Numerical investigation of Transient Temperature Field on the Selective Laser Melting process with Al6063

Xinyue Chen\textsuperscript{1,}\textsuperscript{*}, Xianyin Duan\textsuperscript{2,}\textsuperscript{*}, Guozhang Jiang\textsuperscript{3,}\textsuperscript{b}

\textsuperscript{1}Institute of precision manufacturing, Wuhan University of Science and Technology, Wuhan, China.
\textsuperscript{2}Hubei Key Laboratory of Mechanical Transmission and Manufacturing Engineering, Wuhan University of Science and Technology, Wuhan, China.
\textsuperscript{3}Key Laboratory of Metallurgical Equipment and Control Technology, Ministry of Education, Wuhan University of Science and Technology, Wuhan, China.

*Corresponding author e-mail: dxyv@qq.com, cxybella@foxmail.com, whjgz@wust.edu.cn

Abstract. The finite element simulation of the selective laser melting process with Al6063 metal powder was carried out by using ABAQUS. The loading of the laser Gaussian moving heat source is realized, and a model of the three-dimensional transient temperature field is established. The effects of scanning speed and scanning pitch on temperature distribution and temperature changes on different scanning channels were investigated. The simulation results show that due to the heat accumulation effect and heat conduction, the previous scan will have effect on the surrounding powder, which results the rise of temperature. Different scanning speed and the scanning pitch have influence on the temperature distribution. As the scanning speed increases, the temperature gradually decreases, and the increase in the scanning pitch also lead to lower temperature of the powder layer.

1. Introduction

Selective laser melting is one of additive manufacturing and the rapid prototyping techniques of metal powder. Compared with other traditional processing methods, such as welding and casting, SLM forming can realize one-time forming of complex shapes without the need of fixed molds and fixed tools. Therefore, SLM forming has a wide range of applications in advanced fields such as Molds, Aerospace and Biomedical Science.

Due to the extreme changes in temperature during the SLM forming process, the interior of the material changes to cause some defects. In order to reduce the occurrence of such defects, the temperature field using the Finite Element Analysis (FEA) forming process is an effective method for predicting the temperature distribution field of the SLM. Professor S. Kolossov [1] established a thermal model of selective laser sintering (SLS) and simulated the temperature evolution and forming process of sintered parts using a three-dimensional finite element analysis method based on continuum theory. Vinod Yadava et al. [2-3] established a thermal model based on transient finite element method to calculate the temperature distribution in a single metal layer during metal laser sintering, and studied the effect of process parameters on the temperature distribution in the titanium alloy.
model during the forming process. Tawfik et al. [4] used ABAQUS to establish a three-dimensional finite element model, simulating the deposition process to predict part deformation. Liu et al. [5] conducted a finite element analysis considering heat flux, convective heat transfer and heat transfer heat transfer, and obtained the temperature field of AlSi10Mg powder under different scanning times. Chee-Kai Chua et al. [6] established a finite element model on SLM to consider the transition of powder to solid. At the same time, the validity of the model is verified by experiments.

In this paper, the subroutine written in Fortran language of ABAQUS is used to realize the loading of Gaussian mobile heat source for Al6063 material. Numerical simulation of the distribution of three-dimensional transient temperature field in selective laser melt forming. The effects of different scanning pitch and scanning speed on temperature changes were discussed.

2. Establishment of 3D finite element model of selective laser melting temperature field

2.1. Establishment of finite element model

The selective laser melting finite element model is mainly composed with two parts. The lower part is 45 steel material and the upper layer is Al6063 powder. The size of the 45 steel under layer is 1.5 mm × 1.5 mm × 0.6 mm, and the size of the Al 6063 powder layer is 0.6 mm × 0.6 mm × 0.05 mm. The grid is divided by a hexahedral eight-node DC3D8 type. The local refinement grid facilitates computational accuracy and simulation optimization.

![Figure 1. Finite element model and scanning method](image)

2.2. Material properties

During selective laser melting processing, the material changes from powder to liquid and is finally cooled to solid state. In the molding process, the thermal conductivity of the material, thermal conductivity and specific heat capacity are all changed with temperature. The thermal conductivity of the entity is several dozen times larger than that of the powder [7]. Therefore, it is important to determine the thermophysical parameters for different temperatures at different stages of the material.

The metal powder used in this paper is Al6063, and the substrate material is 45 steel. The thermal properties of Al6063 compact and 45 steel materials are shown in the Table 1. It is assumed that the density of the materials studied in this paper does not change with temperature. The latent heat of phase change usually adopts the equivalent specific heat capacity method [8]. According to the literature, the phase transition region of Al6063 is generally 615℃ ~ 655℃. The maximum latent heat is 390000 J / Kg. So the phase change in the simulation process can not be ignored.
Table 1. Al6063 and 45 steel thermal property parameters

| TEMPERATURE (°C) | 20  | 100 | 200 | 300 | 400 | 2000 |
|------------------|-----|-----|-----|-----|-----|------|
| Density (Kg/m³)  | 2700|     |     |     |     |      |
| Al6063 Thermo.    | 119 | 121 | 126 | 130 | 135 | 145  |
| Conductivity (W/ (K·m)) | 900 | 921 | 1005| 1047| 1089| 1129 |
| Specific heat (J/(K·K)) | 900 | 921 | 1005| 1047| 1089| 1129 |
| 45 steel Density  | 7890|     |     |     |     |      |
| Thermal Conductivity (W/ (K·m)) | 47.6| 43.5| 40.4| 38.1| 36.0| 24.0 |
| Specific heat (J/(K·K)) | 472 | 480 | 498 | 560 | 589 | 602  |

2.3. Determination of initial and boundary conditions

This paper considers the heat conduction and penetration mechanism of the laser. Because the laser processing speed is faster and the time is shorter. Gaussian surface heat source model can be expressed as

$$q(r) = \frac{3\eta P}{\pi R^2} e^{-\frac{r^2}{R^2}}$$  \hspace{1cm} (1)

In equation (1), $P$ is the laser power, $\eta$ is material absorption rate of laser energy, The absorption rate studied in this paper is 0.1 [9], $R$ is laser heat source radius, $r$ is the distance from any point on the molded part to the center of the laser heated spot. The heat source is loaded by the Fortran language programming DFLUX subroutine. Time is embedded in the heat source equation, so that the heat source can be moved.

In the process of selective laser melting of Al6063, the temperature field is defined as a nonlinear transient heat conduction problem. The heat transfer mechanism includes heat radiation, heat conduction and heat convection. According to Fourier's law and the energy conservation, the following heat transfer equation [10] can be obtained:

$$\lambda \left( \frac{\partial^2 T}{\partial x^2} \cdot \frac{\partial T}{\partial y} + \frac{\partial^2 T}{\partial y^2} \cdot \frac{\partial T}{\partial z} \right) + \rho C_p \frac{\partial T}{\partial t} = Q$$  \hspace{1cm} (2)

In formula (2), $\lambda$ is Al6063 powder thermal conductivity, $T$ is temperature, $t$ is time, $Q$ is latent heat, $\rho$ is powder density, $C_p$ is specific heat.

3. Analysis and discussion

The process parameters selected in this paper are shown in Table 2 below. The simulation uses a serpentine scanning method, which scans two times each time. The temperature field of the molding process was simulated by changing the scanning speed and the scanning pitch.
In this paper, the powder layer parallel to the middle of the two laser paths is selected for study. The overall distribution of the simulated temperature field is simulated by changing the scanning pitch and scanning speed. Finally, the nodes on the midline are selected for data extraction. Figure 2 shows the laser sweep and the location of the selected node in the three-dimensional model. The simulation results are as follows

| Simulation groups | Initial temperature $T_0$ (°C) | Scanning pitch $s$ (mm) | Scanning speed $V$ (mm/s) | Laser power $P$ (W) |
|-------------------|---------------------------------|-------------------------|--------------------------|---------------------|
| 1-4               | 20                              | 0.07                    | 100,200,300,400          | 400                 |
| 5-8               | 20                              | 0.05, 0.07, 0.09, 0.11   | 200                      | 400                 |

Figure 2. Node and center line selection

Figure 3 shows the temperature profile for different speeds with $P=400$W and $s=0.07$mm. Figure 3 (a) shows the overall temperature distribution on the two scan midlines when the heat source is at the end of the first analysis step in the simulation. Figure 3 (b) shows the same in second analysis step. According to the information in Fig. 3, when $V=100$mm/s, the peak values are 1392°C and 1486°C. When $V=200$mm/s, the peak values are 1226°C and 1307°C. When $V=300$mm/s, the peak values are obtained 1103°C and 1175°C. When $V=400$ mm / s, the peak temperatures were 1007°C and 1071°C. As the laser scanning speed increases, the temperature gradually decreases. When the laser speed is too fast, the laser energy drops insufficient to melt more powder. The melting temperature gradient increases, resulting in a discontinuous molten pool and easy formation of spheroidization, which seriously affects the molding quality. When the second pass of the laser sweeps through the powder layer, the temperature is accumulated due to the preheating and heat accumulation effects of the first pass. The temperature change is not obvious when the scanning speed is fast. This is mainly because the heat absorbed by the material per unit time is small, the thermal diffusion is correspondingly reduced, the heat accumulation effect is not obvious, and the preheating temperature is not high.
Figure 3. Temperature distribution of different scanning speeds on the midline

Figure 4 shows the effect of changing the scan spacing on the temperature distribution field. The scanning speed is 200mm/s and the laser power is 400W. Since the laser scanning method is the same as before, the temperature distribution of different scanning pitches generally has the same trend. The temperature profile of the Node 1061 changing with time at different scanning intervals exhibits a certain regularity. As can be seen from Fig. 4, as the scanning pitch increases, the temperature decreases. The two peaks 927 °C and 1270 °C are the highest temperatures when the scanning pitch s = 0.05 mm. When the spacing is small, the distance between the two heat sources is also reduced. Due to the heat conduction and thermal diffusion of the powder, the energy of the heat source absorbed around the material increases and the temperature rises. As the spacing increases, the distance of the heat source increases correspondingly. The energy absorbed by the material decreases resulting in a decrease in temperature. Since the second laser is scanned for the previous preheating, the temperature is gradually increased, presenting a temperature accumulation phenomenon.

Figure 4. Temperature changing with time at Node 1061 with different scanning spacing

4. Conclusion
In this paper, the temperature field of selected laser melting process is numerically simulated by ABAQUS, which considering the influence of materials thermal properties and latent heat of phase transition. The following conclusions can be drawn by changing the technological parameters in the scanning process to study the temperature distribution rule of the forming process and the thermal effect between the scanning:

(1) In the process of laser forming with the same technological parameters. Heat source from the first scan to the second. Due to the thermal accumulation effect and thermal conduction of energy.
There is a large temperature gradient in the forming process. The accumulation of temperature causes the latter temperature and pool size to be significantly larger than the previous one.

(2) Due to latent heat and conduction during the movement of the heat source. The temperature near the heat source gradually increases. The temperature away from the heat source drops rapidly.

(3) With the change of scanning speed and scanning pitch, the temperature also shows a certain distribution tendency. As the scanning speed increases, the material absorbs less energy and the temperature is lower. On the contrary, the temperature distribution is higher. When the scanning pitch is increased, the heat source distance is correspondingly increased, the heat diffusion is large, and the temperature is gradually lowered.

Acknowledgments
This work was supported by National Natural Science Foundation of China under Grant No. 51605346 and National Natural Science Foundation of China under Grant No. 51875379.

References
[1] Kolossov S, Boillat E, Glardon R, et al. 3D FE simulation for temperature evolution in the selective laser sintering process [J]. International Journal of Machine Tools & Manufacture, 2004, 44 (2-3):117-123.
[2] Patil R B, Yadava V. Finite element analysis of temperature distribution in single metallic powder layer during metal laser sintering [J]. International Journal of Machine Tools & Manufacture, 2007, 47 (7-8):1069-1080.
[3] MATSUMOTO, SHIOMI, OSAKADA, et al. Finite element analysis of single layer forming on metallic powder bed in rapid prototyping by selective laser processing[J]. International Journal of Machine Tools & Manufacture, 2002, 42 (1):61-67.
[4] Samer M. Tawfik, Mohamed N.A. Nasr, Hassan A. El Gamal. Finite element modelling for part distortion calculation in selective laser melting [J]. Alexandria Engineering Journal, 2019, 58 (1):67-74.
[5] Liu B, Li B, Bai P, et al. Numerical investigation on heat transfer of multi-laser processing during selective laser melting of AlSi10Mg [J]. Results in Physics 12 (2019) 454–459.
[6] Numerical investigation and an effective modelling on the Selective Laser Melting (SLM) process with aluminium alloy 6061 [J]. International Journal of Heat and Mass Transfer, 2015, 80:288-300.
[7] Sih, Samuel Sumin, Barlow, Joel W. Measurement and prediction of the thermal conductivity of powders at high temperature. [C].Austion,1994: 321-329.
[8] JIANG XIANFENG,MENG XIANGCHEN,SONGRONGWEI,et al.Study on the effects of temperature field of material state change in the SLM process[J].Applied Laser,2015,35 (2):155-159.
[9] CHEN Jun, ZHANG Qun-li, YAO Jian-hua, et al. Study on laser absorptivity of metal material [J]. Applied Laser, 2008, 29 (5).
[10] CARSLAWHS, JAEGERJC. Conduction of heat in solids[M].New York: Oxford University Press,1967.