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Lattice Boltzmann Simulation of Metallic Powder Melting during Additive Manufacturing

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Additive manufacturing (AM) is a prevailing topic. Among all the processes during AM, the initiation and evolution of melt pool is of vital importance. Lots of studies are devoted to the fundamental mechanism of melt pool, but most of them only focus on the macroscopic level. However, when it comes to the mesoscopic level, it can be founded that the melt pool is the result of melting and fusion of powders. To better understand the melt pool, it is necessary to understand the melting and fusion characteristics of powders. This paper aims to provide a new kind of mesoscopic perspective to the melt pool through the investigation on single powder melting. Enthalpy based Lattice Boltzmann method, combined with Neumann boundary, is adopted to model the powder melting under fixed and moving laser beam. Results indicate that for the fixed laser beam, the melting front presents a symmetric convex. The increase of the laser power input can increase the energy absorbed by the powder, speed up the melting process and enhance the flow inside the powder. For the moving laser beam, the melting front loses its symmetry. The increase of the scanning speed can decrease the energy absorbed by the powder, the melting volume fraction and the inside flow. The fast moving speed could easily result in partially melted powder. All these results could help us better understand the powder melting under different laser inputs, and thus arranging the laser power reasonably to make the best use of it according to various occasions.

1. Introduction

Additive manufacturing (AM) is one of the most advanced manufacturing technologies that attract much attention (Sing et al., 2016). Compared to conventional methods, AM makes it convenient to manufacture geometrically complicated parts and even application-optimized parts with tailored mechanical properties (Thompson et al., 2015). It is quite promising in making aerospace engine and precision parts in high-end equipment (Chen et al., 2017). Quality of the AM products is highly related to its thermal history, which is mainly related to the evolution of melt pool. Therefore, lots of studies are concentrated on the flow and heat transfer inside the melt pool and the numerical model to model the melt pool is improving day by day. Firstly, it was a pure conduction model that neglected the inside flow, which was introduced from the modelling of weld pool (Han et al., 2005). Then the intense convection inside the melt pool and Marangoni effect induced by the high-temperature gradient around the surface was further considered (Li et al., 2014). Nowadays, even the free surface of the melt pool could be tracked by various methods (Bian et al., 2017). Macroscopic behaviour of the melt pool can be properly modelled, and the impacts of different factors such as laser powder, spot size, scanning speed have been revealed (Bian et al., 2018). However, all these models are built in the macroscopic level, the lack of multi-scale researches are preventing us from insight view of the formation of microstructure features and defects. In fact, melt pool is an accumulation of melting and fusion of numerous powders, events like partial melting of powder and gas entrapment during the fusion of powders would finally result in serious defects in the final products (Gu et al., 2013).Therefore, to promote the quality of the final products, it is quite important to figure out the fundamental mechanism of melt pool evolution from the powder level. However, studies on the powder level are quite limited.

To solve the flow and heat transfer problems on the powder level, lattice Boltzmann method (LBM) would be quite suitable. Based on kinetic theory and its mesoscopic nature, LBM has several obvious advantages compared to traditional CFD methods, such as simple calculation procedure, easy boundary treatment, and inherent parallel processing structure. Jiaung et al. (2001) firstly introduced the enthalpy based LBM into the

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conduction dominated melting problem. And then Huber et al. (2008) modified Jiaung's model and successfully applied it to natural convection melting in cavity. Recently, we (Dai et al., 2018) have employed this method to investigate the angle between the input heat flux and gravity on the melting issues. Li et al. (2018) also employed this method to discuss the gravity effect on the melting process. All these researches had proved that it was a solid and reliable method for melting problems.

In summary, this paper mainly focuses on the investigation of single powder melting under fixed and moving laser beam, using enthalpy based lattice Boltzmann method. It aims to provide a mesoscopic perspective from the powder level. This is the first step for many following researches to study the fundamental mechanisms of the melt pool evolution.

2. Numerical model

2.1 Mathematical model

A single metallic power melting under fixed and moving laser, as is shown in Figure 1(a), is to be modelled in this study. To define this problem mathematically, those assumptions are needed to be made as follows: (1) the flow inside the cavity is incompressible and laminar; (2) thermo-physical properties of both solid and liquid phase are constant and equal; (3) viscous diffusion can be neglected and Boussinesq approximation is adopted for the liquid phase. Under those assumptions, the dimensionless form of the governing equation for this problem can be written as:

$$\nabla \mathbf{u}^{*} = 0 \tag{1}$$

$$\frac{\partial \mathbf{u}^{*}}{\partial t^{*}} + \mathbf{u}^{*} \cdot (\nabla \mathbf{u}^{*}) = -\nabla p^{*} + Pr\,\nabla^{2}\mathbf{u}^{*} - Pr\,Ra\beta T^{*} \tag{2}$$

$$\frac{\partial T^{*}}{\partial t^{*}} + \mathbf{u}^{*}\nabla T^{*} = \nabla^{2} T^{*} - \frac{1}{Ste}\frac{\partial f_{l}}{\partial t^{*}} \tag{3}$$

The laser beam intensity profile is assumed to be Gaussian distribution. The surface temperature of the powder is determined by the energy balance between the input laser energy and heat loss induced by the evaporation, convection, and radiation. It is acted as the thermal boundary in this paper. Details are to be found in Han et al. (2005).

2.2 Lattice Boltzmann model

To solve the melting problem, enthalpy based lattice Boltzmann method is employed. Huber's model (Huber et al., 2008) is adopted to handle the phase change term in the energy equation. The total enthalpy at each time step is obtained by:

$$H = C_{p}T + Lf_{l} \tag{4}$$

Then the liquid fraction can also be obtained by:

$$f_{l} = \begin{cases} 0 & H < H_{s} \\ \dfrac{H - H_{s}}{H_{l} - H_{s}} & H_{s} \le H \le H_{l} \\ 1 & H > H_{s} + L \end{cases} \tag{5}$$

With the classic discrete velocity model of D2Q9 and BGK expansion, the evolution equation can be present as follows.

$$f_{\mathrm{i}}(\mathbf{x} + \mathbf{e}_{\mathrm{i}}\Delta t, t + \Delta t) - f_{\mathrm{i}}(\mathbf{x}, t) = -\frac{f_{\mathrm{i}}(\mathbf{x}, t) - f_{\mathrm{i}}^{eq}}{\tau_{f}} + \Delta t F_{\mathrm{i}} \tag{6}$$

$$g_{i}(\mathbf{x} + \mathrm{e}_{i}\Delta t, t + \Delta t) - \mathrm{g}_{i}(\mathbf{x}, t) = -\frac{\mathrm{g}_{i}(\mathbf{x}, t) - \mathrm{g}_{i}^{eq}}{\tau_{T}} - w_{i}\frac{L}{C_{p}}(f_{l}^{\,n} - f_{l}^{\,n-1}) \tag{7}$$

To model the spherical powder melting, it is of vital importance on how to deal with the curved boundary. Here the extrapolation boundary developed by Guo et al. (2002) is adopted.

3. Results and discussion

3.1 Model validation

Since there are no benchmark results available against powder melting, this numerical model is verified by the comparison of weld pool under moving laser between simulation and experimental results. The weld pool cross sections for laser power of 1,967 W and pulse duration of 3 ms under the laser beam with the radius of 0.57 mm and scanning speed of 500 mm/s is experimentally observed by He et al. (2003). To model this problem in LBM, these parameters are expected to be converted into dimensionless form as described in Elsen et al. (2008). The physical property for the metal used in the experiment and the corresponding LBM unit are listed in Table 1. For all simulations in this paper, the length scale, mass scale, temperature scale and time scale are considered as $\triangle x$ = 5.0×10^{-6} m, $\triangle t$ = 2.2×10^{-7} s, $\triangle m$ = 9.0×10^{-13} kg and $\triangle T$ = 5.78×10^{-4} K respectively. The material parameters follow by multiplying the dimensionless quantities with the relevant scales such as $\rho^{(1)}=\rho\left(\Delta x^3/\Delta m\right)$ and $\upsilon^{(1)}=\upsilon\left(\Delta t/\Delta x^2\right)$.

Table 1: Physical property and corresponding LBM unit

	Density	Melting temperature	Viscosity	Thermal diffusivity
Physical	7,200 kg/m^3	1,727 K	1.0×10^{-6} m^2/s	1.01×10^{-5} m^2/s
LBM unit	1.0	1.0	0.0088	0.0892

Since the physical size of the experimental wok part is 1.5×1.5 mm, the grid system in this simulation is chosen as 300×300 accordingly. As is shown in Figure 1(b), the simulation results agree well with the experimental results. Therefore, it can be believed that the numerical model in this paper is reliable.

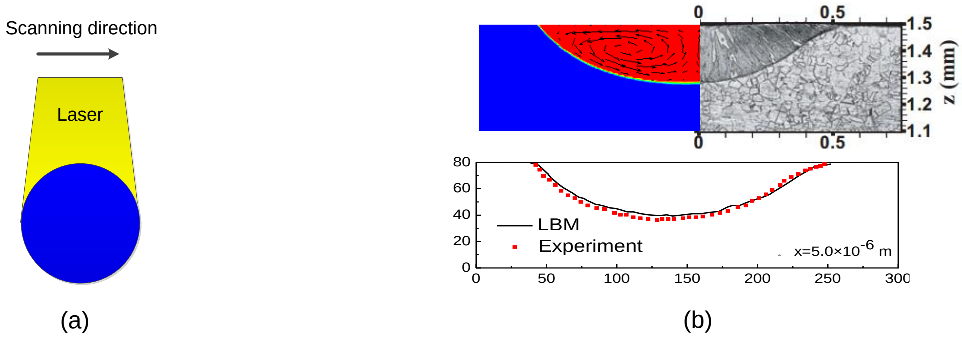

Figure 1: (a) Schematic of the physical model and (b) experimental and calculated weld pool cross sections

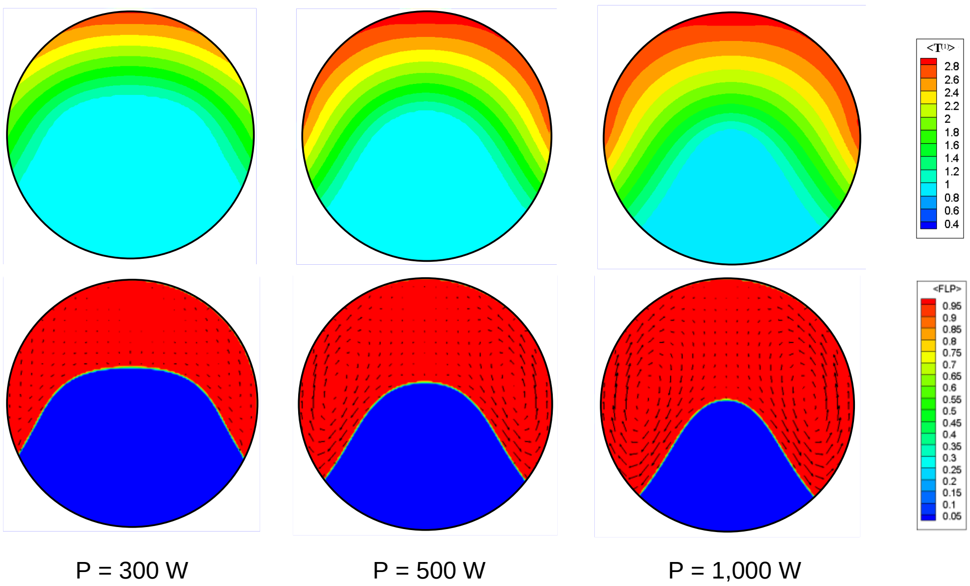

Figure 2: Temperature distribution, melting front and vector field under different laser energy

3.2 Fixed laser with varying energy input

To simplify the problem, it is assumed that the physical property of the metallic powder is the same as that listed in Table 1. Therefore, the relevant scales aforementioned are also adopted in the following simulation. Besides, the radius of laser beam is 0.7 mm, which is equal to the radius of the metallic powder. The laser beam power ranges from 300 W to 1,000 W.

As is depicted in Figure 2, it is obvious that all the phenomena are symmetric. Moreover, as the laser input energy increases, the hot region also increases, the melting front turns sharper and the convection cell inside gets larger. For that in the Gaussian-distribution laser beam, the input energy decreases intensely from the centre to the margin. Therefore, under the laser irradiation, the bulk of energy in the centre would result in melting quickly, but soon it is limited by the effect of evaporation. The energy input in the margin area is what decisive to understand the inside phenomena. If it is small, the surface temperature would increase gently and the margin region would melt slowly, resulting in a convex plate for the melting front. If it is large enough, the surface temperature would increase intensely and the margin region would melt quickly, resulting in a sharp corner for the melting front. The increase of the energy input means the increase of the energy input in the margin area, which explains the phenomena depicted in Figure 2. Moreover, the average temperature and melting volume fraction under different laser energy are depicted in Figure 3. The powder absorbs the laser energy and the temperature increases, thus the average temperature can be deemed as an indicator of the energy absorption. Apparently, as the energy increases, the average temperature increases, which means the powder absorbs more energy and the melting volume fraction increases intensively. Besides, as is shown in Figure 4, the average velocity increases sharply as the energy input increases, which means the inside convection enhances drastically. The increase of average velocity can be explained in this way. The convection inside the liquid region mainly results from the temperature gradient. When the energy input increases, it can be clearly observed that the hot region expands, and the temperature difference in the fluid region also increases, thus resulting in stronger inside flow.

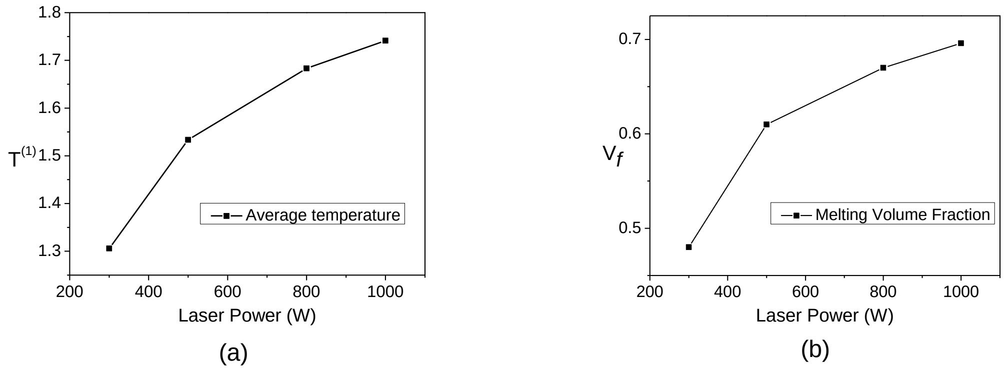

Figure 3: (a) Average temperature and (b) melting volume under under different laser energy

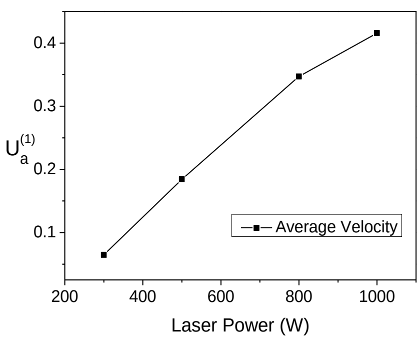

Figure 4: Average velocity inside the liquid region under under different laser energy

3.3 Moving Laser with varying scanning speed

To investigate the melting characteristics under different scanning speed, the laser power is assumed to be fixed at P=500 W and the laser scans from the centre to the right with the scanning speed ranging from 4 mm/s to 16 mm/s. The temperature distribution, melting front and vector field under different scanning speeds are displayed in Figure 5. With the increase of scanning speed, the melting characteristics gradually lose their symmetry, the melting edge point on the left side gradually rises, as well as the top point gradually moves to the left side. These results implicate that the right side melts faster than the left side, and it would result in partially melted powder as the scanning speed increases. As is shown in Figure 6(a), the average temperature inside the powder under different scanning speed is illustrated. As the scanning speed increases, the average temperature drops almost linearly, which indicate that the powder absorbs less energy under high scanning speed. That is also the reason for the decrease of melting volume fraction with the increase of the scanning speed, which is shown Figure 6(b). The faster the moving laser scans, the larger the un-melted region is left.

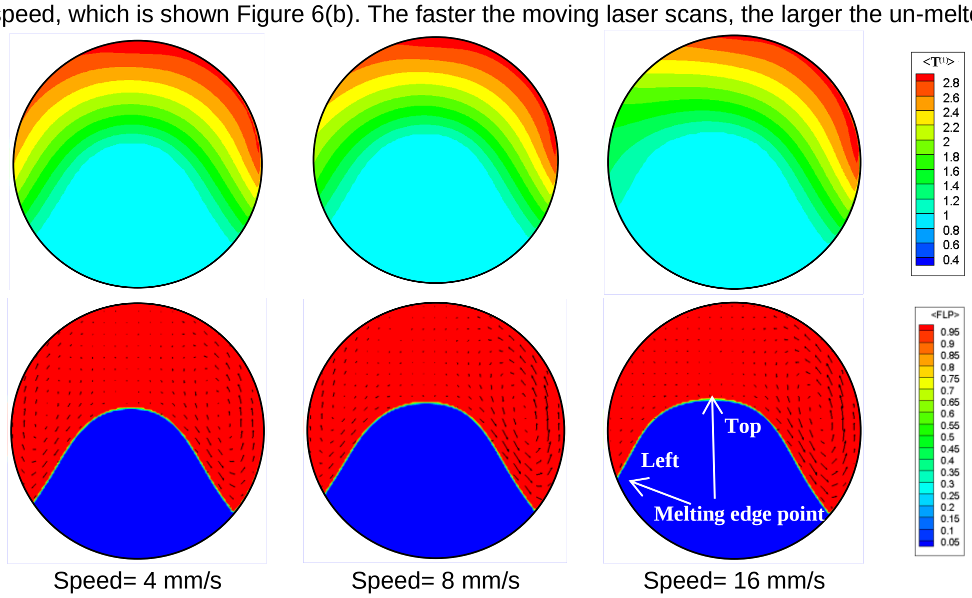

Figure 5: Temperature distribution, melting front and vector field under different laser energy

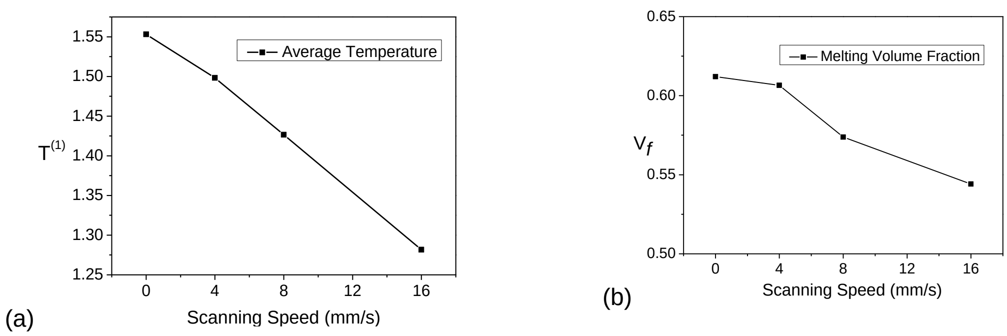

Figure 6: (a) Average temperature and (b) melting volume under different scanning speed

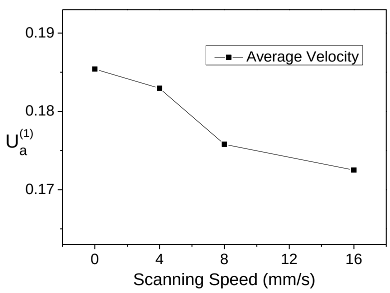

Figure 7: Average velocity inside the liquid region under different scanning speed

As is shown in Figure 7, the average velocity also decreases with the increase of the scanning speed. For that the major temperature difference gradually turns to the right, the convection in the left gradually vanishes, as is displayed in Figure 5. Moreover, as the melting region gradually decreases, the space for the development of convection is also limited, which also affects the average flow velocity.

4. Conclusions

In the present study, single powder melting under fixed and moving laser beam are investigated using enthalpy based lattice Boltzmann method. Results can be concluded as follows:

(1) The increase of the laser power input can increase the energy absorbed by the powder, speed up the melting process and enhance the flow inside the powder.

(2) For the moving laser beam, the melting front loses its symmetry. The increase of the scanning speed can decrease the energy absorbed by the powder, the melting volume fraction and the inside flow. The fast moving speed could easily result in partially melted powder.

All these results could help us better understand the powder melting under different laser inputs, and thus arranging the laser power reasonably to make the best use of it according to various occasions. Moreover, the current study is just the first step of many relevant studies. To better illustrate the melt pool evolution from the powder level, advanced researches on the morphology of powder melting, the fusion characteristics of melting powders and so on are to be carried out soon.

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