.

As we can see, for the low temperature difference of $8\text{ }^{\circ}\text{C}$, the temperature field is decoupled from the velocity field almost. So, we can notice the temperature decreases linearly. For the temperature difference of $45\text{ }^{\circ}\text{C}$, the flow of fluid and the distribution of temperature were influenced by the Marangoni flow obviously. The temperature is no longer dropping linearly and we can notice how the flow causes the advection of the isotherms.

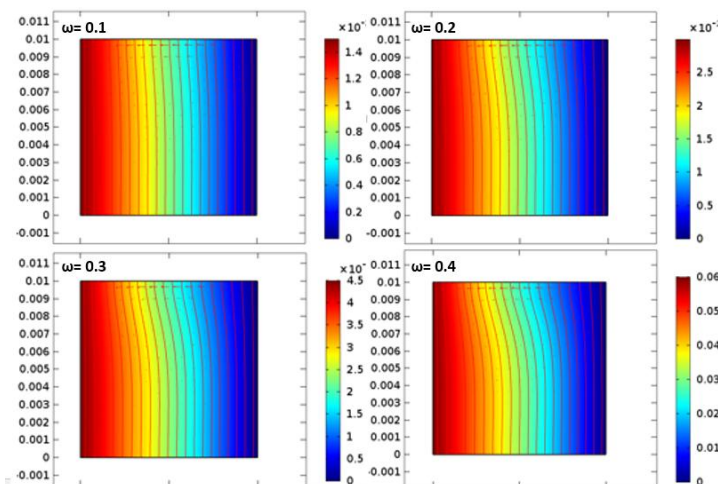


Figure 3. The Marangoni Flow affected by different temperature field Delta T: 8 — 15 °C

4. Results and discussion

As shown in Fig.4, we selected two representative sets of simulations: $\omega=0.1$ and $\omega=0.4$ J/mm², to discuss the coupling relationship between the velocity and the temperature field. As we can see, the Marangoni flow flows radially from the center of the bath to the edge of the bath. With the energy density increases, the coupling relationship became clearly visible. When the energy density rose from 0.1 to 0.4 J/mm², the coupling angle between the temperature field and the velocity field in the weld pool decreases significantly. Guo et al [10] proposed a field synergy number F_c , in order to measure the synergy degree of the fluid velocity and temperature gradient. Then F_c is proportional to $\cos\theta$, where θ is the included angle between temperature field and the velocity vector. We can notice that the θ become smaller with the energy density increases, so that the magnitude of F_c increases, it enhances convective heat transfer. We can deduce that when the energy density is low, convective heat transfer is so small that laser energy accumulates in the pool center, resulting in the high temperature area becomes relatively larger, and the molten pool becomes narrow but deep. When the energy density is high, convective heat transfer becomes intensely so the heat in the pool center spreads faster, the high temperature area becomes relatively smaller, and the molten pool becomes wide and shallow. The conclusion about the area of high temperature is consistent with our previous simulation of temperature field as shown in Fig.2

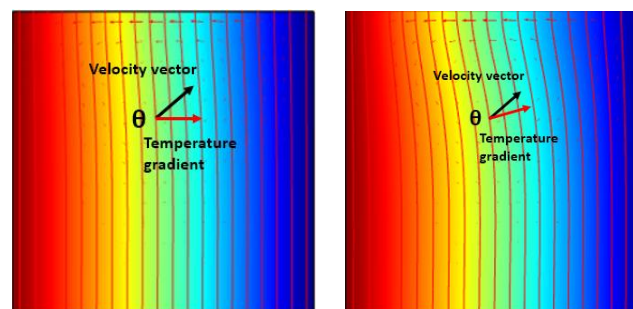


Figure 4. the relationship between velocity field and temperature gradient

5. Conclusions

In this work, we have simulated the temperature field with the different energy density from 0.1 — 0.4 J/mm², and achieved each group's temperature gradient from 15 — 60 °C. The Marangoni Flow has been simulated based on the different temperature gradient. And we noticed that: with the energy density increases, the flow influenced the advection of the isotherms more obviously. Finally, we can also achieve the relationship between velocity field and temperature gradient with different energy density. The results indicate that the Marangoni flow strongly influences the flow of fluid and the

distribution of temperature: with the energy density increases, the convective heat transfer becomes intensely, so the heat in the pool center spreads faster, the high temperature area becomes relatively smaller, and the molten pool becomes wide and shallow.

Acknowledgments

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