

Numerical Modeling of Metal-Based Additive Manufacturing Using Level Set Methods

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ABSTRACT

The advance in computational science and engineering allows people to simulate the additive manufacturing (AM) process at high fidelity, which has turned out to be a valid way to model, predict, and even design the AM processes. In this paper, we propose a new method to simulate the melting process of metal powder based AM. The governing physics is described using partial differential equations for heat transfer and Laminar flow. Level set methods are applied to track the free surface motion of the molten metal flow. Some fundamental issues in the metal-based AM process, including free surface evolution, phase transitions, and velocity field calculation, are explored, which help us gain insight into the metal-based AM process. The convergence problem is also examined to improve the efficiency in solving this multiphysics problem.

1 INTRODUCTION

The additive manufacturing technology produces parts by adding material in layers [1]. Compared with conventional manufacturing methods which cut off the excess material, additive manufacturing uses an energy source to melt the material and deposit it layer by layer [2]. AM allows fabricating products with great freedom in the shape, configuration, and function.

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Many materials can be included in the AM process, such as metals, ceramics or composites. In this paper, we focus on metal-based AM process since metal products are extensively employed in the industry. Metal-based AM products can be obtained with either a direct or an indirect procedure [3]. In the direct procedure, the metal particles are melted in the AM process. Selective Laser Melting (SLM) and Electron Beam Melting (EBM) are two standard direct methods. In SLM or EBM, the powder is spread in a layer and melted by a laser or electron beam. When the temperature drops, the molten material solidifies and forms a layer of the part. This procedure is repeated with each layer adhered to the last one until the part is completed. In the indirect way, the layers of the products are bonded by a binder. The Binder Jetting based AM is one of the commonly used indirect methods. The metal particles are firstly sintered, and after infiltration, the metal particles are bonded together. Though AM techniques have been widely developed these years, the process is not completely explored, which lays the groundwork for the monitoring and control of AM. As in Figure 1, both the direct and the indirect ways involve complex multi-physics phenomena, for example, melting and solidification, fluid flow, heat transfer, vaporization or radiation. Also, in the SLM or EBM processes, the wetting mechanism should be studied as well [4]. Those physical phenomena are closely tied up with the AM process parameters which directly affect the quality of the products [5]. However, those critical parameters, such as laser power, scanning speed, scanning space, particle size or packing density, are mostly determined empirically. Those methods resting on empirical evidence are often unreliable and hard to manage when the manufacturing process varies.

Nowadays, predictive science-based simulation technologies have arisen as an effective tool to investigate the impact of the AM process parameters. Physical phenomena such as the heat

transfer in solid, heat absorption from the heat source, or heat radiation between solid with the surrounding gas, have been successfully simulated [6, 7]. Fan and Liou [8] simulated the AM process of Titanium alloy and compared the simulation results with experiment, which showed a good agreement. However, some phenomena are not well captured in current computational models due to the complexity of physics, for instance, the Marangoni convection due to surface tension gradients, the motion of liquid, and the radiation losses at the fluid/gas interface.

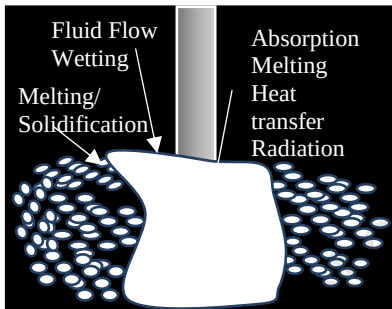


Figure 1. Simulation of selective electron beam melting processes[9]

The objective of this paper is to simulate the metal-based AM process at the mesoscale using level set methods and multiphysics finite element simulation. In this research, the simulation model is built for the SLM process, where the material is spread in a layer and then melted by a laser beam. This research focuses on Titanium Alloy powders with a size between $10\mu m$ to $150\mu m$. The heat transfer phenomena is modeled by solving the PDEs of physics transportation. By applying the level set method, the complex changes of particle geometries and the liquid/gas interface can be captured at high fidelity.

This paper is organized as follows: Section 2 describes the mathematical method and simulation techniques for modeling the metal-base AM process. In Section 3, two numerical

examples simulating the power-based SLM melting process are presented. The computational results and future work are discussed in Section 4.

2 SIMULATION OF MELTING PROCESS OF POWDER-BASED SLM

2.1 Level set methods for powder-based SLM modeling

As introduced in section 1, AM contains many physical processes. To reproduce the behavior of the AM system with a computer model, we first need set up the physical models before carrying out the numerical simulation. In this section, two principal physical models are introduced.

One is modeling the phase transition process. One way to model this is to simulate the solid-liquid interface at small scale [11]. This approach is straightforward, but demands a lot of computing resources, so it only applies to small domains (0.1m to 10mm). For the macroscopic transport problem, the representative elementary volume (REV) is introduced in dealing with the size difference between the fully solid or liquid region and the mushy zone. This model selects a zone to include a representative and uniform sampling of the mushy region, so the local scale solidification can be characterized by variables averaged over the REV [8, 10]. Based on the concept, the transportation equations for the conservation in the process can be developed and solved.

The molten metal flow in the AM processes is a free-surface flow, which means the viscous stresses in the molten metal flow is assumed to be zero. Both the Lagrangian method and the Eulerian method have been applied to model the shape of the free-surface flow [12]. However, the Lagrangian method becomes more difficult in dealing with fluid problems with topological changes [11]. The Eulerian method is more suitable to handle moving boundary problems. For

instance, the Eulerian method can be used in modeling the powder-based AM process for tracking the mergers and splits at the interface of the melt pool. [8].

In this paper, the level set method is employed to track the motion of the molten metal flow. The underlying idea of the level set methods is to use an implicit function with one higher dimension to represent the shape as the zero level set, as shown in equation 1. Imagine we have an interface Γ on an enclosed region Ω . The level-set ϕ can be defined as equation 1 [11]. So we can easily get the interface $\Gamma(t)$ where ϕ equals 0.

$$\begin{cases} \phi(x, t) < 0 & \text{in } \Omega(t) \\ \phi(x, t) = 0 & \text{on } \Gamma(t) \\ \phi(x, t) > 0 & \text{in } R^n \setminus \Omega(t) \end{cases} \quad (1)$$

Embedding the design in one higher dimension allows the flexibility in topological changes such as the merging or splitting of the molten metal flow in the AM process. In equation 1, after differentiating the level set function $\phi = 0$ with respect to time t , we get the Hamilton Jacobi equation, as in equation 2.

$$\phi_t + \mathbf{u} \cdot \nabla \phi = 0, \quad (2)$$

where $\mathbf{u}$ is the velocity at the interface. The application of level set methods to fluid dynamics problem has been carried out, for instance, Chung and Das [12] used the level set method to solve the Stefan problem and successfully tracked the interface between the liquid and solid phases. In this paper, the free-surface motion of the melt pools can be captured by solving the Hamilton-Jacobi partial differential equation [13, 14]. The later motion is determined by the velocity field $\mathbf{u}$, which rests on the external physical or geometric information of the interface. Once the initial level set $\phi(x, y, t=0)$ is identified, a proper velocity field needs to be calculated to update the level set function and drive the boundary.

2.2 Physics governing equations

The computational domain for the SLM process modeling comprises the melt pools, deposited metal powder, and the surrounding air, as shown in Figure 1. The continuum model which describe the liquid in collective variables is employed to estimate the properties of the solid-liquid coexisting area. The molten metal is assumed to be a Newtonian fluid, with a linear relationship between the rate of its deformation and the applied shear stress. The melt pool is considered as an incompressible laminar flow, the density of which is constant with the changes in pressure and temperature.

The conservation equations for the whole computational domain are formulated as below.

Mass conservation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{V} = 0, \quad (3)$$

Energy conservation:

$$\frac{\partial(\rho h)}{\partial t} + \nabla \cdot (\rho \mathbf{V} h) = \nabla \cdot (k \nabla T) - \nabla \cdot \rho (h_l - h) \mathbf{V}, \quad (4)$$

Momentum conservation:

$$\frac{\partial \rho \mathbf{V}}{\partial t} + \nabla \cdot (\rho \mathbf{V} \mathbf{V}) = \nabla \cdot \left(\mu_l \frac{\rho}{\rho_l} \nabla \mathbf{V} \right) - \nabla p + A \mathbf{V} + \mathbf{F}_{st} + \mathbf{F}_c + S, \quad (5)$$

where $\rho, t, \mathbf{V}, \mu, k, T, p, A, h$ are density, time, velocity, molten fluid dynamic viscosity, heat conductivity, temperature, pressure, permeability, enthalpy, respectively. $\mathbf{F}_{st}$ represents the capillary forces and S represents the source term which related to the gravity, and $\mathbf{F}_c$ refers to the thermo-capillary force. The subscription “s” represents solid, and “l” represents liquid.

During melting and solidification, the phase shifts in a certain temperature zone, which lead to a solid-liquid coexist zone called mush zone. To accurately simulate the momentum of this area, we employ a damping term represented by the permeability A , following [15]:

$$A = -K_0 \frac{(1 - g_l)^2}{g_l^3 + \epsilon_0}, \quad (6)$$

where K_0 is the permeability coefficient, g_l is the mass fraction of liquid, and ϵ_0 is an small constant. From the equation, the permeability A vanishes in the liquid region and approaches to infinity in the solid region. By adding this damping term, the momentum equation is valid for both solid and liquid phases.

In this study, the level set method tracks the interface on a fixed grid. The source terms in the momentum equations are applied as interfacial forces in the fluid flow, such as capillary force, buoyancy force, or thermocapillary force [16].

The capillary force and surface tension are used to characterize the liquid contractive tendency when the fluid flows in a narrow space. Besides the surface tension, the forces allow the fluid part to resist the external forces like gravity. For the liquid and gas interface, the capillary force is represented by the following equation:

$$\mathbf{F}_{st} = \sigma \kappa \mathbf{n}, \quad (7)$$

where σ is the surface tension stress, $\mathbf{n}$ and κ are normal vector and curvature of the liquid and gas interface, which can be calculated by level set function. From the equation, the capillary force $\mathbf{F}_{st}$ works on the normal direction on the liquid-gas interface.

$$\mathbf{n} = \frac{\nabla \phi}{|\nabla \phi|}, \quad (8)$$

$$\kappa = \nabla \cdot \mathbf{n}, \quad (9)$$

The body source term S is calculated based on the Boussinesq approximation [17] which represents the natural convection of the liquid under non-isothermal condition. The force is caused by the material temperature dependent density gradient in the liquid phase [18], which is shown in equation (10):

$$S = \rho g [1 - \alpha(T - T_{ref})], \quad (10)$$

where α , g and T_{ref} are the thermal expansion coefficient, the acceleration of gravity and the reference temperature, correspondingly.

A simple case is that the density of metal in the liquid and solid is the same, this source term S can be simplified as the gravity of the flow [19], that is,

$$S = \rho g \quad (11)$$

The surface tension gradient causes the thermocapillary force in the tangential direction. By the thermos-capillary force, the surface of the fluid flow from the lower surface tension to the higher surface tension coefficient [20].

$$\mathbf{F}_c = \nabla_s T \frac{d\sigma}{dT}, \quad (12)$$

where σ is the surface tension; $\nabla_s T$ refers to the surface gradient of the temperature field T . By multiplying the delta function δ , we can apply the source terms only on the interface of liquid and gas. The delta function δ can be defined as a smoothed Dirac delta function in equation (13):

$$\delta(\phi) = \frac{1}{h\sqrt{\pi}} e^{-\frac{\phi^2}{h^2}} \quad (13)$$

where h is a parameter for the smooth Dirac delta.

Adding these terms into the momentum equations in the x and y directions, the final formula of momentum equations are as below:

$$\frac{\partial \rho u}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = \nabla \cdot \left(\mu_l \frac{\rho}{\rho_l} \nabla u \right) - \nabla p + A u + \mathbf{e}_x \left(\sigma \kappa \mathbf{n} + \nabla_s T \frac{d\sigma}{dT} \right) \delta(\phi), \quad (14)$$

$$\begin{aligned} & \frac{\partial \rho v}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) \\ &= \nabla \cdot \left(\mu_l \frac{\rho}{\rho_l} \nabla v \right) - \nabla p + A v + \mathbf{e}_y \left(\sigma \kappa \mathbf{n} + \nabla_s T \frac{d\sigma}{dT} \right) \delta(\phi) \\ &+ \rho g [1 - \alpha(T - T_{ref})] \delta(\phi), \end{aligned} \quad (15)$$

2.3 Methods for simulating the phase change during the melting-solidification process

The phase change during the melting and solidification process is very complicated. It is a nonlinear problem due to the absorption and releases of latent energy at the melting point. The phase change is a temperature-dependent process. The enthalpy-porosity method [21] is used to simulate this phenomenon. It is assumed that the phase change occurs only when the temperature reaches the melting temperature T_m . According to the temperature field, the computational domain can be decomposed into three regions: the solid region, the liquid region and the mushy zone, as shown in equation (16) below. We use 1 and 0 to indicate the liquid and solid phase respectively. The region with a fraction between 0 and 1 is the mushy area. This area is considered as a porous medium, where both the porosity and the fluid velocity decreases to 0 in the solid area.

The fraction of the liquid phase can be calculated with equation (16):

$$f_l(T) = \begin{cases} 1, & T \geq (T_m + \epsilon), \\ \frac{T_m + \epsilon - T}{2\epsilon}, & (T_m + \epsilon) > T \geq (T_m - \epsilon), \\ 0, & T < (T_m - \epsilon), \end{cases} \quad (16)$$

where ϵ denotes the half width of the transition zone across the liquid and solid phases. The temperatures of the solid and liquid phases, as well as the enthalpy describing the total heat content of each phase, are represented by the following equations:

The temperature of the solid phase:

$$T_s = T_m - \epsilon, \quad (17)$$

The temperature of the liquid phase:

$$T_l = T_m + \epsilon, \quad (18)$$

The enthalpy in the solid phase:

$$h_s = \int_0^T c_{ps} dT, \quad (19)$$

The enthalpy in the liquid phase:

$$h_l = \int_0^{T_s} c_{ps} dT + L_m + \int_{T_s}^T c_{pl} dT = c_{pl}T + (c_{ps} - c_{pl})T_s + L_m, \quad (20)$$

where $\rho, t, V, \mu, k, T, p, K, h, c_p$ are density, time, velocity, molten fluid dynamic viscosity, heat conductivity, temperature, pressure, permeability, enthalpy, heat capacity, respectively. The subscription "s" represents solid; "l" represents liquid; L_m represents the latent heat for melting, which is the absorbed energy when phase changes from solid to liquid.

2.4 Continuum model for temperature-dependent material properties

There exist three phases in the entire computational domain: the solid metal, the liquid metal, and the gas. A continuum model is used to describe the physical laws of the entire domain [18].

The liquid and solid phases coexist in the mush zone. When calculating the material properties, we followed the work in [15, 22] to derive the compound thermal physical properties using the mass fractions and volume fractions, which are formulated as below:

$$\rho = g_s \rho_s + g_l \rho_l, \quad (21)$$

$$c_p = g_s c_{ps} + g_l c_{pl}, \quad (22)$$

$$k = g_s k_s + g_l k_l, \quad (23)$$

$$h = f_s h_s + f_l h_l, \quad (24)$$

where f_s and f_l , g_s and g_l refer to mass fractions and volume fractions for solid and liquid phases, respectively; c_p is the heat capacity; c_{ps} and c_{pl} are the specific heat for solid metal and liquid metal.

Also, the volume fraction and mass fraction are assumed to satisfy the following relationship:

$$f_l = \frac{g_l \rho_l}{\rho}, \quad (25)$$

$$f_l + f_s = 1, \quad (26)$$

$$g_l + g_s = 1. \quad (27)$$

2.5 Modeling of the laser beam

The laser beam is modeled as a Gaussian beam, which means the intensity I takes a Gaussian distribution. The highest intensity exists in the center of the laser beam and keeps decreasing while away from the center. The intensity distribution of laser power along the distance of the laser beam center are shown as in Figure 2.

$$I = \frac{2\eta P_{laser}}{\pi R^2} e^{\left(-\frac{2r^2}{R^2}\right)}, \quad (28)$$

where η is the absorptivity coefficient R and r are the beam radius and the distance from the calculated point to the beam center; P_{laser} stands for the power of laser beam. The laser beam moves starting from the center on the top surface. In the 2D model, we use a sine function along the x direction to simulate the motion of laser beam.

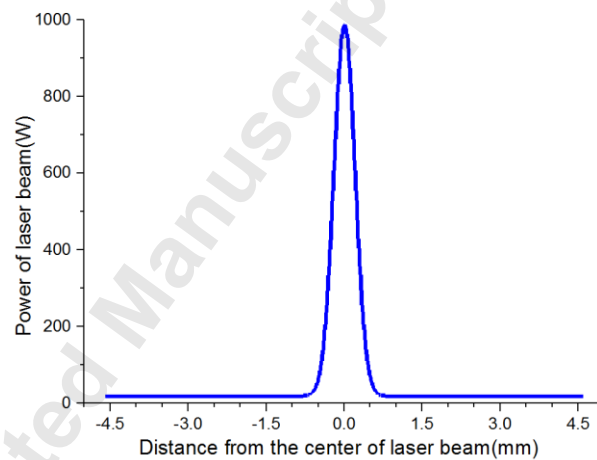


Figure 2: Power intensity distribution of laser beam

2.6 Mapping of material properties with the geometric level set model

In this model, the gas and metal interface is traced by level set methods. The material properties of metal and gas are mapped from the level set function by the Heaviside function.

Initially, a domain including metallic particles is defined and discretized with a finite element mesh. The gaps between particles are filled with gas. A level set function as equation (29) is introduced to present the surface between metal and gas at each time step:

$$\begin{cases} \phi(\mathbf{x}, t) > 0 & \text{in } \Omega_g, \\ \phi(\mathbf{x}, t) = 0 & \text{on } \Gamma(t), \\ \phi(\mathbf{x}, t) < 0 & \text{in } \Omega_m, \end{cases} \quad (29)$$

where the subscript g denotes the gas, and m stands for the metal. The area with the negative sign of the level set function describes the metallic phases. The area with the positive sign designates the gas.

When applied to solve the multiphase flow problem, the level set function must be reinitialized every several iterations to maintain the numerical stability [23] and conserve mass of the phases [24]. In this research, we implement the model with the multiphysics finite element software COMSOL 5.0. The phase-injection method proposed by Deshpande et.al [25] is used to enforce the mass conservation. The basic idea is to add constraint into the level set function to match with the calculated mass loss.

The interface moves with the fluid velocity, the movement of the interface can be described by the following equation [16]:

$$\frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = \varphi \delta \phi, \quad (30)$$

where φ represent the mass change before and after the level set function is updated. The constraint is only applied to the interface, and the level set function need not be a signed distance function.

To avoid numerical instability due to the physical property jump across the liquid/gas interface, we use the smoothed Heaviside function to specify a transition zone where the physical properties are graded. The Heaviside function is given in equation (31):

$$H(\phi) = \begin{cases} 0, & \text{if } \phi < -\varepsilon, \\ \frac{1}{2} \left[1 + \frac{\phi}{\varepsilon} + \frac{1}{\pi} \sin\left(\frac{\pi\phi}{\varepsilon}\right) \right], & \text{if } |\phi| \leq \varepsilon, \\ 1, & \text{if } \phi > \varepsilon, \end{cases} \quad (31)$$

In equation (31), ε represents the half width of the transition zone along the interface, where the smoothed Heaviside function changes from 0 to 1 across the boundary [26].

With the Heaviside function, the thermal properties of the whole computational domain can be mapped as follows:

$$\rho = \rho_m \cdot H(\phi) + \rho_g \cdot (1 - H(\phi)), \quad (32)$$

$$c_p = c_{pm} \cdot H(\phi) + c_{pg} \cdot (1 - H(\phi)), \quad (33)$$

$$k = k_m \cdot H(\phi) + k_g \cdot (1 - H(\phi)), \quad (34)$$

where ρ , c_p and k represent the density and heat capacity, heat conductivity, respectively. The subscripts m and g represent metal and gas.

2.7 Boundary conditions of the free surface

The boundary condition can be described as the heat loss or heat gain from the system. In this model, the absorbed heat simulates the gained heat from the laser beam. Also, two kinds of heat loss are considered: the convective heat loss q_c and the radiation heat loss q_{rad} , which can be calculated as equations below [27].

$$q_c = h_c(T - T_\infty), \quad (35)$$

$$q_{rad} = \varepsilon \sigma (T^4 - T_\infty^4), \quad (36)$$

where h_c is the heat transfer coefficient; σ the Stefan-Boltzmann's constant; ε the surface radiation emissivity; and T_∞ the atmosphere temperature.

In the liquid/gas (L/G) interface, the heat flux caused by temperature gradient approximates to the heat loss and heat gain from the system. This energy balance in the L/G interface can be expressed using the following equation:

$$k \frac{\partial T}{\partial n} = q_{laser} - h_c(T - T_\infty)\delta - \varepsilon \sigma (T^4 - T_\infty^4), \quad (37)$$

where q_{laser} refers to the heat power distribution at the deposited particles, because the laser beam is the only heat source in this model, by neglecting the heat absorbing difference in different angles, the heat power is equal to laser intensity,

$$q_{laser} = I_{laser}. \quad (38)$$

Also, the thermal contact between melt pool and the walls is neglected.

3 SIMULATION RESULTS AND NUMERICAL VERIFICATION

3.1 Numerical verification of melting and spreading of a single particle

In this experiment, the algorithm for free surface tracking and surface tension are tested. In the verification studies, the material properties of Ti-6Al-4V are considered constant in both solid and liquid phases. In this part, the model is built to simulate melting and spreading of a single particle onto a substrate. The particle is assumed to be spherical, which in this 2D case is a circle

with radius 0.3mm. The size of the study domain is 1.5 mm long and 0.7mm wide. The particle is represented by a level set function ϕ . The interface between the particle and gas locates where ϕ equals 0. The objective of this model is to study the case involving both the free surface flow and the melting process of a metal particle. The effects of convection are neglected. The method can be extended to a more complex situation.

The initial interface between the solid and gas is a circle represented by the following level set function (39):

$$\phi(t = 0) = \sqrt{x^2 + y^2} - r, \quad (39)$$

where x, y, r refer to the x, y coordinates and the radius of metal particle.

The melting and spreading of a single particle problem is solved for a 10ms period of time with a time step 0.01ms. Experimental results are shown in Figures 3. At each time step, the figures in the first row display the changes of the particle. Figures in the second row refer the changes of temperature field as time increases.

From the observation of computational results, the process can be broken down into three parts:

1. Heating (0ms-0.39ms): during the heating procedure, the temperature in the domain keeps increasing. Because the heat conductivity is higher in metal, so the heat transfers faster in the metal particle.
2. Phase change (0.40ms-0.42ms): during this period, the particle melts. The latent heat absorption is observed within the range of transition temperatures in Figure 4. The color contours represent temperature, and the legend illustrates the heat capacity caused by latent heat.

3. Spreading (0.43ms-10ms): The temperature of the whole computational domain is higher than the melting temperature. The phase change has completed in the particle. There are only two phases in the domain: liquid and gas. The liquid spreads under the effects of surface tension and gravity.

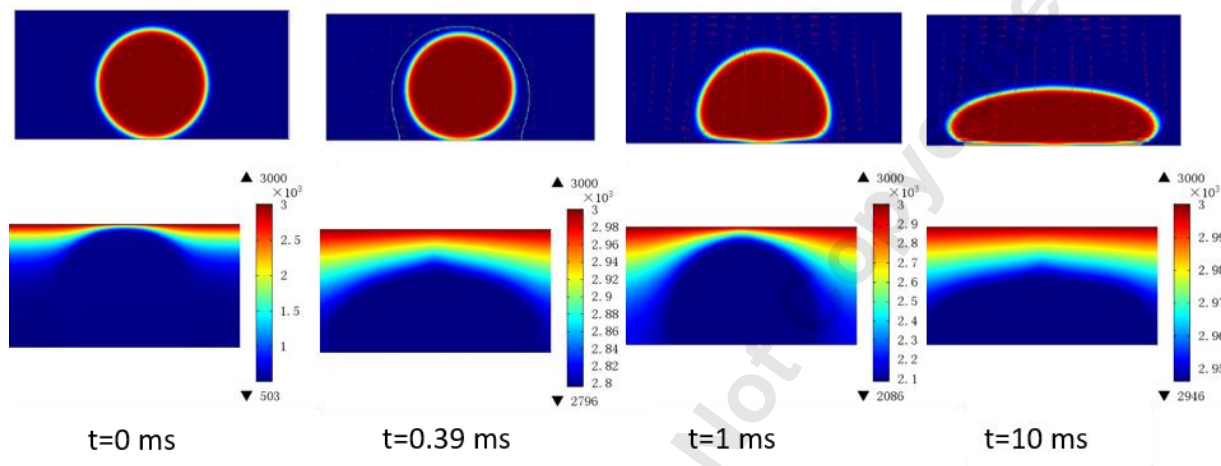


Figure 3: Simulating results of melting and spreading of a single particle

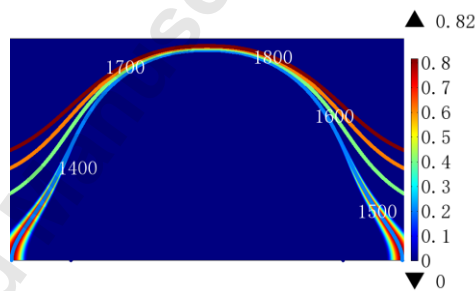


Figure 4: Heat capacity of latent heat at $t= 0.5$ ms

The level set function at 0 level can clearly show the deformation of the surface as illustrated in figure 5.

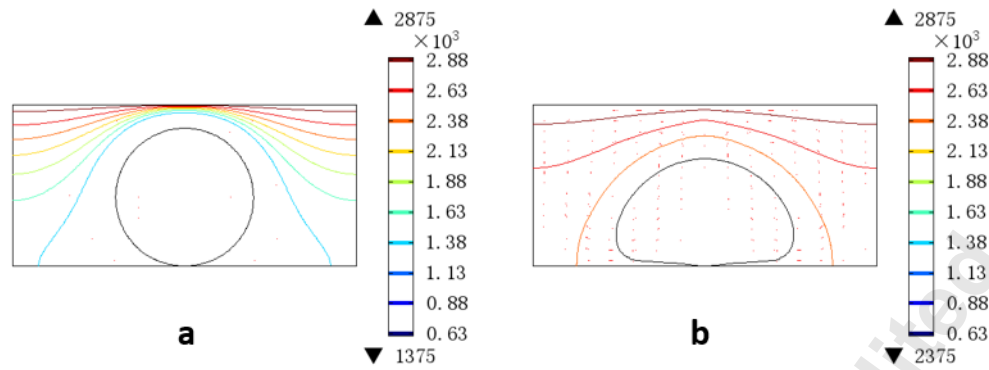


Figure 5: Temperature contours and interface changes at different time (a. $t=0.10\text{ms}$; b. $t=1.1\text{ms}$)

3.2 Modeling and simulation of the SLM process

In this section, the model simulating the melting process of metal-based AM is built. The governing equations for mass, energy, and momentum conservation apply to the whole computational domain. Three phases are considered in the model: the gas, the liquid metal, and solid metal. Instead of tracking the interface between the solid and liquid phases explicitly, the boundary of these two phases is identified by the fraction of the liquid phase. Here, each particle is assumed to be a sphere with the same radius, and the radius of the laser beam ranges from $10\mu\text{m}$ to $150\mu\text{m}$. The initial interface between the solid and the gas is presented by a level set function at $\phi(x, y) = 0$. Initially, the geometry of one 2D particle is represented as following equation:

$$\phi_n(x, y, t = 0) = \sqrt{x^2 + y^2} - r, \quad (40)$$

where n , x , y and r represent the number of the particles, the x and y coordinates and the radius, respectively. Boolean operations are applied between the level set functions of particles to merge them together when melted, as shown in equation (41):

$$\phi = \max \phi_1, \phi_2, \dots, \phi_n . \tag{41}$$

The intensity of the laser beam is represented by a Gaussian function. The total simulation time is 0.9ms with a 0.001ms time step. Because of the short calculation time, the heating process can be assumed to be instantaneous, so it is also reasonable to assume that the laser beam is fixed during this brief period. When the laser beam directly heats the surface of powders, the energy balance can be calculated as below:

$$k \frac{\partial T}{\partial n} = q_{laser} - h_c (T - T_\infty) \delta - \varepsilon \sigma (T^4 - T_\infty^4) \delta. \tag{42}$$

In equation (42), the first term on the right side q_{laser} stands for the heat power of the laser beam; the second and third term in the right side represent the heat loss between the melt pool and ambient gas; σ, ε, h_c are the Stefan-Boltzmann constant, radiation emissivity and heat transfer coefficient, respectively; T_∞ refers to the ambient temperature, which equals to 500K in this study. By applying the delta function, we only apply the heat loss to the L/G interface.

Here, instead of using constant thermal properties, we consider temperature dependent properties in both solid and liquid phases in Table 1, the value of the constant in this model is given in Table 2. The metal powder is distributed in a rectangular domain with 1.5 mm long and 1 mm wide. The laser beam is set at the point (0.25mm, 0.6mm) with a radius of 3mm. Initially, the geometry of the powder bed is shown in Figure 6. The laser beam intensity is 1000W. The constants of physical properties and the process parameters are detailed in Table 1 and Table 2.

Table 1: Physical properties of solid and liquid phases [28]

Physical Properties	Solid	Liquid	Unit
Specific heat	$\begin{cases} 483+0.215T, & T \leq 1268K \\ 412+0.180T, & 1268 < T \leq 1923 \end{cases}$	831	$\frac{J}{kg \cdot K}$

Density	4420-0.154(T-500K)	3920-0.68(T-1923K)	$\frac{kg}{m^3}$
Thermal conductivity	$\begin{cases} 1.26+0.016T, T \leq 1268K \\ 3.513+0.013T, 1268 < T \leq 1923 \end{cases}$	-12.752+0.024T	$\frac{W}{m \cdot K}$
Surface Tension	$1.525-0.28 \times 10^{-2}(T-1941K)$		$\frac{N}{m}$

Table 2: AM process parameters in the simulation model

Definition	Value	Units
Initial temperature	500	K
Radius of metal powder	10-150	μm
Acceleration of gravity	-9.8	m/s^2
Power of laser beam	1000	W
Absorptivity coefficient	0.2	1
Stefan-Boltzmann constant	5.67×10^{-3}	$W/m^2 K^4$
Radiation emissivity	0.8	1

Finally, the computational domain is discretized with a quadrilateral mesh with the maximum element size equal to 1.8×10^{-5} mm. The capillary force, buoyancy force and thermos-capillary force are applied to the L/G interface.

Figure 6 shows the simulation results. At each time spot, the figure on the left side shows the melt pool geometry, the temperature and velocity field. The numbered color contours refer to the temperatures with the SI unit of kelvin (K); the black contours are the interface between metal and gas. The red arrows refer to the velocity field of the molten metal flow. It is observed that the highest temperature happens in the area nearest to the center of the laser beam. By the end of the simulation, the highest temperature reaches to 2750K. The particles change from the solid phase to the liquid phase. The deformation of molten particles can be observed. Figures on the right side demonstrate the liquid fraction evolution during the phase change. From the results, the phase transition begins in the area closest to the laser beam. Only regions higher than the melting

point is simulated as liquid. This is in accordance with the fraction function discussed in Section 2.2. The phase change is an energy absorbing or releasing process. In this case, the absorbed energy while melting is called the absorbing latent heat assimilated only within the range of transition temperatures.

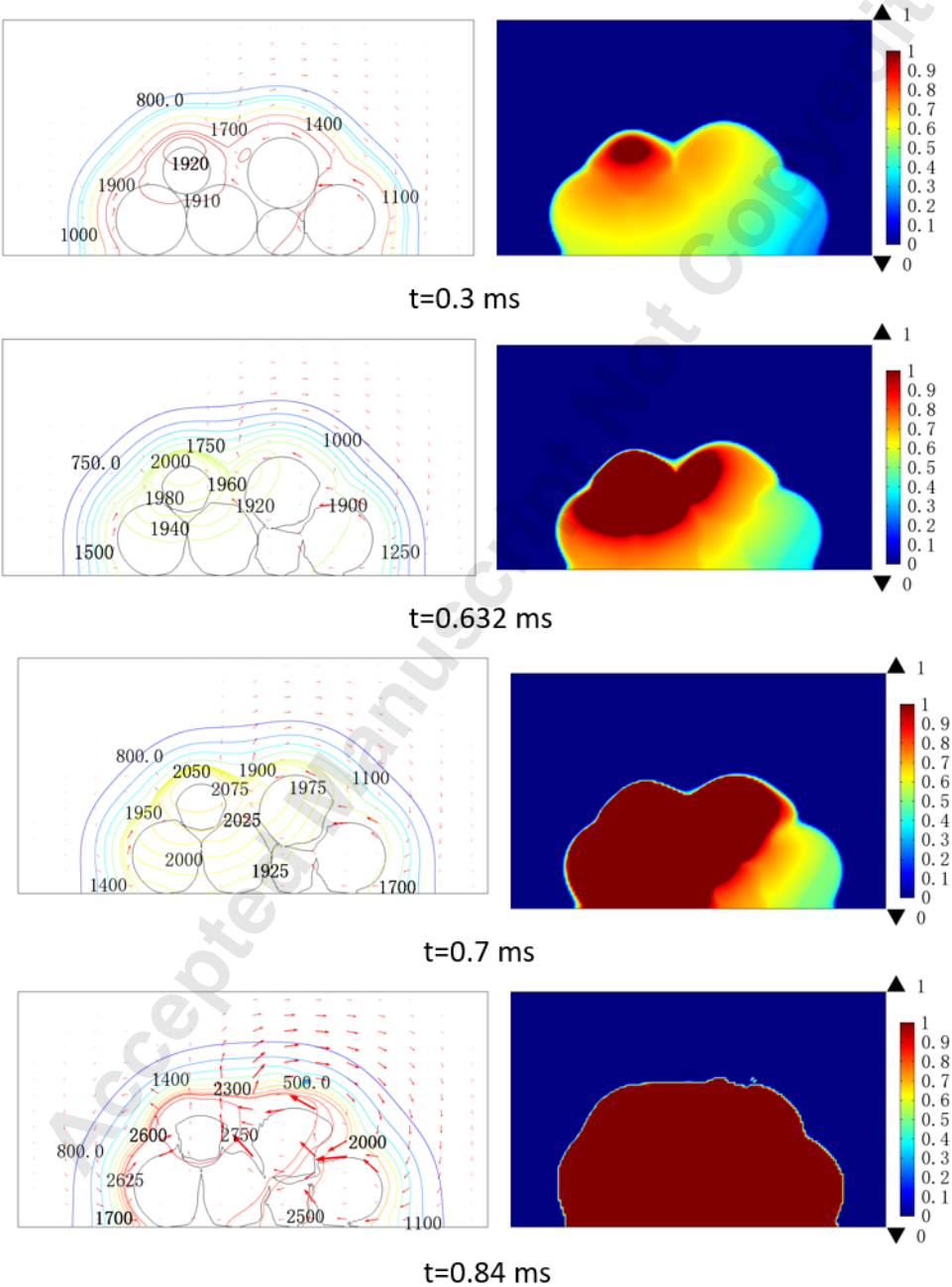


Figure 6: Evolution of the melt pool geometry, temperature contours, velocity fields and liquid friction

3.3 Convergence study

As discussed in Section 1, the problem is a highly nonlinear multiphysics one. There are three models to be solved: the heat transfer, the fluid flow, and level set. The heat transfer and fluid flow are physics related model, the geometric level set method is only used to track the interface. To find an efficient way to solve the problem, both the fully coupled solver and the segregated solver are utilized in this study.

The fully coupled solver solves the heat transfer, the fluid flow PDEs, and the level set equation simultaneously. This approach is straightforward but is memory costing and time consuming. The segregated approach first solves the physics governing equations and then the level set equation at each step. The computer solves one specific model at a time and inherits other state variables from the previous step [29]. The comparison of the convergence plots of each solver is shown in Figure 7.

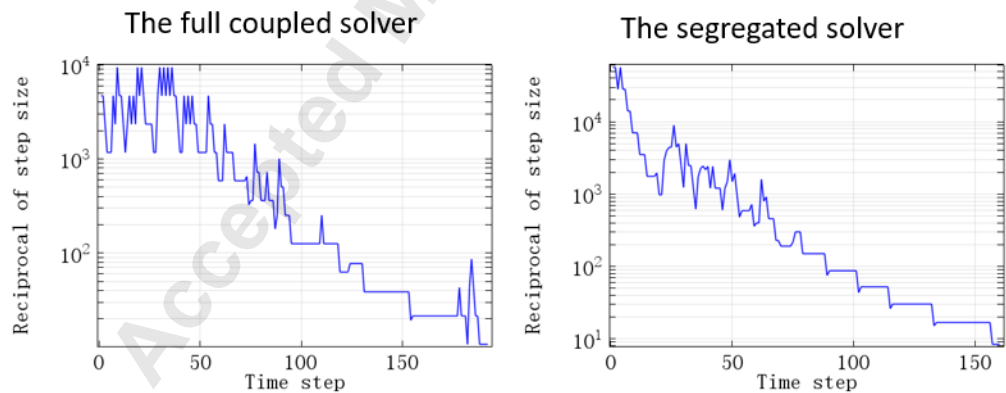


Figure 7: Convergence plots of the full coupled solver and the segregated solver

From the observation, by using the segregated solver, the number of total computational time steps reduce from 180 to 155, which means the approach is faster than the fully coupled approach. Also, the convergence plot for segregated solver is smoother than the full direct couple solver. So we can conclude that the segregated solver shows greater efficiency in solving this multiphysics problem.

4 SUMMARY

In this study, a 2D numerical model has been built to simulate the melting process of metal-based SLM. The metal melting process is studied in different aspects: the temperature field, the velocity field and the interface between liquid and gas phases. The model couples heat transfer and fluid dynamics with level set methods to trace the boundary of melt pools. A segregated finite element solver is adopted to solve the multiphysics models in a sequential way. Compared with the fully coupled solver, the segregated solver shows higher efficiency.

There are still some issues needing to be examined and addressed in the future research. In the current implementation, the effects of evaporation are neglected, but in the real AM process, the temperature in the melt pool may exceed the evaporating point. So the mass loss during evaporation should be considered later. The wetting effects between molten particles with un-molten particles and the thermal contacts between melt pool and the substrate are not studied. The above issues will be further explored in our future research. Also, the re-initialization of the level set function must be further improved to avoid the possible interface shifting. The current work focuses on 2D particles. The extension of the proposed method to a more complex 3D model will be further investigated. For our next step, the simulation of the residual stress, which leads

distortion and deformation in the parts [30], will be predicted using the stated variables calculated in our model [31]. The deformation can be presented by level set function as well. In addition, the experimental validation is needed in the future work [1].

ACKNOWLEDGMENTS

The authors acknowledge the support from the National Science Foundation (CMMI-1462270), Ford Motor Company, and the start-up funds from the State University of New York at Stony Brook.

REFERENCE

- [1] B. Schoinochoritis, D. Chantzis, and K. Salonitis, "Simulation of metallic powder bed additive manufacturing processes with the finite element method: a critical review," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, p. 0954405414567522, 2015.
- [2] B. Baufeld, O. V. d. Biest, and R. Gault, "Additive manufacturing of Ti-6Al-4V components by shaped metal deposition: microstructure and mechanical properties," *Materials & Design*, vol. 31, pp. S106-S111, 2010.
- [3] N. Guo and M. C. Leu, "Additive manufacturing: technology, applications and research needs," *Frontiers of Mechanical Engineering*, vol. 8, pp. 215-243, 2013.
- [4] J.-P. Kruth, G. Levy, F. Klocke, and T. Childs, "Consolidation phenomena in laser and powder-bed based layered manufacturing," *CIRP Annals-Manufacturing Technology*, vol. 56, pp. 730-759, 2007.
- [5] S. Das, "Physical aspects of process control in selective laser sintering of metals," *Advanced Engineering Materials*, vol. 5, pp. 701-711, 2003.
- [6] A. J. Pinkerton and L. Li, "Modelling the geometry of a moving laser melt pool and deposition track via energy and mass balances," *Journal of Physics D: Applied Physics*, vol. 37, p. 1885, 2004.
- [7] T. Chande and J. Mazumder, "Two - dimensional, transient model for mass transport in laser surface alloying," *Journal of applied physics*, vol. 57, pp. 2226-2232, 1985.

- [8] Z. Fan and F. Liou, "Numerical modeling of the additive manufacturing (am) processes of titanium alloy," *TITANIUM ALLOYS-TOWARDS ACHIEVING ENHANCED PROPERTIES FOR DIVERSIFIED APPLICATIONS*, p. 1, 2012.
- [9] E. Attar, "Simulation of selective electron beam melting processes," Ph. D. Thesis, 2011.
- [10] V. Voller, A. Mouchmov, and M. Cross, "An explicit scheme for coupling temperature and concentration fields in solidification models," *Applied Mathematical Modelling*, vol. 28, pp. 79-94, 2004.
- [11] S. Osher and R. P. Fedkiw, "Level set methods: an overview and some recent results," *Journal of Computational physics*, vol. 169, pp. 463-502, 2001.
- [12] H. Chung and S. Das, "Level Set Methods for Modeling Laser Melting of Metals," *Ann Arbor*, vol. 1001, pp. 48109-2125, 2003.
- [13] C. Li, C. Xu, C. Gui, and M. D. Fox, "Level set evolution without re-initialization: a new variational formulation," in *Computer Vision and Pattern Recognition, 2005. CVPR 2005. IEEE Computer Society Conference on*, 2005, pp. 430-436.
- [14] J. A. Sethian, *Level set methods and fast marching methods: evolving interfaces in computational geometry, fluid mechanics, computer vision, and materials science* vol. 3: Cambridge university press, 1999.
- [15] L. Han, F. W. Liou, and S. Musti, "Thermal behavior and geometry model of melt pool in laser material process," *Journal of Heat Transfer*, vol. 127, pp. 1005-1014, 2005.
- [16] T. Marin, "Solidification of a Liquid Metal Droplet Impinging on a Cold Surface," in *Proceedings of the COMSOL Users Conference*, 2006.
- [17] P. Goyal, A. Dutta, V. Verma, and I. T. R. Singh, "Enthalpy Porosity Method for CFD Simulation of Natural Convection Phenomenon for Phase Change Problems in the Molten Pool and its Importance during Melting of Solids."
- [18] H. Qi, J. Mazumder, and H. Ki, "Numerical simulation of heat transfer and fluid flow in coaxial laser cladding process for direct metal deposition," *Journal of applied physics*, vol. 100, p. 024903, 2006.
- [19] L. Han and F. Liou, "Numerical investigation of the influence of laser beam mode on melt pool," *International journal of heat and mass transfer*, vol. 47, pp. 4385-4402, 2004.
- [20] Z. Fan and F. Liou, "Numerical Modeling of the Additive Manufacturing (AM) Processes of Titanium Alloy," 2012.
- [21] Y. Belhamadia, A. S. Kane, and A. Fortin, "An enhanced mathematical model for phase change problems with natural convection," *Int. J. Numer. Anal. Model*, vol. 3, pp. 192-206, 2012.

- [22] F. Vásquez, J. A. Ramos-Grez, and M. Walczak, "Multiphysics simulation of laser–material interaction during laser powder deposition," *The International Journal of Advanced Manufacturing Technology*, vol. 59, pp. 1037-1045, 2012.
- [23] S. Osher and R. Fedkiw, *Level set methods and dynamic implicit surfaces* vol. 153: Springer, 2003.
- [24] H. Grzybowski and R. Mosdorf, "Modelling of two-phase flow in a minichannel using level-set method," in *Journal of Physics: Conference Series*, 2014, p. 012049.
- [25] W. B. Zimmerman, *Multiphysics Modeling With Finite Element Methods (series on Stability, vibration and control of systems, serie)*: World Scientific Publishing Co., Inc., 2006.
- [26] O. Desmaison, M. Bellet, and G. Guillemot, "A level set approach for the simulation of the multipass hybrid laser/GMA welding process," *Computational Materials Science*, vol. 91, pp. 240-250, 2014.
- [27] L. Han, K. Phatak, and F. Liou, "Modeling of laser cladding with powder injection," *Metallurgical and Materials transactions B*, vol. 35, pp. 1139-1150, 2004.
- [28] K. C. Mills, *Recommended values of thermophysical properties for selected commercial alloys*: Woodhead Publishing, 2002.
- [29] S. Chen, B. Merriman, S. Osher, and P. Smereka, "A simple level set method for solving Stefan problems," *Journal of Computational Physics*, vol. 135, pp. 8-29, 1997.
- [30] X. Wang, X. Gong, and K. Chou, "Review on powder-bed laser additive manufacturing of Inconel 718 parts," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, p. 0954405415619883, 2016.
- [31] J.-P. Kruth, J. Deckers, E. Yasa, and R. Wauthlé, "Assessing and comparing influencing factors of residual stresses in selective laser melting using a novel analysis method," *Proceedings of the institution of mechanical engineers, Part B: Journal of Engineering Manufacture*, vol. 226, pp. 980-991, 2012.

Figure Captions List

- Fig. 1 Simulation of selective electron beam melting processes[9]
- Fig. 2 Power intensity distribution of laser beam
- Fig. 3 Simulating results of melting and spreading of a single particle
- Fig. 4 Heat capacity of latent heat at $t= 0.5\text{ms}$
- Fig. 5 Temperature contours and interface changes at different time (a.
 $t=0.10\text{ms}$; b. $t=1.1\text{ms}$)
- Fig. 6 Evolution of the melt pool geometry, temperature contours, velocity fields
 and liquid friction
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Table Caption List

Table 1	Physical properties of solid and liquid phases [28]
Table 2	AM process parameters in the simulation model

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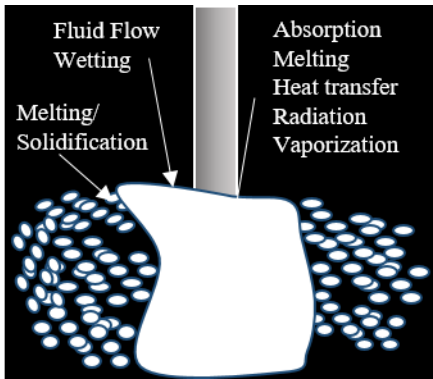


Figure 1. Simulation of selective electron beam melting processes[9]

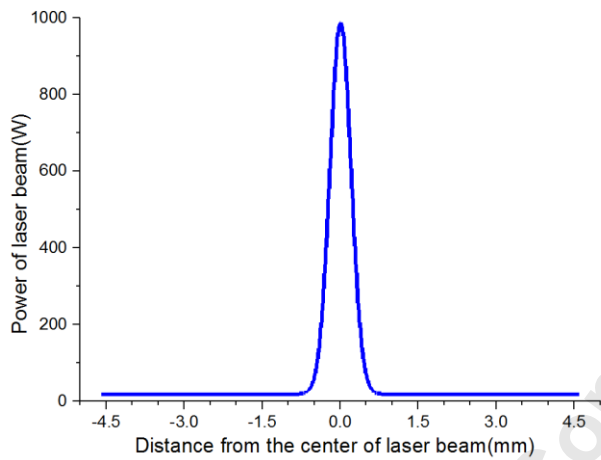


Figure 2: Power intensity distribution of laser beam

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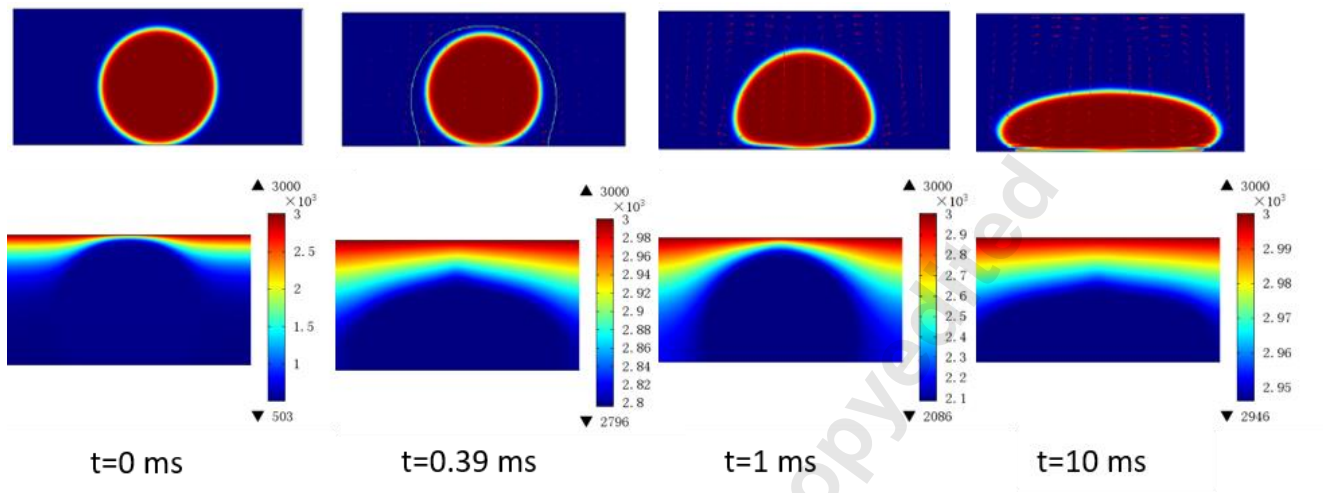


Figure 3: Simulating results of melting and spreading of a single particle

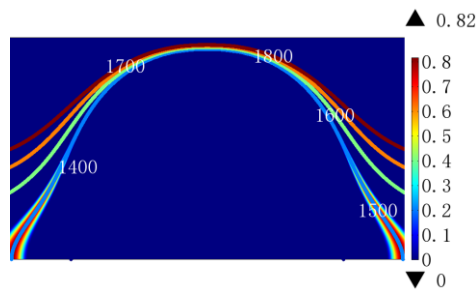


Figure 4: Heat capacity of latent heat at $t = 0.5\text{ms}$

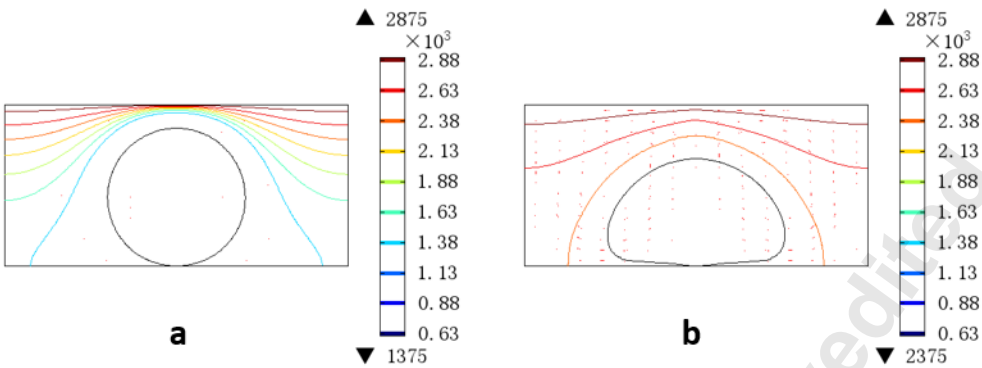


Figure 5: Temperature contours and interface changes at different time (a.
t=0.10ms; b. t=1.1ms)

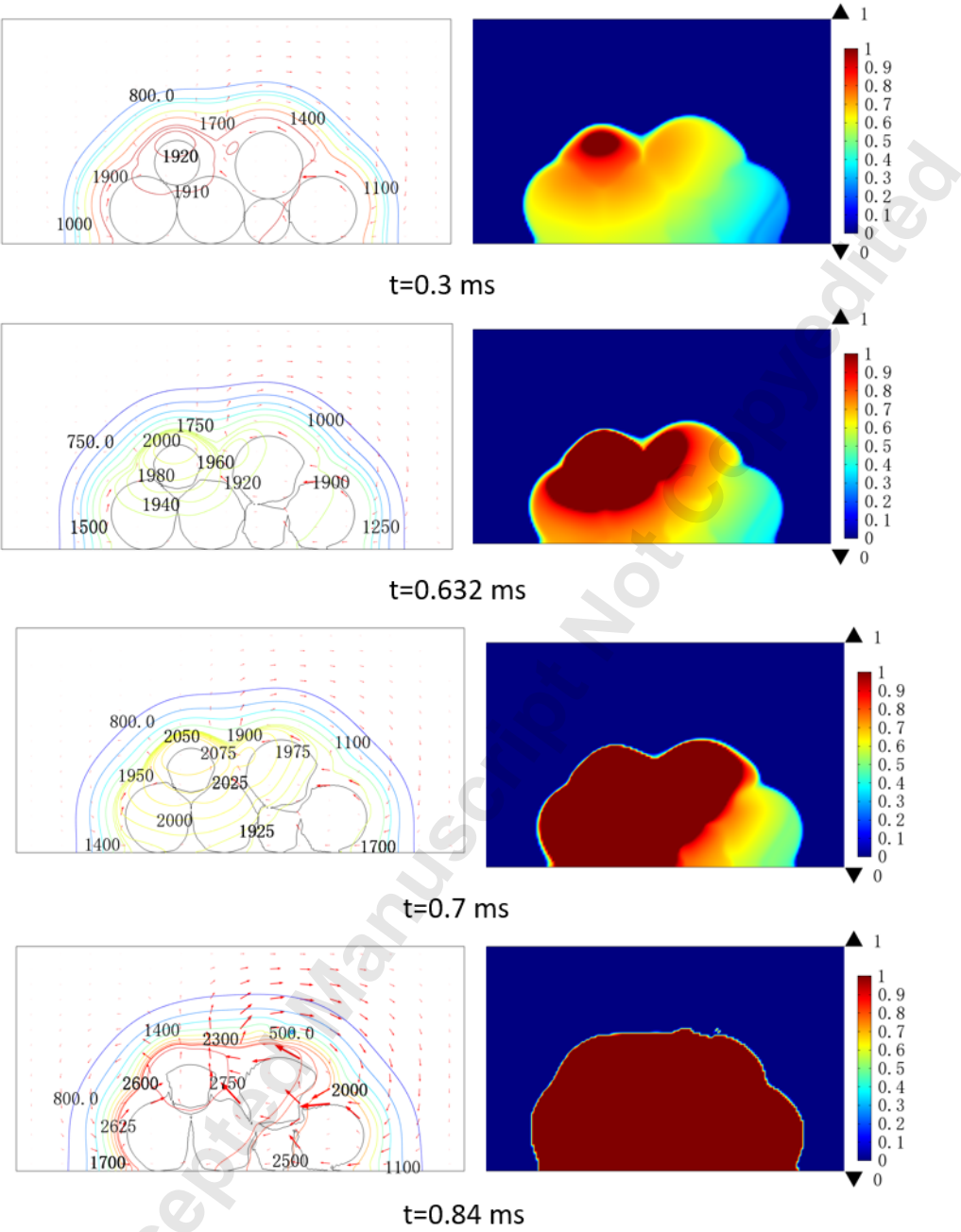


Figure 6: Evolution of the melt pool geometry, temperature contours, velocity fields
and liquid friction

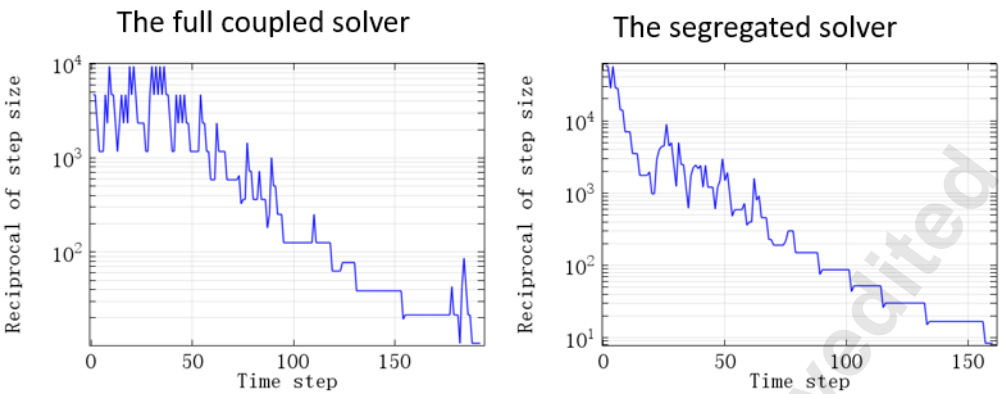


Figure 7: Convergence plots of the full coupled solver and the segregated solver

Table 1: Physical properties of solid and liquid phases [28]

Physical Properties	Solid	Liquid	Unit
Specific heat	$\begin{cases} 483+0.215T, T \leq 1268K \\ 412+0.180T, 1268 < T \leq 1923 \end{cases}$	831	$\frac{J}{kg \cdot K}$
Density	$4420-0.154(T-500K)$	$3920-0.68(T-1923K)$	$\frac{kg}{m^3}$
Thermal conductivity	$\begin{cases} 1.26+0.016T, T \leq 1268K \\ 3.513+0.013T, 1268 < T \leq 1923 \end{cases}$	$-12.752+0.024T$	$\frac{W}{m \cdot K}$
Surface Tension	$1.525-0.28 \times 10^{-2}(T-1941K)$		$\frac{N}{m}$

Table 2: AM process parameters in the simulation model

Definition	Value	Units
Initial temperature	500	K
Radius of metal powder	10-150	μm
Acceleration of gravity	-9.8	m/s^2
Power of laser beam	1000	W
Absorptivity coefficient	0.2	1
Stefan-Boltzmann constant	5.67×10^{-3}	$\text{W/m}^2\text{K}^4$
Radiation emissivity	0.8	1