Temperature Field Simulation of Powder Sintering Process with ANSYS

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Abstract: Aiming at the “spheroidization phenomenon” in the laser sintering of metal powder and other quality problems of the forming parts due to the thermal effect, the finite element model of the three-dimensional transient metal powder was established by using the atomized iron powder as the research object. The simulation of the mobile heat source was realized by means of parametric design. The distribution of the temperature field during the sintering process under different laser power and different spot sizes was simulated by ANSYS software under the condition of fully considering the influence of heat conduction, thermal convection, thermal radiation and thermophysical parameters. The influence of these factors on the actual sintering process was also analyzed, which provides an effective way for forming quality control.

1. Introduction
As a modern manufacturing technology, selective laser sintering technology has its own unique advantages. In theory, it can make almost any shape of parts\(^{[1]}\). As one of the hot spots, metal laser selective sintering has been widely studied by scholars. The most common problems are the phenomenon of ”spheroidization” and warpage. These are caused by the thermal coupling between the metal powder and the laser. Therefore, the study of the distribution of temperature field in the process of laser sintering and the relationship between forming characteristics and process parameters is the key to solving the problem\(^{[2]}\).

2. Temperature field simulation

2.1. Establish finite element model
The establishment of finite element model is divided into three steps, the size of the shape, the definition of material properties and the division of the grid. In order to meet the size of heat-affected zone during sintering, a rectangular block of size 100mm × 50mm × 6mm was established as the shape of the finite element model. Water atomized iron is regarded as a common engineering practice materials because of their excellent material properties in the water atomized iron powder. The grid is divided by considering the grid type, the grid size and the grid distribution. The solid70 hexahedron eight-node cell is used as meshing model\(^{[3]}\), which can fill the heat loss due to the new added powder material\(^{[5]}\). The control grid size is 0.8mm, which subdivides the research object at the edge of the model.

2.2. Determine the constraints
Constraints are the basis to determine the general solution or solution in the simulation analysis.
process\cite{4}. In the simulation of thermal analysis, there are a variety of heat transfer ways, such as radiation, conduction and convection, which are used to determine the following constraints.

The first one is the space temperature distribution in the material before simulation, which can be expressed by the equations (1) and (2) as,

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

(1)

\[
T(x,y,z,t)\big|_{t=0} = \phi(x,y)
\]

(2)

In the above two equations, the initial temperature of the object is the temperature distribution in the object, both of which indicate that the initial temperature distribution of the object is not uniform.

The second constraint is the temperature distribution of the space in contact with the experimental powder material, which can be expressed by equations (3) and (4).

\[
T_x(x,y,t) = T_0
\]

(3)

\[
T_x(x,y,t) = f(x,y,t)
\]

(4)

In Eqs. (3) and (4), \(T_0\) is the initial boundary temperature of the space in contact with the powder material, and \(f(x,y,t)\) is the expression of the temperature of the space boundary. Eq. (4) indicates that the temperature of the initial boundary of this space changes with time.

The third is the input and output of powder material boundary energy, which can be expressed by Eqs.(5) and (6).

\[
-k \frac{dT}{dn} = q
\]

(5)

\[
-k \frac{dT}{dn} = g(x,y,t)
\]

(6)

In Eqs.(5) and (6), \(q\) is the heat flux density value on the surface of the powder material, and \(g(x,y,t)\) is the heat flux density function.

The fourth is the thermal convection between the powdered material and the molten liquid metal, which can be expressed by Eq.(7).

\[
-k \frac{dT}{dn} = a(T - T_f)
\]

(7)

In Eq.(7), \(a\) is the heat transfer coefficient between the powder material and the liquid metal and \(T_f\) is the liquid metal temperature.

2.3. Determine material parameters and process parameters

In the process of thermal analysis, it needs to define the material’s specific heat capacity, thermal conductivity and other material parameters\cite{6}. The final value of specific heat capacity and thermal conductivity are obtained from the experimental measurements as shown in Table 1. The process parameters are some reasonable experimental data to perform the experiment setup, as shown in Table 2.

\textbf{Table 1 Thermal properties of the parameters}

| Temperature/\(K\) | 273 | 573 | 673 | 773 | 873 | 107 | 117 | 127 | 137 | 147 | 157 | 1773 |
|-------------------|-----|----|----|----|----|-----|-----|-----|-----|-----|-----|------|
| Coefficient of thermal conductivity/\(\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}\) | 74.7 | 55.5 | 49.2 | 43 | 38.2 | 74.7 | 29.4 | 28.2 | 29.3 | 32.2 | 32.2 | 32.2 |
| Specific Heat Capacity/\(\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}\) | 435 | 552 | 602 | 661 | 753 | 832 | 656 | 569 | 606 | 640 | 736 | 836 |
| (\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}) | 1 | 3 | 5 | 1 | 1 | 6 | 9 | 569 | 7 | 2 | 4 | 8 |
Table 2 Process parameters

| Laser power | Spot diameter | Scanning speed | Convection coefficient | Bed temperature |
|-------------|---------------|----------------|------------------------|----------------|
| $P$ / $W$   | $D$ / $mm$    | $V$ / $mm \cdot s^{-1}$ |                          | $T$ / $°C$ |
| 215         | 0.4           | 50             | 10                     | 20            |

2.4 Mobile Gaussian heat source simulation

During the process of laser sintering, the laser moves at a constant velocity. The energy is transmitted to the powder material in the form of heat flux during the movement. The laser's power density follows the Gaussian distribution, which can be expressed as follows,

$$q(x, y) = \frac{2AP}{\pi \omega^2} \exp\left(-\frac{x^2 + y^2}{\omega^2}\right)$$

In Eq.(9), $q(x, y)$ is the laser power density at point $(x, y)$. $A$ is the absorption of the laser energy by the powder material. $P$ is the output power of the laser and $\omega$ is the laser power set in the experiment.

3. Results and analysis

3.1 Temperature field analysis under given conditions

After the process of model creation, meshing, material definition, unit type definition and definitive solution conditions, the temperature profile of the surface and side of the model at 0.44 s is obtained, as shown in Fig. 1 and Fig. 2.

![Figure 1](image1)

**Figure 1** Temperature distribution in model surface

![Figure 2](image2)

**Figure 2** Temperature distribution in model side

From Fig. 1 and Fig. 2, the maximum temperature of the temperature field lags slightly behind the laser spot center because the laser contacts the water atomized iron powder at room temperature in the direction of the laser movement[^7], which is different from the maximum temperature of the laser source at the laser spot center.

In order to find out the relationship between the quality of formed parts and the setting of laser parameters during the laser sintering process, the relationship between the quality of formed parts and the laser parameters during laser sintering process is discussed separately by changing the two intrinsic parameters of laser power and laser spot size.

3.2 Analysis of the temperature field under the change of laser power

The laser power is changed with other conditions remain unchanged. When the laser power is 100W and 400W, the temperature profile of the model at 0.44s is obtained, as shown in Figure 3 and Figure 4.
It can be seen from Figure 3 that when the laser power is 100W, the temperature at the center of the sintering spot is only 934.486°C due to insufficient energy compared with that shown in Figure 2 and Figure 4. In Figure 2 and Figure 4, the temperature does not reach the melting point of the powder material and the material can not be melted. Powder can not be sintered nor be shaped into parts. As shown in Figure 4, when the laser power reaches 400W, the laser spot temperature is as high as 3293°C due to too much laser energy. On the one hand, the increase of laser power contributes to the increase of the temperature in the whole region, and the length of the linear region above the melting temperature of the iron increases. On the other hand, the temperature of the spot center is much higher than the melting point of the iron material, the melting speed of the material is too fast and vaporization may even occur. At this moment, the melted material has too much fluidity, resulting in shear stress between the two layers of powder, which may cause warpage and deformation. It is not easily conducive to molding and may even have over-burning phenomenon. The adhesion between the layers may also affect the sintered surface of the uneven phenomenon.

3.3 Analysis of the temperature field under the change of spot sizes

Under the given conditions, when the laser spot size is 0.2 mm and 0.8 mm, the temperature profile is obtained with only changing the laser spot sizes, as shown in Figure 5 and Figure 6.

As it can be seen from Figure 5, when the spot size is 0.2mm, the laser energy is densely distributed. Compared with Figure 1 and Figure 5, in the case of the same size of laser power and the same size of energy input, the center temperature is up to 2929°C and the metal powder can be melted to a liquid state faster. In addition, as the linear spot length is larger than the melting point of the iron material, the length of the linear region become larger than the melting point of the iron material which the spot size decreases. On the one hand, when the proportion of liquid phase increases, the liquid-phase sintering mechanism can conduct a more thorough, internal tissue adhesion and the quality of the molded parts become better. On the other hand, the sintering center of the spot temperature is as high
as 2929℃, which may cause the forming parts appearing as "ball phenomenon", "warp deformation" and other defects[10].

It can be seen from Figure 6 that when the spot size is 0.8mm, the spot center temperature decreases and the laser energy distribution is dispersed. Comparing Figure 1 and Figure 2, it can be seen that with the same size of laser power and same size of energy input, the temperature of the spot center is lower when the spot size is larger. The maximum temperature is 1084℃, which is lower than the melting point of iron material and the liquid phase sintering mechanism can not be carried out nor be shaped.

4.Conclusion
The three-dimensional transient temperature field of metal powder was numerically simulated. The water atomized iron powder was used as the research object. The finite element model was established and the Gaussian moving light source was loaded on the model surface. At the same time, the influence of convection heat transfer was considered. The simulated temperature field distribution of 0.44s was analyzed under different laser powers and different spot sizes. The results show that within a certain range, when the laser power increases, the spot size decreases and the sintering spot temperature increases, which can effectively improve the quality of the forming parts. When the laser power is too high, the spot size is too small and the workpiece appears "spheroidization", "warpage" and other defects, resulting in the quality of forming parts. This paper proposed some reasonable choices of laser power, spot size of the laser sintering process, which may benefit the research of laser sintering.

5. References

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