ABSTRACT
A robust numerical method based on smoothed particle hydrodynamics (SPH) is developed for simulations of laser melting of metals and melt pool dynamics. The method accounts for all major interfacial effects, including surface tension, Marangoni stress, recoil force due to vapor pressure, as well as mass removal and cooling due to evaporation. The developed SPH method is combined with a classical ray tracing method for prediction of propagation and absorption of laser radiation. The optimum values of artificial viscosity coefficient and number of SPH particles for developed method are found in preliminary simulations of the keyhole drilling by a continuous wave laser. The method is then used to study melt expulsion from a keyhole during laser drilling in two-dimensional simulations. It is also shown that the method can be used to predict the keyhole formation and material binding in selective laser melting of metal powders.

Keywords: Laser drilling, smoothed particle hydrodynamics (SPH), ray tracing, recoil vapor effect, Marangoni stresses

1. INTRODUCTION
Continuous wave (CW) lasers are used in various industrial applications, including welding, drilling, and cutting of metals. The interest towards understanding the CW laser-metal interaction has revived with introduction of 3D printing technologies such as powder bed fusion additive manufacturing based on selective laser melting (SLM) of metal powders. The SLM-manufactured parts suffer from multiple defects, e.g., porosity, and variability of local material properties. Theoretical and computational studies can provide insights into mechanisms responsible for formation of the material defects in the course of laser melting, subsequent material binding, and solidification [1].

The shape of the molten pool and geometry of the free surface in SLM are determined by a trade-off between various interfacial effects, including surface tension, Marangoni stress, recoil effect of evaporation and evaporation cooling, as well as volumetric processes dominated by viscosity and thermal diffusivity of the molten material. Mass and heat transfer in the molten pool also strongly depends on the distribution of heat sources, associated with the deposited laser energy. The prediction of the heat source distribution is a non-trivial problem, since the incident laser radiation is absorbed by the target material during multiple reflections from surfaces of powder particles or keyhole walls.

Simulations of deep laser drilling and SLM require numerical methods that can be used when transient and topologically complex free surfaces are formed in the melt pool. One of the numerical methods designed for simulations of free surface flows is the smoothed particle hydrodynamics (SPH) method. The SPH method is a Lagrangian, meshless, particle-based numerical approach for solving continuum equations of fluid and solid mechanics, as well as heat transfer [2]. In this approach, a medium or material is represented by a set of particles (SPH particles) interacting with each other by means of a “force field,” which is derived directly from the equations of continuum mechanics and describes the mass, momentum, and energy exchange between SPH particles.

In the present paper, a two-phase formulation of the SPH method is developed, which accounts for melting and solidification of the target material based on the enthalpy formulation and major interfacial effects, including surface tension force, Marangoni stresses, recoil force due to vapor pressure, mass removal, and evaporative cooling. The classical method of ray tracing (RT) [3] is coupled with the SPH method in order to simulate the propagation, multiple reflections, and absorption of incident laser radiation. Absorption and reflection of the radiation at a target surface represented by SPH particles is implemented in a form that does not require explicit interface reconstruction, putting no restrictions on the topological changes of the free surface in the course of a simulation. The attenuation and scattering of individual rays or energy packages from the material surface are described by Fresnel equations. The developed combined computational methodology is
applied to study CW laser drilling of a bulk metal target and SLM of a powder on a substrate in two-dimensional (2D) simulations.

2. SPH METHOD FOR SIMULATION OF MOLTEN MATERIAL FLOW

2.1 Model of laser radiation and interfacial effects leading to formation of a keyhole

The target material surface is assumed to be heated by a CW laser with the beam propagation in the direction normal to the surface. The distribution of the laser intensity \( I(r) \) in the radial direction is assumed to be Gaussian [4]:

\[
I(r) = I_L \exp \left[ -\left( \frac{r}{R_L} \right)^2 \right],
\]

where \( I_L \) is the laser intensity at the spot center, \( 2R_L \) is the full width at the half maximum (FWHM) spot size, and \( r \) is a coordinate counted from the spot center along the irradiated surface. For a cylindrical beam, the peak laser intensity \( I_L \) is related to the laser power \( P_L \) by the equation

\[
P_L = 2\pi \left( \frac{R_L}{\sqrt{2\ln 2}} \right)^2 I_L.
\]

In the 2D simulations described in Section 3, the laser beam cross section represents a strip with a characteristic thickness of \( 2R_L \). In order to perform 2D simulations of CW laser heating with the peak laser intensities specific for actual applications, where cylindrical beams are utilized, we use the equivalent laser power of a cylindrical beam \( P_{L(2D)} \) and half beam size \( R_L \) as input parameters, calculate peak intensity from Equation (2), and then assume that the distribution of laser intensity is given by Equation (1). Then the actual laser power density per unit length of the 2D beam \( P_{L(2D)} \) is related to the power of the equivalent cylindrical beam \( P_L \) by the equation

\[
P_{L(2D)} = \frac{\ln 2 P_L}{\pi R_L} \approx 0.47 \frac{P_L}{R_L}.
\]

In this work, stainless steel 316L is considered as material of the irradiated target. Thermo-physical properties of the target material are given in Table 1.

During laser heating, the temperature in the center of the melting pool can raise up to \( \sim 4000 \) K, while the surface temperature at the spot periphery is close to the melting temperature of 1700 K. For the laser spots with typical for SLM diameters of 25-100 \( \mu \)m, laser heating creates strong temperature gradient across the spot. This temperature gradient induces the surface forces that dominate the material expulsion from the spot center and formation of the keyhole.

The large temperature gradient along the surface can result in the pronounced effect of Marangoni convection, which drives the melt flow from the region of low surface tension coefficient to the region of high surface tension coefficient. The surface tension coefficient of stainless steel 316L decreases with temperature (Table 1), so that the Marangoni stresses induce flow of the molten material from the spot center to outwards. This process reduces the thickness of the molten pool in the center and results in the formation of a depression in the central part of the molten pool.

The large temperature gradient along the molten pool can also create strongly non-homogeneous distribution of vapor pressure at the free surface, inducing the melt flow from a region of high pressure at the spot center towards the spot periphery, where the vapor pressure can be orders of magnitude smaller. This recoil effect of vapor pressure provides the second major mechanism driving the formation of the keyhole.

In this work, the dependence of the vapor pressure \( P_e \) on temperature \( T \) is described by the Clapeyron-Clausius equation [1]

\[
P_e(T) = 0.54 p_{oe} \exp \left( \frac{L_b M}{k_B N_a} \left( \frac{1}{T_{oe}} - \frac{1}{T} \right) \right),
\]

where \( k_B \), \( N_a \), and \( M \) are the Boltzmann constant, Avogadro constant, and molar mass of the target material respectively, \( L_b \) is the latent heat of boiling, and \( p_{oe} \) is the saturated vapor pressure at a reference temperature \( T_{oe} \) (Table 1). The net mass flux density of the evaporated material \( F_e \) is calculated based on the Hertz-Knudsen model of evaporation [1,5]

\[
F_e(T) = 0.82 \frac{p_e(T)}{2\pi k_B N_a T/M}.
\]

The coefficient 0.82 in Equation (5) suggests that 18% of the vapor condenses back to the surface as predicted by the Knudsen layer models [1].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ( \rho )</td>
<td>7500 kg m(^{-3})</td>
</tr>
<tr>
<td>Viscosity ( \mu )</td>
<td>0.00642 kg m(^{-1}) s(^{-1})</td>
</tr>
<tr>
<td>Specific heat of solid material ( C_p )</td>
<td>462.656 + 0.1338T J kg(^{-1}) K(^{-1})</td>
</tr>
<tr>
<td>Specific heat of liquid material ( C_p )</td>
<td>776 J kg(^{-1}) K(^{-1})</td>
</tr>
<tr>
<td>Thermal conductivity of solid material ( k )</td>
<td>9.248 + 1.571 \times 10^{-2} T W m(^{-1}) K(^{-1})</td>
</tr>
<tr>
<td>Thermal conductivity of liquid material ( k )</td>
<td>12.41 + 3.279 \times 10^{-3} T W m(^{-1}) K(^{-1})</td>
</tr>
<tr>
<td>Melting temperature ( T_m )</td>
<td>1700 K</td>
</tr>
<tr>
<td>Latent heat of fusion ( L_m )</td>
<td>2.7033 \times 10^5 J kg(^{-1})</td>
</tr>
<tr>
<td>Reference boiling temperature ( T_{oe} )</td>
<td>3086 K</td>
</tr>
<tr>
<td>Reference boiling pressure ( p_{oe} )</td>
<td>10^5 Pa</td>
</tr>
<tr>
<td>Latent heat of boiling ( L_b )</td>
<td>7.46 \times 10^6 J kg(^{-1})</td>
</tr>
<tr>
<td>Surface tension ( \sigma(T) )</td>
<td>3.282 \times 8.9 \times 10^{-4} T N m(^{-1})</td>
</tr>
<tr>
<td>Molar mass ( M )</td>
<td>0.056 kg mole(^{-1})</td>
</tr>
</tbody>
</table>

2.2 SPH method

Following the SPH approach, the material sample is divided into a number of SPH particles. In this work, all SPH particles are initially placed in nodes of a Cartesian mesh with square cells of size \( \Delta x \). Additional variable \( \phi(T) \) equal to the
volume fraction of liquid material is assigned to every SPH particle. In the initial state, before onset of irradiation of the target with a CW laser, all SPH particles represent solid material and \( \phi = 0 \) for every particle. Melting and solidification are described based on the enthalpy formulation approach [7] as a variation of the liquid volume fraction due to consumption or release of the latent heat of fusion. In the present work, we use a simplified approach, where the formation of the mushy zone is neglected, and it is assumed that all SPH particles with \( \phi \geq 0.5 \) represent molten material, while other particles belong to the solid part of the sample. This approach is justified by relatively small thickness of the mushy zone obtained in our preliminary simulations, where the finite thickness of the mushy zone was taken into account. For solid material, only the heat conduction equation is solved. Molten material is considered as a weakly compressible fluid. For simplicity, the description of the SPH method below is focused only on the flow of the molten material. The method of calculation of the fluid volume fraction adopted in the present work is identical to the method used in Ref. [5].

The standard SPH kernel function in the form of cubic splines [2]

\[
W_{ij}(r_{ij},h) = \begin{cases} 
\frac{2}{3} \left( \frac{1}{6}\left(2-r^2\right)^3, & 0 \leq r < 1; \\
\frac{1}{6}\left(1-r^2\right)^3, & 1 \leq r < 2; \\
0, & r \geq 2 
\end{cases}
\]

is used in simulations, where \( r_{ij} \) is the distance between two SPH particles, \( h = \sqrt{2\Delta x} \) is the smoothing length, \( \vec{r} = r_{ij}/h \), and value of \( a_d = (15/7)\pi h^2 \) is given by the normalization condition for the two-dimensional SPH kernel function [2]. According to this definition of \( W_{ij} \), SPH particle \( i \) with position \( \vec{r}_i \) can interact only with such SPH particles that are located within a circle of radius \( 2h \) with the center in point \( \vec{r}_i \).

The variation of density \( \rho_i \) of SPH particle \( i \) is calculated based on the SPH approximation of the continuity equation [2]

\[
\frac{d\rho_i}{dt} = \sum_j m_j v_{ij} \cdot \nabla_i W_{ij},
\]

where \( \rho_i \) is the particle mass, \( \vec{v}_i \) is the particle velocity, \( \vec{v}_{ij} = \vec{v}_i - \vec{v}_j \), and \( \nabla_i W_{ij} \) is the gradient of the kernel function with respect to coordinates of particle \( i \).

The momentum equation of SPH particle \( i \) accounts for accelerations due to pressure gradient \( f_{pi} \), viscous force \( f_{vi} \), gravitational force \( f_{gi} \), surface tension force \( f_{si} \), and recoil force due to vapor pressure \( f_{ei} \):

\[
\frac{d\vec{v}_i}{dt} = f_{pi} + f_{vi} + f_{gi} + f_{si} + f_{ei}.
\]

The particle acceleration caused by pressure gradient is calculated as [2]

\[
f_{pi} = - \sum_j m_j \left( \frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} \right) \nabla_i W_{ij},
\]

where \( p_i = p(\rho_i) \) is pressure in particle \( i \). The acceleration due to viscous force is defined in the form [2]

\[
f_{vi} = \sum_j m_j \left( \frac{2(\mu_i + \mu_j)v_{ij} \cdot \vec{r}_{ij} + \Pi_{ij}}{\rho_i \rho_j r_{ij}^2} \right) \nabla_i W_{ij},
\]

where \( \vec{r}_{ij} = \vec{r}_i - \vec{r}_j \), \( \Pi_{ij} \) is the artificial viscosity term

\[
\Pi_{ij} = \begin{cases} 
-2\nu_{art} \frac{v_{ij} \cdot \vec{r}_{ij}}{\rho_i + \rho_j} r_{ij}^{-1} + \epsilon \rho_i h^2, & \text{if } v_{ij} \cdot \vec{r}_{ij} < 0; \\
0, & \text{otherwise}.
\end{cases}
\]

\( \nu_{art} \) is the artificial viscosity coefficient measured in units of kinematic viscosity, and term \( \epsilon \rho_i h^2 \) with \( \epsilon = 0.01 \) is introduced in Equation (11) to eliminate singularity. The term \( f_{gi} \) is defined as \( -g \vec{j} \), where \( g \) is Earth’s gravity acceleration and unit vector \( \vec{j} \) has a direction opposing the direction of incident laser beam. For instance, vector \( \vec{j} \) is directed vertically from bottom to top in Figure 1.

The terms in the right-hand side of Equation (8) that correspond to surface forces at the liquid-vapor interface are calculated based on the continuous surface force (CSF) method [9]. The SPH particle acceleration due to surface tension is represented in the form [10]

\[
f_{si} = \sum_j m_j \left( \frac{\Gamma_i}{\rho_i^2} + \frac{\Gamma_j}{\rho_j^2} \right) \cdot \nabla_i W_{ij},
\]

where

\[
\Gamma_i = \sigma(T) \left( \frac{d}{\rho_i} I - \vec{n}_i \vec{n}_i \right) |\nabla C_i|,
\]

\( d \) is the spatial dimension (\( d = 2 \) in simulations considered in the present paper), \( \nabla C_i \) is the gradient of a color index \( C_i \) of particle \( i \) which has a unit jump across the interface, \( I \) is the unit tensor, and \( \vec{n}_i = \nabla C_i / |\nabla C_i| \). Unique values of \( C_i \) are used for metal and ambient gas [10]. In this work, we do not account for the gas flow above the irradiated target and set \( C_i = 1 \) for both solid and liquid material. The gradient of the color function is then calculated as

\[
\nabla C_i = -\frac{m_i}{\rho_i} \sum_j C_j |\nabla W_{ij}|,
\]

where summation is performed only over the SPH particles representing the target material. It is not necessary to explicitly introduce SPH particles representing the ambient gas, since these particles do not contribute to the sum in the right-hand side of Equation (14).

We use a representation of the particle acceleration due to recoil effect of vapor pressure also based on the CSF method [9] in the form

\[
f_{ei} = -\frac{p_e(T_i)}{\rho_i} \nabla C_i - \frac{p_e(T_i)}{\rho_i} [C_i] \left( \frac{C_i}{\langle C \rangle} \right),
\]

where \( [C_i] \) is the color index jump across the interface which is equal to 1, \( \langle C \rangle = 0.5 \) is the average color index value at the interface, and vapor pressure \( p_e(T) \) is given by Equation (4). The magnitude of the gradient of the color index \( |\nabla C_i| = 0 \) for all SPH particles which are away from the interface. It ensures

\[
\begin{align*}
\text{Copyright © 2019 ASME}
\end{align*}
\]
zero recoil force for such particles even if they have high temperatures.

The energy equation for SPH particle \( i \) is represented in the form

\[
d\frac{T_i}{dt} = \frac{1}{\rho_i c_p i} (q_{i,0} + q_{i,e} - q_{i,l}),
\]

where \( c_p \) is the specific heat, \( q_{i,0} \) is the heat source due to absorption of laser radiation, \( q_{i,e} \) is the heat transfer rate due to heat conduction, and \( q_{i,l} \) is the heat transfer rate due to the cooling effect of evaporation. The conduction term in Equation (16) is calculated using the RT method [9] in the form

\[
q_{i,e} = \frac{L}{k_i} F_{e_i} (T_i - T_c),
\]

where \( k_i \) is the thermal conductivity of material in SPH particle \( i \). We obtain the equation for the evaporative cooling term using again the CSF method [9] in the form

\[
q_{i,e} = L_{n} F_{n} (T_i - T_{c}),
\]

where the mass flux density \( F_{n} \) of evaporated material is calculated using Equation (5). The laser heating term is represented in the form

\[
q_{i,l} = \frac{m_i}{\rho_i} \Delta E_i,
\]

where \( \Delta E_i \) is the energy absorbed by SPH particle \( i \) per unit time. This energy \( \Delta E_i \) is calculated using the ray tracing method described in Section 2.3.

Pressure \( p \) in Equation (9) is given by the equation of state [2]

\[
p = \frac{\rho_i c^2}{\gamma} \left[ \left( \frac{\rho_i}{\rho_0} \right)^\gamma - 1 \right],
\]

where \( \gamma = 7 \), \( c \) is the speed of sound in the material, and subscript “0” denotes reference quantities. We use the explicit Euler method for the time integration of Equations (7), (8), and (16). Then value of \( c \) affects the maximum integration time step that is determined by the CFL stability condition,

\[
\Delta t \leq \frac{h}{c}.
\]

In order to perform integration with large time step, it is beneficial, therefore, to use smallest possible value of \( c \) in Equation (20). At small values of \( c \), however, the effect of fluid compressibility becomes pronounced. We performed preliminary simulations of CW laser drilling, where we found that the variation of the molten material density predicted by Equation (7) is below 1% if \( c = 1000 \text{ m/s} \). This value is used in all simulations described below. The determined threshold of compressibility agrees with the analysis presented, e.g., in Ref. [8].

### 2.3 Ray tracing method

The propagation of laser radiation is simulated based on the ray tracing method, when the laser beam is represented by a number of discrete rays or energy packets that travel in space and scattered and attenuated at surface elements that represent pieces of the interphase boundaries or inside the volume of the medium. In this work, we use the RT method for non-participating medium, assuming that individual rays are scattered and attenuated only due to reflections from the SPH particles with \( |C_i| \neq 0 \), which are located in the vicinity of the liquid-vapor interface (Figure 1).

The incident laser beam is divided into a number of rays. Each ray \( k \) is associated with a part \( \Delta A_k \) of the beam area and transfers power \( \Delta Q_k \), which is initially equal to the incident laser power \( I(r_k) \Delta A_k \) corresponding to area \( \Delta A_k \), where laser intensity \( I(r) \) is given by Equation (1) and \( r_k \) is the initial distance of ray \( k \) from the beam center. When ray \( k \) crosses the support domain of SPH particle \( i \), the part of its energy

\[
\Delta E_{ik} = \alpha_i(\theta_{ik}) \Delta Q_k
\]

is assumed to be absorbed by that particle, where \( \alpha_i(\theta_{ik}) \) is the absorptivity coefficient of SPH particle \( i \), which depends on the angle of incidence \( \theta_{ik} \) of ray \( k \). The attenuated ray with energy \( \Delta Q_k' = \Delta Q_k - \Delta E_{ik} \) is reflected from the boundary of the support domain of SPH particle \( i \) following the law of specular reflection,

\[
\hat{a}_k' = \hat{a}_k - \alpha \hat{n}_k \cdot \hat{n}_k \hat{n}_k,
\]

where \( \hat{n}_k \) is the unit normal to the liquid-vapor interface associated with SPH particle \( i \), \( \hat{a}_k \) and \( \hat{a}_k' \) are the unit vectors defining the direction of propagation of ray \( k \) before and after reflection, and \( \alpha = \hat{n}_k \cdot \hat{n}_k \). The ray is traced until its energy \( \Delta Q_k' \) falls below some threshold value or it escapes the

![FIGURE 1: Sketch of cavity in the target material (grey area) and discrete rays (red lines) representing the laser beam and propagating inside the cavity. Only 10 rays are shown in this figure, while 6000 rays are used in actual simulations.](Image)
system. The total laser power $\Delta E_i$ absorbed by SPH particle $i$ in Equation (19) is calculated by summation of $\Delta E_{ik}$ given by Equation (22) for all rays incident to the particle.

The absorptivity of the target material is described by Fresnel equations. For a light beam falling on the material interface at an incident angle $\theta$, the absorptivity is equal to [14]

$$
\alpha_s(\theta) = 1 - \frac{\cos\theta - (n^2 - \sin^2\theta)^{1/2}}{\cos\theta + (n^2 - \sin^2\theta)^{1/2}},
$$

(24)

$$
\alpha_p(\theta) = 1 - \frac{n^2\cos\theta - (n^2 - \sin^2\theta)^{1/2}}{n^2\cos\theta + (n^2 - \sin^2\theta)^{1/2}},
$$

(25)

where the subscripts “$S$” and “$P$” denote values obtained when the electric field is either perpendicular ($S$) or parallel ($P$) to the plane of incidence, and $n$ is the complex index of refraction of the target material. For stainless steel, it is equal to $n = 3.27 + 4.48i$ [15]. In this work, following to common approach, when the polarization of the incident radiation is unknown, the laser radiation is assumed to be circularly polarized and absorptivity is assumed to be equal to an average of $\alpha_s(\theta)$ and $\alpha_p(\theta)$:

$$
\alpha_i(\theta) = \frac{1}{2}[\alpha_s(\theta) + \alpha_p(\theta)].
$$

(26)

Figure 2 shows the absorptivities $\alpha_s(\theta)$, $\alpha_p(\theta)$, and $\alpha_i(\theta)$ for stainless steel as functions of the angle of incidence.

2.4 Combined SPH-RT method

Every time step of the computational algorithm includes two sub-steps, implementing the RT and SPH methods. First, the RT method is applied to calculate $\Delta E_i$ for every SPH particles in Equation (19). The RT calculations are based on the distribution of SPH particles obtained at the end of the previous time step of the computational algorithm. The RT calculations are followed by SPH method which results in updating the density, velocity, and temperature of every SPH particle by integrating Equations (7), (8), and (16). Finally, we use the enthalpy formulation approach to update fluid volume fraction and temperature of every SPH particle. The simulations are performed with an in-house C++ computational code that implements both SPH and RT parts of the combined method and is parallelized based on the MPI communication library.

3. RESULTS AND DISCUSSION

We perform two-dimensional simulations of CW laser drilling of a bulk 316L stainless steel target of size 0.32×0.5 mm (Figure 3). In order to correlate the simulation conditions with typical laser powers used for drilling with cylindrical laser beams, we use the equivalent laser power of a cylindrical beam $P_L$ as an input parameter for all simulations and then calculate the laser intensity $I_L$ for the given half beam size $R_L$ from Equation (2). In simulations, the size parameter of the Gaussian laser beam $2R_L$ is equal to 31.8 $\mu$m and the equivalent laser power $P_L$ varies from 70 W to 210 W, so that the power density $P_L(2D)$ varies, according to Equation (3), from $\sim$1.03 $W/\mu m^2$ to $\sim$3.1 $W/\mu m^2$. The sample is divided into SPH particles which are initially placed in the nodes of a Cartesian mesh with square cells of size $\Delta x$. In order to reveal the effect of $\Delta x$ on the simulation results, we performed simulations with $\Delta x$ varying from 0.5 $\mu$m to 0.0625 $\mu$m. 6000 rays are used to represent the laser beam which extends from $-3R_L$ to $3R_L$. In this case, $\Delta A_k$ is equal to $R_L/1000$ and is constant for all rays. Each ray is terminated when its power becomes smaller than 1% of its initial power. All simulations are performed with the parallel computational code using only 4 CPU cores.

![FIGURE 2](image1.png)  
**FIGURE 2:** Absorptivities $\alpha_s$ (dashed curve), $\alpha_p$ (dash-dotted curve) and $\alpha_i$ (solid curve) of stainless steel as functions of the angle of incidence $\theta$ given by Equations (24)-(26). Values of $\alpha_i(\theta)$ (solid curve) are used in simulations reported in Section 3.

![FIGURE 3](image2.png)  
**FIGURE 3:** Typical shape of the computational domain in simulations of CW laser drilling. The snapshot is obtained for a target of 316L stainless steel heated with CW laser of an equivalent power of $P_L = 210$ W at time $t = 32 \mu s$. Molten and solid materials are colored red and blue, correspondingly.
The use of artificial viscosity given by Equation (11) is necessary in the SPH method in order to suppress numerical instabilities [2]. We found, however, that excessively large artificial viscosity can strongly affect the accuracy of numerical solution in the laser drilling problem. In particular, increasing artificial viscosity reduces the overall melt velocity, which, in turn, decreases the rate of melt expulsion from the keyhole and the keyhole depth. Figure 4 illustrate the effect of $\nu_{art}$ on the keyhole depth during laser drilling at an equivalent laser power of 280 W at different times. The relative change in the keyhole depth is within 10 % if $\nu_{art}/v \leq 35$. The relative change in the keyhole depth with variation of the artificial viscosity is practically independent of the drilling time. If $\nu_{art}$ is further increased, then the difference in the keyhole depth becomes significantly larger. For example, the keyhole depth is underestimated in ~31% if $\nu_{art}/v = 350$. Based on these conclusions, value $\nu_{art}/v = 35$ is adopted for all simulations described below.

Figure 5 shows the convergence of the keyhole depth with decreasing initial inter-particle spacing $\Delta x$ and, correspondingly, increasing number of SPH particles representing the target material. For this study, smaller sample of size 0.16x0.32 mm is used, so that the total number of SPH particle increases from 204800 to 13107200 when spacing $\Delta x$ decreases from 0.5 $\mu$m to 0.0625 $\mu$m. At the considered laser power $P_L = 280$ W, the drilling process is rapid. One can see that the keyhole depth is only marginally affected by the SPH particle spacing if $\Delta x < 0.5$ $\mu$m. The difference in the keyhole depth becomes insignificant when $\Delta x < 0.125$ $\mu$m. Since at small $\Delta x$ the maximum time step given by the stability condition in Equation (21) becomes excessively small, we chose value $\Delta x = 0.25$ $\mu$m for further simulations, which ensures calculations of the keyhole depth with the difference less than 2% compared to case of $\Delta x = 0.0625$ $\mu$m.

The shape of the cavity obtained at $P_L = 210$ W by a time of 32 $\mu$s with the chosen major numerical parameters of the SPH method is shown in Figure 3. At this laser power, the melt temperature at the spot center reaches ~3800 K and the vapor pressure raises up to 10 bar, providing strong repulsive effect on the melt pool and inducing velocities of about 16 m/s along the keyhole surface. The strong melt expulsion reduces the thickness of the molten pool, which becomes barely visible at the keyhole center. The material expelled from the keyhole forms a “crown” that is detaching from the surface with formation of a peripheral liquid jet. The detached part of the crown is disintegrated into droplets. Although the disintegration of the liquid crown is in agreement with experimental observations, the current simulations cannot predict this process quantitatively due to 2D nature of the computational model and insufficiently fine discretization of the molten pool.

With increasing $P_L$, the surface temperature increases more rapidly. It results, in turn, in higher recoil pressure at the center of the laser beam. The increased pressure difference between the center and periphery of the molten pool enhances tangential velocity of the molten material, especially close to the free surface, and increases the overall rate of laser drilling (Figure 6). We attribute strongly inhomogeneous velocity distribution across the layer of the molten material inside the keyhole to the Marangoni stresses. At the smallest laser power of 105 W considered in Figure 6, the molten material is not fully detached from the target, but forms a rim at the edges of the keyhole. With increasing laser power, the free surface of the jet inside the keyhole becomes unstable with formation of an irregular “landscape.” Such irregularities are usually seen on the internal surfaces of high-aspect ratio cavities obtained by CW laser drilling.
At a given time, the keyhole depth almost linearly increases with laser power in the considered range of \( P_L \). At a fixed \( P_L \), the keyhole depth also linearly increases with time at \( t \equiv 20 \pm 35 \) \( \mu s \) (Figure 7). It is expected, however, that the drilling rate will drop with increasing drilling time and keyhole depth due to the distribution of laser energy over gradually increasing area of the quasi-conical keyhole wall. This effect is only barely visible during the time considered in Figure 7, where, e.g., one can notice a decrease in the slope of the curves corresponding to \( P_L = 175 \) \( W \) and \( P_L = 210 \) \( W \) at \( t > 20 \) \( \mu s \).

In order to verify the ability of the developed computational methodology to simulate the SLM of metal powders, we applied our combined SPH-RT method for 2D simulations of CW laser melting of a layer of cylindrical

**FIGURE 6:** Fields of temperature (a,c,e) and absolute velocity (b,d,f) obtained by a time of 26 \( \mu s \) in simulations of laser drilling with different equivalent powers: (a,b), \( P_L = 105 \) \( W \); (c,d), \( P_L = 175 \) \( W \); and (e,f), \( P_L = 210 \) \( W \).

**FIGURE 7:** Cavity (keyhole) depth versus time for various laser powers of an equivalent cylindrical beam \( P_L \).

**FIGURE 8:** Snapshots obtained in 2D simulation of selective laser melting of 316L stainless steel powders using CW laser with an equivalent power of 280 \( W \) and scan speed of 1.5 \( m/s \). In panel (a), the molten and solid material are colored red and blue, correspondingly. Panels (b) and (c) show the temperature and velocity fields.
particles with a diameter of 54 μm on a substrate of size 250 μm × 650 μm (Figure 8). The material of both the powder particles and substrate is stainless steel 316L. The particles are irradiated by a CW laser with equivalent power \( P_L = 280 \text{ W} \) and half-size \( R_L = 15.9 \mu m \), moving from the left to the right with a scan speed of 1.5 ms\(^{-1}\). These process parameters are similar to parameters of physical experiments in [1]. The numerical parameters, including the initial SPH particle spacing \( \Delta x \), artificial viscosity coefficient, and number of discrete rays are chosen to be identical to these in the laser drilling simulations. In comparison to the CW laser drilling with a motionless laser, the non-zero laser scan speed results in asymmetry of the keyhole with respect to the laser beam center and increased thickness of the molten pool behind the laser beam. The moving laser also induces strongly non-symmetrical fields of temperature and velocity, when the maximum temperature and velocity are shifted with respect to the beam center in the direction of its motion, i.e. located on the right side of the keyhole in Figure 8. These finding are in qualitative agreements with results of simulations obtained in Ref. [1] based on a sophisticated three-dimensional (3D) model of laser melting.

4. CONCLUSION

The computational method combining the SPH method for molten material flow and RT method for radiation propagation and absorption is found to be a computationally effective and robust tool for studying CW laser melting problems, such as laser drilling and SLM. The first results on the dynamics of the molten pool obtained with this method in 2D simulations are found to be in qualitative agreement with experimental results and computational results obtained based on more sophisticated 3D computational models. Our ongoing work is focused on extension of our computational code for 3D simulations of deep laser drilling and 3D particle-resolved simulations of SLM.

ACKNOWLEDGMENTS

This work is supported by the NSF (projects CMMI-1554589 and CMMI-1663364). The computational support is provided by the Alabama Supercomputer Center.

REFERENCES