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Process prediction of selective laser sintering based on heat transfer analysis for polyamide composite powders

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ABSTRACT

With the increasing research into selective laser sintering of composite powders, a modified numerical model was introduced to provide appropriate process predictions for the production of different functional composites. This numerical method included an effective volumetric heat source model and an integrated testing procedure, in which the differences of polyamide/carbon fiber (PA/CF) and PA/NaCl composite powders in thermo-physical and optical properties were studied. The unknown variables in the numerical model were all determined by experiments. The simulated temperature distributions of different powder beds exhibited a big difference in the melting depth. Entirely different processing parameters were planned for the two composites according to their simulation results. In the following experiments, highly porous PA derived from PA/NaCl composites had a maximum porosity of 59%. Compared with pure PA, CF reinforced PA showed a dramatic increase of the flexural strength and modulus by a factor of 100% and 380%, respectively. Therefore, the design objectives of two PA composites were both well accomplished. In addition, the experimental investigation became more efficient due to the process prediction. The accuracy of the model was validated by the microstructures of PA/CF and PA/NaCl, which meant this method could be used to provide appropriate process planning for more composites.

1. Introduction

Selective Laser Sintering (SLS), one of the additive manufacturing (AM) processes, is a powder bed fusion technique, in which 3D parts are created by scanning the laser spot over the corresponding cross-sectional area in each layer, and then melting and bonding all these successive layers together to form physical objects [1], as shown in Fig. 1. Compared with other AM processes, SLS has a remarkable advantage in material design as powders can be easily mixed with other controllable compositions [2,3]. Moreover, SLS provides a wide choice of raw materials, such as various polymers, ceramics, metals or their composite forms, among which polymer powders are the most widely used materials. This mentioned superiority of SLS has led to increasing applications in many fields such as bio-fabrication, membrane science, automotive and aerospace [4–7].

Due to the limited performance of single-component polymers, polymer composites are far more investigated in order to achieve the desired thermal, mechanical or electrical properties or other functions. Particularly, polyamide (PA) composites have become a main research focus because of their preferable processability [8]. For example, carbon nanotubes (CNTs) and carbon black (CB) were tried to prepare PA nanocomposites for SLS. The mechanical properties and electrical conductivity of sintered parts were greatly enhanced, respectively [9,10]. The researchers also simply proposed that adding CNTs or CB in PA12 matrix improved the laser absorption. Yan et al. [11] successfully made porous PA by the SLS of PA/NaCl powders, while the effect of the addition of NaCl on the laser-powder interaction was not considered, as NaCl was transparent to CO_2 laser. Although the research on SLS of PA composites seems to be highly effective, the practical experimental investigation is still based on trial and error. Heat transfer in the powder bed is seriously affected by the properties of different additives, causing different laser-powder bed interactions. Furthermore, the relationship between the laser-powder bed interaction and sintering process planning of composites has not been systematically discussed.

The laser-powder bed interaction is a complicated process involving the optical properties of powders, energy conversion and heat transfer, which means temperature is the most important factor in SLS. Most researchers used to investigate the temperature

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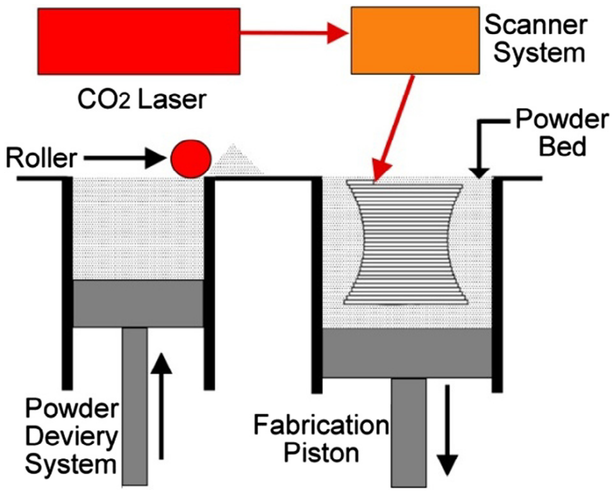

Fig. 1. Schematic diagram of SLS process.

distribution through numerical models without considering the optical properties [12,13]. The optical properties of powders include the laser absorptance, reflectance and transmittance. The transmittance of a powder bed indicates the in-depth laser energy distribution, which is crucial for both experimental and numerical analysis to get an accurate melting depth. Fan et al. and Laumer et al. [14,15] studied in detail on the optical properties of different powders. Both results showed that nearly all the laser energy was dissipated within a thickness of 200 µm. However, they did not combine experimental results with heat transfer analysis. Further, Patrice et al. [16] established a more practical volumetric laser model according to the measurement results of transmitted laser power. In addition, a finite element model, adopting optical penetration depth, was introduced to accurately simulate the melt pool size [17]. However, these analyses were not used to predict appropriate processing parameters for the production of real functional parts, especially for different composites.

Herein, with the purpose of analyzing the heat transfer processes in different composite powders as accurately as possible, an integrated testing procedure is incorporated into a modified numerical model with a volumetric heat source. Taking PA, PA/CF and PA/NaCl composite powders for example, this paper presents their differences in thermal and optical properties, which is further used to simulate the temperature distribution of the powder bed, thus providing an efficient optimization strategy for SLS process. Based on the results of the model, the required processing parameters are predicted according to the design objectives of different composites.

2. Model of SLS process

The model of SLS process was created in the commercial software ANSYS®, using finite element method for space and time discretization. Heat transfer processes were solved by the nonlinear transient thermal analysis. A single-line scanning model was considered to reduce computing time because the temperature distribution or melting depth stayed almost constant after the first scanning track according to previous experimental studies. The geometry of the physical model is shown in Fig. 2. The red[1] spot is the laser beam, which is defined as a non-uniform volumetric heat source, moving along X axis in X-Y plane. The linear cuboid element solid70 is adopted to mesh the model with a mesh size of 25 µm, which is small enough, compared with the laser beam diameter of 300 µm. The laser power is 10 W with a scanning speed of 3500 mm/s. The continuous movement of the laser was discretized into incremental movement at each time step, which was set as 7.143 µs. The independence of mesh size and time step was assessed on PA material before the simulation of PA composites (seen in supporting information).

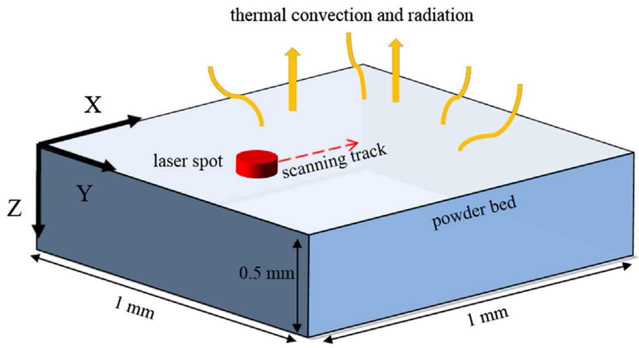

Fig. 2. Physical model of the powder bed.

Because the objective of present research was primarily focused on the laser-powder bed interactions of different PA composites, this simulation model was based on the following hypotheses. (1) The powder bed is an isotropic material because the powders are microscopic while the model is macroscopic. (2) The laser absorptance of PA is 100% because it has been addressed that PA has a laser absorptance of over 90% [14]. (3) The lateral and bottom surfaces of the model have no heat flux because the practical powder bed is maintained at a constant temperature and much larger than the model in size.

2.1. Thermal modeling

The governing equation of three-dimensional heat transfer within an isotropic material is described as:

$$\rho c \frac{\partial T}{\partial t} = q_V + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) \tag{1}$$

where ρ is the material density (kg/m^3), c is the temperature-dependent specific heat capacity (J/kg K), T is temperature (K), t is time (s), q_V is the heat flux per unit volume (W/m^3) and k is the thermal conductivity (W/m K).

The initial condition was defined as a uniform temperature distribution at $t = 0$ s:

$$T(x, y, z, 0) = T_b \tag{2}$$

where T_b is the preheating temperature for the powder bed, which is determined by the melting and crystallization point.

For boundary conditions, convection and radiation as two forms of heat transfer were considered. When the powder bed was preheated, the ambient environment was also warmed up. The temperature difference between powder bed and ambient air caused the heat loss of powder bed. Meanwhile, for the simplification of modeling, the radiation term was integrated into convection term as follows:

$$-k\frac{\partial T}{\partial z} = h_i(T - T_e) \tag{3}$$

where h_i is the integrated convection coefficient (W/m^2 K) set as 25 [18], T_e is the environment temperature set as 403 K (130 °C).

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[1] For interpretation of color in Figs. 2, 8, and 10, the reader is referred to the web version of this article.