Modeling and simulation of the temperature field of selective laser sintering

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Abstract. Selective Laser Sintering (SLS) is a kind of powder-bed additive manufacturing technology, which can directly shape parts with complex geometry. The heat transfer process has an important influence on the forming quality of the SLS process. Computational methods are useful to study the heat transfer in the process since the temporal and spatial scale is extremely tiny. This paper presented a model, coupling the discrete element method and heat transfer equations, to calculate the powder-applying and heat-transfer phenomenon. Firstly, the discrete element method and the basic framework of the heat pipe model were introduced, and then the process of manufacturing a mini propeller blade by SLS was simulated.

1. Introduction
Selective Laser Sintering (SLS) is one of the important technologies in the field of powder-bed additive manufacturing, and it has many advantages such as fast manufacturing speed, low cost, durability, and reliability of the formed parts, and no support needed [1]. The basic process of the SLS process is [2]: the powder material is laid on the substrate that can be lifted up and down, and the section of the part is sintered through laser scanning. The substrate then drops and the next layer is further sintered so that the target part is formed layer by layer. The heat transfer in the laser scanning process has an important influence on the manufacturing quality of the parts, and the hole defects caused by insufficient heating in the powder bed are the main factors restricting the mechanical properties and forming accuracy [3]. The research of the heat transfer in the SLS process has the following difficulties: On the one hand, the particle size of the powder is tens of microns, and the laser spot diameter is hundreds of microns, so the experimental observation is difficult to achieve the corresponding accuracy [4]; On the other hand, the discontinuous heat transfer model and theory are still in development, so it is difficult to provide reliable theoretical analysis results for this problem. Therefore, numerical simulation is concerned in the SLS process-related researches.

Discrete Element Method (DEM) can be used to simulate the sintering process of the SLS process when the melting and flow of powder materials are ignored. Steuben et al. [5] coupled the heat transfer equation in the DEM model to calculate the heat transfer between particles and introduced additional inter-particle bonds to simulate the sintering and deformation. Zohdi et al. [4, 6, 7] developed a comprehensive model that takes the contact forces between particles and walls into consideration, like normal contact forces, frictional contact forces, damping, and adhesive bond. Ganeriwala et al. [8] used the DEM model coupled with the finite difference method (FDM) to take the phase transition and flow behavior in the sintering process into consideration and carried out a single-track sintering simulation. Zhang et al. [9] established a phase-field (PF) model of the SLS process and analyzed the influence of
different particle size distributions on the material transport rate and porosity of the finished parts. Compared with the discrete element model coupled with heat-transfer equations, using the FDM and PF to model the SLS process can capture the influence of phase transition and flow behavior on the heat transfer process. Meanwhile, their disadvantages are obvious, such as huge computational cost and difficulty in simulating the sintering process of part scale.

In this paper, a DEM-heat-transfer coupled model is introduced for the SLS process to simulate heat transfer phenomena. This allows for quick optimization of process parameters for different materials and/or powder size distributions. Then a case of sintering a propeller blade is shown, and the effect of heat transfer on the precision of the part is analyzed. Finally, conclusions are drawn, along with planned future work on this topic.

2. Modeling
The schematic of the heat transfer model of the SLS process is shown in Fig. 1. The powder layer is laid on the substrate according to the preset thickness, and a laser beam is used to scan the current slice of the part along a specific path to make it sintered. The powder used in the industry is nearly spherical, and it is thus regarded as a sphere in this model.

\[
\begin{align*}
\frac{dm_i}{dt} &= m_i g + \sum_j (F_{n,ij} + F_{s,ij}) \\
I_i \frac{d\omega_i}{dt} &= \sum_j (R_i \times F_{s,ij} - \mu r_i F_{n,ij})
\end{align*}
\]

where \(m_i\), \(g\), \(I_i\), \(v_i\), and \(\omega_i\) represent the mass of powder \(i\), gravitational acceleration, the moment of inertia, translational velocity, and angular velocity, respectively. \(F_{n,ij}\) and \(F_{s,ij}\) are the normal and tangential contact forces, respectively. \(R_i\) is a vector from the center of the particle to the contact point with a magnitude equal to the particle radius \(r_i\), and \(\mu_i\) is the rolling friction coefficient.

To obtain the temperature field in SLS, a 3D thermal model was developed. The thermal process in SLS accompanied by the body heat flux is determined by the general heat governing equation, given by

\[
\nabla \cdot k \nabla T + Q_e = \rho c_p \frac{\partial T}{\partial t}
\]

where \(T\) is a temporal and spatial temperature field, \(k\) is thermal conductivity, and \(\rho\) is density. For the
powder bed, the effective density and thermal conductivity are related to its porosity. Term $Q_e$ is the volumetric heat defined as the heat input from the laser beam, and $c_p$ is the specific heat capacity.

In DEM, materials are usually regarded as round or spherical particles. For a single particle, there are assumptions of uniformity and isothermal property, that is, there is no temperature gradient inside the particle. In the heat conduction model of DEM, heat is reserved only inside the particles, and treating the particles as a "heat reservoir" is a comparative metaphor. The thermal energy flowing between particles mainly depends on the contact bonds between them, and a "thermal pipe" is used to describe the flow channel of heat. It should be noted that the "thermal pipe" only has the function of circulating heat instead of storing heat. Based on the law of conservation of energy, the heat equation of the target particle is given by

$$-\sum_i^N Q_i + Q_0 = m c_p \frac{dT}{dt}$$  \hspace{1cm} (4)

where $Q_i$, $Q_0$, $m$, and $c_p$ are the thermal power exchanged by the target particle through the $i$-th thermal pipe, thermal power of pellet storage, mass, and specific heat, respectively.

Additionally, we assume that the particles are small enough so that the effect of their rotations to their centers of mass is negligible to their overall motion. The simulation approach can be conducted as the steps: (1) simulation of applying the powder particles; (2) simulation of the temperature evolution by the laser beam; (3) doing the aforementioned steps alternatively.

3. Simulation and results

In the simulations, particles with a radius ranging from 20 to 25 $\mu$m are randomly packed in the calculation domain. The physical properties and processing parameters are shown in Table 1.

Table 1. The physical properties and processing parameters

| Parameter                        | Symbol | Value      |
|----------------------------------|--------|------------|
| Dynamic friction coefficient     | $\mu_d$| 0.1        |
| Specific heat of particles       | $c_p$  | 896 J/(kg $\cdot$ K) |
| Ambient temperature              | $T_{env}$ | 273 K    |
| Preheat temperature              | $T_0$  | 323 K      |
| The sintering temperature of particles | $T_s$       | 1273 K    |
| The thickness of the powder layer| $h$    | 50 $\mu$m  |
| The diameter of the laser spot   | $\omega$ | 200 $\mu$m |
| Scanning speed of laser          | $v_{laser}$ | 1000 mm/s |
| Power of laser                   | $P$    | 200 W      |

The simulation case is a mini propeller blade, which has a diameter of 1.6mm and a height of 2mm. A few frames of the simulation are shown in Fig. 2. When the laser passes through, the powder is rapidly heated above the sintering temperature $T_s$. As the laser leaves, the powder temperature drops slowly. When the laser finished a track, most of the powder at the head of the track is still above $T_s$, and only the temperature of powder at the edge of the track drops below $T_s$, as shown in Fig. 2(a). When the laser completes scanning of the second track, the temperature of the powders in the front half of the first track almost drops below $T_s$ completely, while some of the temperature of the powders in the rear half is still above $T_s$, as shown in Fig. 2(b). As the number of layers increases, heat accumulates gradually in the powder bed, and the temperature decline slows down, as shown in Fig. 2(c)-(f). Moreover, the width of the sintering track slightly increases. When the number of layers is 1, 20, and 40, the width is 159.7 $\mu$m,
174.3 μm, and 187.6 μm, respectively, and the increased amplitude from bottom to top is approximately 17.4%.

Fig. 2. A few frames of the simulated temperature field during the sintering of a mini propeller blade.
The propeller blade obtained after sintering is shown in Fig. 3, which conforms to the geometric shape of a propeller blade, but there are many convex particles on its surfaces, reducing the surface quality. Measuring the thickness of the blade, it also increases gradually from bottom to top, which is consistent with the temperature field simulation results mentioned above.

![Fig. 3. The finished mini propeller blade obtained by the simulation of SLS.](image)

4. Conclusion
In this paper, a DEM-heat transfer coupled model is introduced, which is capable of realizing the mesoscale and part-scale temperature field simulation of the SLS process. The model was used to simulate the sintering of a mini propeller blade, and the results showed that the thermal accumulation effect on the width of the sintering track increased, specifically, from bottom to top by 17.4%. This result is greater than that in the engineering practice, which may be due to the mini dimension of the tested case. More experimental work needs to be done to correct and validate this model in the future, and then it could be employed to optimize the processing parameters of SLS.

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