Journal of Materials Processing Technology 212 (2012) 2058–2065

Contents lists available at SciVerse ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Micro scale 3D FEM simulation on thermal evolution within the porous structure in selective laser sintering

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ARTICLE INFO

Article history:
Received 20 January 2012
Received in revised form 18 May 2012
Accepted 20 May 2012
Available online 27 May 2012

Keywords:
Finite element model (FEM)
Selective laser sintering (SLS)
Thermal evolution
Porous structure

ABSTRACT

A micro scale 3D finite element model (FEM) with consideration of powder arrangements was developed by selective laser sintering (SLS), where a multi-layer powder stacking model with cubic powders interlaced each other was established to describe the porous powder bed. All the powders directly exposed to laser irradiations were loaded with the Gaussian function of heat flux, and the non-linear thermal conductivity and specific heat owing to temperature change and phase transformation were considered. Comparison between the modeling and experiment indicated that both the simulated length of the sintered piece and shrinkage depth of the powder bed agreed well with the experiment data. The temperature field of laser sintering was intermittent in the micro scale due to the discretely distributed particles with maximum temperature produced in the top layer of the powder bed, and two primary ways of bonding were found in the powder bed during laser sintering.

1. Introduction

Selective laser sintering (SLS) is a technology to fabricate a three dimensional (3D) object layer by layer, which is first proposed by Deckard (1986). Since then, a lot of materials including polymer, metal, ceramic even compound powders have been employed to form the functional parts. Song et al. (2007) studied the manufacturing of phenol formaldehyde resin (PF resin)/silica sand composites and qualified patterns by SLS were obtained. Salmoria et al. (2009) fabricated the starch-cellulose and cellulose acetate scaffolds by SLS for tissue engineering, and the influence of process parameters on scaffold properties was addressed. Yan et al. (2011) investigated the carbon fibre/polyamide-12 composites by SLS also aiming at manufacturing high performance components.

Since the physical process of SLS associates with complex modes of heat and mass transfer, some theoretical models have been developed in the past years. Anestiev and Froyen (1999) proposed a theoretical model to describe the rearrangement process of the powder bed and analyzed the interaction between two particles during the SLS process. Zhang and Faghri (1999) built up an analytical model to theoretically investigate the melting behavior of a subcooled powder bed with mixed powders. The temperature distributions in the liquid and solid phases were respectively obtained by an exact solution and an integral approximate solution respectively. Gusarov et al. (2003) established an analytical model to elucidate contact thermal conductivity of a powder bed in SLS, where the small contact necks were proposed to bond the particles. Chen and Zhang (2007) proposed an analytical model to study laser sintering of the two-component metal powders.

In order to clearly capture the transient variations of the temperature, stress or mass in the powder bed, some numerical models were also developed. Nelson et al. (1993) used 1D finite element method for the density prediction of sintered polycarbonate. Williams and Deckard (1998) developed a 2D model for laser sintering of amorphous polymers. However, it was regarded that the 1D or 2D modeling was not suitable to address the sintering because the significant temperature gradient existed at the edges of the part. Therefore, some 3D models were subsequently developed with consideration of improving the accuracy of predictions. Bugeda et al. (1999) established a numerical model to study the temperature and density distribution by a coupled model with the powder bed assumed as a compact box. The temperature dependent density change of the powder bed was first obtained by the analytical models, then coupled into the numerical simulation. Similarly, Dai and Shaw (2004) built up a 3D FEM model to study the thermo-mechanical behavior of laser sintering of metal and ceramic powders. Such properties as thermal conductivity, radiation and convection of the compact powder box were obtained by analytical models. Dai and Shaw (2005) further developed their model to study the effect of volume shrinkage during laser densification. A criterion was used to judge whether the element in the powder box remained as powder or became liquid during the simulation. Kolossov et al. (2004) established a 3D finite element model to study temperature evolution on the compact powder box using

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http://dx.doi.org/10.1016/j.jmatprotec.2012.05.010

the temperature dependent thermal conductivity and specific heat. More recently, Dong et al. (2009) developed a 3D finite element model to simulate the SLS process by a bi-level structure integration procedure with the powder bed also simplified as a compact box.

From the literature review, we know that most of the models developed, including analytical and numerical models, based on the assumption with the homogeneous powder bed, namely, the powder bed was assumed as a uniform compact box with the laser beam directly struck on the top surface of the box. Less attention has been paid on the thermal behavior of the local powder bed. The purpose of the present study is to develop a 3D finite element model (FEM) in a micro scale to investigate the characteristics of the temperature filed within the powder bed in SLS.

2. Model description

2.1. Formation of the micro-scale model

In order to simulate thermal evolution within the porous structure during the SLS process, a three-dimensional (3D) multi-layer powder stacking model is built up with the assumptions summarized as follows:

(i) The powder bed is made up of layers of powders.
(ii) The particle is assumed cubic block and distributed uniform in each layer.
(iii) The porosity of each layer is the same; therefore, the porosity of the powder bed can be predicted by any layer.
(iv) Stacking way of the layers follows the method shown in Fig. 1(a), that is, each particle in the up layer is positioned on the center of the neighboring four particles of the bottom layer.
(v) The propagation of the melting pool is not considered in the simulation.

For SLS, the partially or completely melting of particles occurs during the sintering process, as a result, the melting depth of the powder bed is usually less than the triple particle size as compared to another rapid prototyping technology, namely selective laser melting (SLM), where several particles are melted simultaneously for a higher laser power input. Therefore, a three-layer powder stacking model was constructed to simulate the thermal field produced by SLS in the present study. As shown in Fig. 1(c), the first layer of the powder bed is bottom layer with 4×4 block particles attached with the matrix. The second layer of the powder bed is called middle layer with 3×3 particles stacking on the bottom layer. Following the method depicted in (iv), the third layer is named as top layer which repeats the structure of the first layer. Then the length of the construction (L) is obtained by

$$L = 3s + D \tag{1}$$

where s is the distance between two neighboring particles, and D is particle diameter. A coefficient, R_a, is defined to characterize the ratio of the distance between two particles to particle diameter

$$R_a = \frac{s}{D} \tag{2}$$

Obviously, R_a is the function of porosity. According to the assumption (iii), the porosity of the powder bed can be represented by the top layer. Considering the continuity of the structure, porosity of the powder bed is calculated within the dash line shown in Fig. 1(a). By calculation, R_a is obtained ranging from 1.0 to 1.5 for the real sintering process. When there are no pores existing in the powder bed, namely solid metal, R_a is equal to 1.0. While for the real compact powder bed, R_a is 1.4 corresponding to the porosity of 50%. In the present study, the porosity of 50% is used in the simulation in order to keep the real porosity of the compact powder bed.

In the paper, numerical simulation was executed by the ANSYS code. A 10-Node tetrahedral element was adopted for the thermal analysis. As shown in Fig. 1(c), a fine mesh was used in the scanning region in order to capture temperature distribution more accurately, while a coarse mesh was employed in remote areas to save the calculation time. The total number of the element in the model was about 60,000.

2.2. Model of the SLS process

The heat transfer behavior in the SLS process is described by the Flourier thermal equilibrium equation written as

$$\lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \dot{q} = \rho C \dot{T} \tag{3}$$

where λ is thermal conductivity, ρ is density of the examined powder, C is specific heat and $\dot{q}$ is rate of heat generation by laser scanning.

Laser scanning is considered as a heat flux moving at a constant velocity from one side to another. The laser power follows the Gaussian distribution

$$I = \frac{2AP}{\pi r^2} \exp\left(-\frac{2((x - v \times t + r)^2 + y^2)}{r^2} \right) \tag{4}$$

where I is thermal flux density of the laser beam, P is laser output power, v is scanning speed, and r is the radius of laser beam, while A is absorption coefficient affected by laser wavelength and surface conditions as well as physical properties of the material. Absorption coefficient of 60% for the pure Fe powder under 1.06 μm wavelength irradiations came from Tolochko et al. (2000). All the powders directly exposed to laser irradiations were loaded with the Gaussian function of heat flux by Eq. (4). An ANSYS Parametric Design Language (APDL) was used to model the moving heat source.

Phase transformation of powders from solidus to liquid is involved in the SLS process, and latent heat of fusion (ΔH_{melt}) is considered by the change of enthalpy given by

$$H = \int_{T_0}^{T} \rho \times c \, dT \quad (T < T_m)$$

$$H = \int_{T_0}^{T} \rho \times c \, dT + \Delta H_{\text{melt}} \quad (T \geq T_m) \tag{5}$$

where H is enthalpy, T_0 is reference temperature which is set to 293 K in the paper, and T_m is melting point of the material.

In order to avoid the oxidation of the Fe powder under the elevated temperature, a shielding gas of Ar was employed during laser scanning in the experiment. Therefore, free heat convection is considered in the model:

$$q = h_f (T - T_0) \tag{6}$$

where h_f is heat transfer coefficient, and T_0 is absolute temperature of the surrounding Ar gas, which is set at 293 K in the present simulation. Radiation is also considered as follows:

$$q = \hbar \Omega A_1 F_{12} (T^4 - {T_0}^4) \tag{7}$$

where $\hbar$ is emissivity, Ω is Stephan–Boltzmann constant (5.47×10^{-8} W/m^2 K^4), A_1 is radiation area, F_{12} is form factor from