Research on the Effect of Key Technological Parameters on Molten Pool during Selective Laser Melting Processing

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Abstract. Selective laser melting (SLM), as an emerging technology in additive manufacturing, often has various defects in the forming process. To ensure the consistency and stability of the parts forming quality, the effects of two typical technological parameters, laser power and scanning speed, on the temperature of molten pool are investigated in this paper. Firstly, the temperature field of Ti-6Al-4V is simulated theoretically via ANSYS software, and the effects of two typical technological parameters on the temperature field are studied. Then, in the experiment, using the designed radiation monitoring device and Ti-6Al-4V powder as forming material, the influence of these two typical factors on the state of molten pool is studied. The simulation and experimental results show that the temperature of molten pool shows positive correlation with the laser power and negative correlation with the scanning speed. This will provide a certain reference value for upgrading and optimizing SLM equipment.

Keywords. Selective laser melting, temperature field simulation, molten pool.

1. Introduction

As one of the most advanced and promising additive manufacturing technologies, selective laser melting (SLM) is widely used in medical devices, template manufacturing, vehicles, aerospace, architecture, military and many other fields. In SLM forming process, it is really essential to understand the influence of different technological parameters on the temperature of molten pool. As the smallest unit in the thermal evolution process of constituent materials, the temperature of molten pool determines the viscosity, affects the wetting and spheroidizing properties, and affects finally the forming quality of SLM. Therefore, to investigate the influence of typical technological parameters on the temperature of molten pool has a certain guiding role for the actual SLM Industrial production. Laser power and scanning speed are important parameters of input energy in SLM equipment, so it is necessary to study their influence on the temperature of molten pool. The experiments in work [1], by way of Ti-6Al-4V Alloy powder as material, show that the relative density, martensite lath size and microhardness of the workpieces increase with the input of laser energy. In [2], the influence of scanning speed on surface roughness is analyzed, and the parameter optimal solution set is established to improve the surface quality by additional milling. In [3], the temperature field and velocity field in SLM process are studied by numerical simulation and experimental test. Three states of molten pool and the threshold of scanning speed are given. In [4], the factors of typical technological parameters affecting porosity are explored, and the post-treatment methods to reduce porosity are also discussed.

In this paper, Ti-6Al-4V Alloy powder is used as the forming material to investigate the effects of the laser power and scanning speed on the temperature of molten pool, and the temperature field of the material is numerically simulated. The forming process of SLM is analyzed from theory, simulation...
and experiment, so as to help the actual SLM production practice set reasonably technological parameters and improve product quality.

2. Theoretical Simulation and Analysis

Finite element analysis is a common mean to research the SLM forming process theoretically. It can be used to theoretically analyze the influence of different parameters on the temperature of molten pool.

2.1. Basis of Simulation

The heat conduction evolution of each molten pool in SLM forming process can be expressed by heat transfer control equation as [5, 6]:

$$\frac{\partial}{\partial x} \left( k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial T}{\partial z} \right) + q = \rho c_p \frac{\partial T}{\partial t}$$ (1)

where, \(x, y\) and \(z\) respectively represent the distance of heat conduction along the X, Y and Z axes in the spatial rectangular coordinate system; \(\rho\) is the material density, \(c_p\) is the specific heat capacity of the material.

For the initial and boundary conditions of the specified temperature, the unique solution of the equation can be obtained, and then the temperature field distribution of the molten pool is getted. For the simulation analysis of temperature field, the classical Gaussian surface heat source is used as the heat source model. In the actual forming, there is latent heat of phase change in the material phase transformation process. In this paper, the thermal method is used to handle the latent heat of phase change. The relationship between enthalpy \(H(J)\) and temperature can be expressed as:

$$H = \int \rho c_p dT$$ (2)

For material properties, it is assumed that Ti-6Al-4V powder belongs to isotropic material, that is, \(k_x = k_y = k_z = k\), the thermal conductivity \(k\) in all directions is taken as 6.7 W/(m \cdot K), and the laser absorptivity of Ti-6Al-4V powder \(\alpha\) is taken as 0.68 .

In order to simulate the temperature field of Ti-6Al-4V powder, the finite element model is established in ANSYS and meshed. The model and meshing of powder layer and substrate are shown in figure 1. The parameter settings are listed in table 1.

![Figure 1](image.png)

**Figure 1.** The finite element temperature field model and mesh generation of Ti-6Al-4V.
Table 1. Parameters in finite element simulation experiment.

| Parameters                              | Ranges                                      |
|-----------------------------------------|---------------------------------------------|
| Laser Power (W) (v=800 mm/s)            | 110, 120, 130, 140, 150                     |
| Laser Scanning Speed (mm/s) (P=130W)    | 400–1800 (200 mm/s interval)                |
| Powder Layer Thickness (μm)             | 30                                          |
| Laser Spot Diameter (μm)                | 50                                          |

2.2. Results of Simulation

As considering the factors such as birth and death element and heat source loading, the simulation results of temperature field can be obtained. For different power, the maximum temperature of molten pools after the heat source moves steps 17, 19 and 21 (corresponding time is 0.56 ms, 0.63 ms and 0.7 ms) are compared. The summary of simulation results is listed in table 2 and the curve is given in figure 2.

Table 2. Maximum temperature of molten pool under different laser power.

| Power (W) | 0.56ms | 0.63ms | 0.7ms |
|-----------|--------|--------|-------|
| 110       | 2028.96| 2028.74| 2028.6|
| 120       | 2103.79| 2103.8 | 2103.75|
| 130       | 2173.3 | 2173.23| 2173.21|
| 140       | 2250.73| 2250.76| 2250.75|
| 150       | 2334.91| 2334.83| 2334.77|

Figure 2. The relation curve between simulation temperature and laser power.

For different speeds, the maximum temperatures of molten pool after steps 17, 19 and 21 of heat source movement are also taken for comparison. The summary of simulation results is listed in table 3, and the curve is shown in figure 3. At different speeds, these three steps correspond to different moving times of the heat source, so they are only marked by steps in the charts for simplicity.

Table 3. Maximum temperature of molten pool at different scanning speeds.

| Speed(mm/s) | Steps 17 | Steps 19 | Steps 21 |
|-------------|----------|----------|----------|
| 400         | 2377.43  | 2378.02  | 2378.52  |
| 600         | 2270.5   | 2270.75  | 2270.87  |
| 800         | 2173.3   | 2173.23  | 2173.21  |
| 1000        | 2083.96  | 2083.91  | 2083.85  |
| 1200        | 2006.8   | 2006.77  | 2006.7   |
| 1400        | 1908.58  | 1908.7   | 1908.75  |
| 1600        | 1828.89  | 1828.9   | 1828.9   |
| 1800        | 1742.36  | 1742.36  | 1742.36  |
Figure 3. The relation curve between simulation temperature and laser scanning speed.

The simulation results show above that the temperature of molten pool is linearly related to the laser power. The stronger the power is, the higher the corresponding temperature of molten pool is; The higher the laser scanning speed, the less energy absorbed by the molten pool and the less energy radiated outward.

3. Experimental Results and Discussion

3.1. Experimental Setup and Design

The metal powder material used in this paper is TC4 (Ti-6Al-4V), which has low density, high strength and good corrosion resistance [7]. Our setup system has been developed in [8], as is shown in the figure 4. And the printed workpiece is shown in the figure 5.

Figure 4. Picture of equipment and molten pool light radiation detection system.  
Figure 5. Picture of printed workpiece.

In order to study the radiation state of molten pool with different above parameters and their settings, two groups of experiments were designed. The scanning span between flutes is 80 μm. Other parameter settings are listed in table 4. Before the formal experiments, the simulation results are compared with the measured results when the laser power is 130 W, with the scanning speed 800 mm/s. The results of comparison show that the simulation results are consistent with the results of the experiments.
Table 4. Parameters of experiments.

| Experimental Groups | The First Group | The Second Group |
|---------------------|-----------------|------------------|
| Number of Test Pieces | 5               | 8                |
| Laser Power (W)     | 110–150         | 130              |
| Laser Scanning Speed (mm/s) | 800          | 400–1800         |
| Scanning Mode        | Unidirectional  | Unidirectional   |
| Distance between Starting Point and Origin (mm) | 2              | 2                |
| Distance between End Point and Origin (mm)  | 35             | 35               |
| Width (mm)           | 1               | 1                |
| Number of Forming Layers | 100            | 100              |

3.2. Experimental Results and Analysis

To explore the impact of power on radiation signal, five test pieces of the first group of experiments in the table 4 are taken. For each test piece, the signals of all melting lanes 5 ~ 30 mm from the origin in the same layer (with an interval of 5mm) are acquired to collect their mean value and standard deviation, and the error bar diagram of signal at each distance is shown in figure 6.

It can be clearly seen from the curves in figure 6 that when the molten pool is more than 10mm away from the origin, the radiation signal and the laser power show a good linearity. This is because the higher the laser power, the more energy the material absorbs. So the higher the temperature is, and the higher the radiation energy. When the molten pool is 5 mm away from the origin, the linearity between the radiation signal and the laser power decreases. And in the range of 110 ~ 130W, the radiation signal attenuates with the increase of power, which may be due to the remelting of the molten pool caused by too high laser energy at the origin, and the molten pool sinks downward.

It can also be seen from the figure 6 that the deviation of radiation signals between different flutes is small, indicating that the forming stability and consistency are good under the condition of maintaining constant power.

Figure 6. Relation curve between radiation signal and laser power.

In order to study the impact of different scanning speeds on the state of molten pool, eight test pieces of the second group of experiments in the table 4 are taken. For each test piece, the signals of all melting lanes 5 ~ 30mm away from the origin in the same layer (with an interval of 5mm) are measured. Their mean value and standard deviation are collected, and the error bar diagram of signal and scanning speed at each distance is shown in figure 7.
It can be seen from the trend of each curve in figure 7 that no matter how far away from the molten pool to the origin, the radiation signal always decreases first and then increases with the enhancement of scanning speed. It is considered that the enhancement of laser scanning speed means that the energy of laser per unit distance is reduced, the energy absorbed by powder is also reduced, and the radiation energy released is also reduced. When the scanning speed continues to increase, the weld bead length corresponding to the sampling data in a sampling period also continues to increase. Because the coaxial optical path system actually observes a circular area with a radius of 1mm centered on the current molten pool, the number of molten pools actually observed increases and the induced radiation energy increases accordingly with the increase of the distance of the observed molten pool.

Additionally, figure 7 also shows that the farther the molten pool is from the origin, the less the influence of the scanning speed on the radiation signal. This may be due to the change of the shape of the laser spot when the distance becomes larger, which has a preheating effect on the subsequent powder and reduces the impact of the change of laser energy density on the energy absorbed by the molten pool.

4. Conclusion
For the effects of different laser power on molten pool temperature or radiation, figure 2 and figure 6 show that the molten pool temperature or radiation is linearly related to the laser power, both of the simulation results and the experimental results have the same trend.

For the influence of scanning speed on molten pool temperature or radiation, comparing figure 7 to figure 3, however, the experimental results are slightly different from the simulation results. It can be considered that this is because the actual detection is the total radiation energy of multiple molten pool areas in a sampling period, while the simulation selects the maximum temperature of a single molten pool. But the essence of the both trends is the same, that is, the faster the laser scanning speed, the less energy absorbed by the molten pool and the less energy radiated outward.

In conclusion, the two typical technological parameters studied in this paper have a direct impact on the state of molten pool. The experimental and simulation results verify each other, and this regulation is helpful to guide the reasonable setting and adjustment of parameters in the actual production processing.

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