Powder Technology 315 (2017) 300–308

Contents lists available at ScienceDirect

Powder Technology

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

# Discrete element modeling of powder flow and laser heating in direct metal laser sintering process

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ARTICLE INFO

*Article history:*
Received 3 June 2016
Received in revised form 25 March 2017
Accepted 1 April 2017
Available online 7 April 2017

*Keywords:*
Direct metal laser sintering
Additive manufacturing
Discrete element model
Simulation
Particle flow
Heat transfer

ABSTRACT

A novel particle-based discrete element model (DEM) is developed to simulate the whole Direct Metal Laser Sintering (DMLS) process, which includes simplified powder deposition, recoating, laser heating, and holding stages. This model is first validated through the simulation of particle flow and heat conduction in the powder bed, and the simulated results are in good agreement with either experiment in the literature or finite element method. Then the validated model is employed to the DMLS process. The effects of laser power, laser scan speed, and hatch spacing on the temperature distributions in the powder bed are investigated. The results demonstrate that the powder bed temperature rises as the laser power is increased. Increasing laser scan speed and laser hatch spacing will not affect the average temperature increase in the powder bed since energy input is kept same. However, a large hatch spacing may cause non-uniform temperature distribution and microstructure inhomogeneity. The model developed in this study can be used as a design and optimization tool for DMLS process.


## 1. Introduction

Direct Metal Laser Sintering is an additive manufacturing (AM) technique that uses a laser fired into a metal powder bed to create a solid structure through a layer-by-layer sintering process [1–3]. DMLS allows the production of complex metallic structures with complex internal and external features. The development of DMLS not only assists in reducing labor cost and time during the product development stage but also opens up new opportunities for creating certain parts that cannot be created using traditional manufacturing processes.

In a typical DMLS process, a layer of loose metal powder with a thickness of 0.1–0.3 mm is deposited and distributed onto the powder bed by scratching a recoating blade. Then the powder is sintered or partially melted by a laser source. The laser heat source moves during the sintering process, and a metallic solid layer with designed pattern is formed. Another layer of powder is then deposited and distributed by the recoating blade. By repeating this "recoating and heating" process, a solid part is fabricated [4]. In DMLS processes, laser power, laser scan speed, hatch spacing are the major processing parameters that affect the performance of DMLS fabricated parts.

The growing need of reliable methods to improve the quality of AM parts greatly depends on the quantitative understanding of powder deposition and laser sintering during 3D printing processes. One of the important research aspects of the DMLS process is to understand how metal particles behave mechanically and thermally on the surface of the powder bed during the printing process [5]. The force and heat interactions between the powders play an important role in the definition of the behavior of the powder bed. Therefore, in order to understand the mechanical and thermal behavior of the powder during the DMLS process, a particle-based model is needed.

Currently, experimental studies suggest that the properties of DMLS fabricated parts are influenced by powder characteristics and process parameters [6–8]. Although much computational work has been done in recent years, the correlation between the processing parameters and printed material properties is still not fully understood [9]. Computational fluid dynamics have been used to study the formation of melting pool and powder phase change. N'Dri et al. [10] presented an uncertainty quantification model to predict the melting pool size, laser track, and residual stress. Their studies show that simulation results are highly dependent on the accuracy of powder conductivity and heat absorption. Mindt et al. [9] developed a particle-based model to predict the morphology of a printed structure in various processing conditions. Zohdi [11] presented a modular computational framework to combine particle dynamics, laser input, and particle thermodynamics to understand the overall laser sintering process. Herbold et al. [12] conducted a DEM study to show the powder deposition and recoating process in DMLS. In summary, most previous studies were focused on a particular step or process, DEM simulation of the whole DMLS process has not been reported. This work presents a DEM simulation of a DMLS process, including four stages: powder deposition, recoating, laser heating, and holding. Fig. 1 shows the flow chart of the DEM simulation in this study.

In this work, a novel DEM is developed to study the complete DMLS process. The paper is outlined as follows. Section 2 presents the details

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http://dx.doi.org/10.1016/j.powtec.2017.04.002
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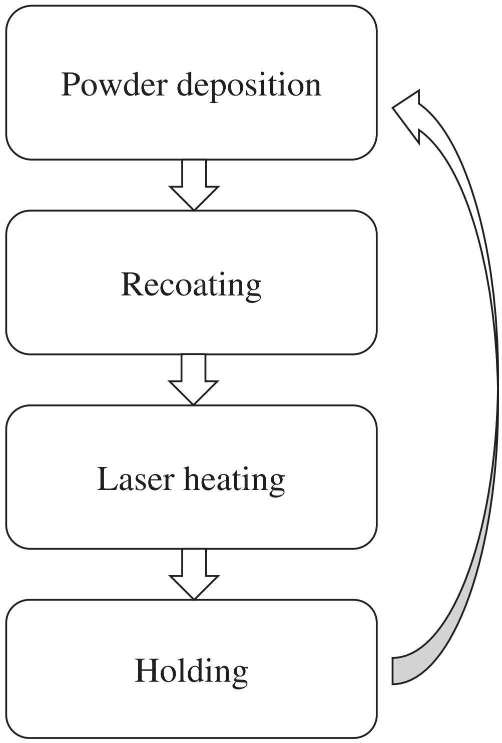


**Fig. 1.** Flow chart of the DEM simulation of DMLS process in this study.

of the model. The governing equations, model validations of particle flow, and heat transfer and the DMLS model, are presented. In the DMLS model, powder deposition, recoating, laser heating, and holding processes are investigated. Section 3 summarizes a series of parametric studies. The effects of laser power, laser scan speed, and laser hatch spacing on the powder bed temperature are systematically investigated. Section 4 shows the conclusion and limitation of the model and the direction of future studies.

## 2. Discrete element modeling details

### 2.1. Governing equations

Discrete element method is a numerical technique that calculates the interaction of a large number of particles [13]. For particle flow simulations, this method calculates defined displacements and rotations of discrete bodies of various types of particle shapes, which can be predicted through the gathering of assembled particles [14]. Particles are simulated through solving the Newton's second law of motion and rigid body dynamics equation combined with specific time-stepping algorithms [15,16]. In this study, the LIGGGTS package [17], with a timestep of 0.00005 s, is used to simulate the interaction among metal particles in the DMLS process, by solving the corresponding governing equations (Eqs. (1) and (2) for translational and rotational motion, respectively) [16]:

$$m_i\ddot{x}_i = m_i g + \sum_j F_{ij} \tag{1}$$

$$I_i\ddot{\theta} = \sum_i (r_{ij}\cdot F_{ij}) \tag{2}$$

with $\ddot{x}_i$ translational acceleration, $m_i$ mass of the particles $i$, $g$ acceleration due to gravity, $F_{ij}$ force at contact with neighboring particles $j$, $r_{ij}$ vector directed from the center of the particle $i$ to the contact point with particle $j$, and $I_i$ the mass moment of inertia of the particle $i$.

For inter-particle interactions, Hertzian potential force with no cohesion reaction is used. As shown in the particle flow validation study in Section 2.2.1, the case with no cohesion gives good agreement with experiment. The Hertzian formulas to compute the pair potential forces are as follows [18–20]:

$$F_{hk} = (k_n\delta n_{ij} - m_{eff}\gamma_n v_n) - (k_t\Delta s_t + m_{eff}\gamma_t v_t) \tag{3}$$

$$\begin{aligned} F_{hz} &= \sqrt{\delta}\sqrt{\frac{R_iR_i}{R_i+R_j}}F_{hk} \\ &= \sqrt{\delta}\sqrt{\frac{R_iR_i}{R_i+R_j}}\left[(k_n\delta n_{ij} - m_{eff}\gamma_n v_n) - (k_t\Delta s_t + m_{eff}\gamma_t v_t)\right] \end{aligned} \tag{4}$$

with $R_i$ and $R_j$ as the radii of particle $i$ and $j$, respectively, $\delta$ the overlap distance of two particles, $k$ the elastic constant, $\gamma$ the viscoelastic damping constant, $\Delta s$ the displacement vector between the two spherical particles which is truncated to satisfy a frictional yield criterion, $n_{ij}$ the unit vector along the line connecting the centers of the two particles, $v$ the component of the relative velocity of the two particles; indices $n$ and $t$ referring to normal and tangential contact respectively. $F_{hk}$ is the force calculated using the Hookean style, $F_{hz}$ is the force calculated using the Hertzian style, and $m_{eff}$ is the effective mass of two particles.

The heat distribution in the powder bed is determined by combining the heat conduction through particle contacts and the heat generation due to the laser source [21]:

$$\dot{Q}_{pi-pj} = h_{c,i-j}\Delta T_{pi-pj} \tag{5}$$

$$h_{c,i-j} = \frac{4k_{pi}k_{pj}}{k_{pi}+k_{pj}}(A_{contact,i-j}) \tag{6}$$

$$m_p c_p \frac{dT_{p,i}}{dt} = \sum \dot{Q}_{pi-pj} + \dot{Q}_{pi,source} \tag{7}$$

with $h_c$ the heat transfer coefficient, $k_{pi}$ the thermal conductivity of particle $i$, $c_p$ the specific thermal capacity, $A_{contact,i-j}$ the particle contact area, $\dot{Q}_{pi-pj}$ the heat flux between particles $i$ and $j$, $T_i$ the temperature of particle $i$, and $m$ the mass of the particle.

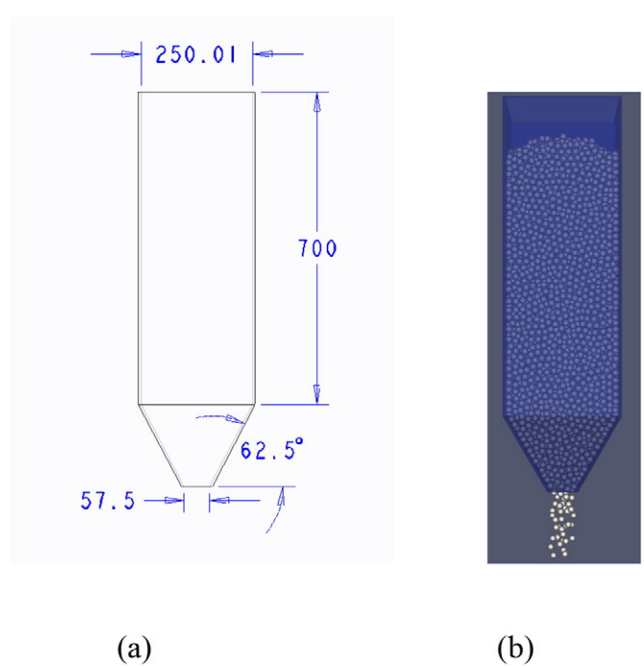


**Fig. 2.** Particle flow validation model. (a) Hopper dimensions (unit: mm), (b) discharge of particles from the hopper.