SOLID-LIQUID-VAPOR PHASE CHANGE OF A SUBCOOLED METAL POWDER PARTICLE SUBJECT TO NANOSECOND LASER HEATING

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Solid-liquid-vapor phase change of a metal particle subjected to nanosecond pulse laser heating is investigated analytically. Temperature distribution in the particle, locations of solid-liquid and liquid-vapor interface, saturation temperature, and recoil pressure around the particle were obtained analytically. Effects of physical parameters including laser fluence, pulse width, initial temperature, and particle diameter on the phase change were investigated. The results show that a decrease in particle radius and laser pulse width, or an increase in laser fluence and initial particle temperature, results in an earlier melting time, a higher surface temperature, more evaporated material, and a higher final thermalized temperature.

KEY WORDS: melting, solidification, evaporation, laser

INTRODUCTION

Selective laser sintering (SLS) is a rapid manufacturing/tooling technology that can fabricate structurally sound parts from powdered material using a directed laser beam. It allows manufacture of complex parts unobtainable by more common manufacturing processes [1, 2]. During the SLS process a laser beam scans the surface of a powder bed to melt the powder, and the interstitial gases among particles are driven out by the formed liquid metal. As the laser beam moves away, the liquid resolidifies into a solid and a layer of object is built. This process is repeated and a solid object can be fabricated layer by layer.

One obstacle of SLS of metallic powder is the balling phenomenon, in which melted powder grains stick to each other via surface tension forces, thereby forming a series of spheres with diameters approximately equal to the diameter of the laser beam [1, 3]. One approach to overcome the balling phenomenon is to use a powder bed consisting of two different types of metal powders with a significantly different melting point [4]. The powder with higher melting point will not melt, breaking up the surface tension forces and forcing out the interstitial gases as desired. Melting of
infinite and finite two-component metal powder beds subjected to constant heat flux was investigated by Zhang and Faghri [5] and Chen and Zhang [6]. An analytical solution of melting and resolidification of a two-component metal powder subjected to temporal Gaussian heat flux was obtained by Konrad et al. [7].

Another approach to minimize the balling effect is to use a pulsed laser to effectively decrease life span of the liquid and thus to avoid the balling effect. Pulsed lasers with pulse widths ranging from milliseconds [8, 9] to nanoseconds [10–12] have been investigated. Evaporation recoil force during nanosecond laser sintering can overcome the surface tension force acting on the melt, therefore improving the cohesion of the powder particles. SLS under a pulsed laser can also result in higher lateral precision due to its shorter wavelength. Sintering is achieved at moderate laser powers, typically below 10 W, which can introduce less residual stress in the workpiece [12, 13].

Fischer et al. [13] investigated a pulsed laser sintering by numerically solving heat conduction in a single grain of the powder bed under nanosecond laser heating. Konrad et al. [14] analyzed melting and resolidification of a subcooled spherical metal powder particle subjected to nanosecond laser heating. With increased laser pulse fluence or reduced pulse width, the surface temperature of a powder particle may reach the saturation temperature and vaporization may occur. Vaporization creates a recoil pressure, which in turn results in a higher saturation temperature. Therefore, vaporization takes place at a at a saturation temperature that is higher than the normal saturation temperature.

In order to discover the advantages of utilizing a short-pulsed laser in an SLS process, melting, vaporization, and solidification of a single powder particle subjected to nanosecond pulsed laser heating will be investigated in this article. Effect of recoil pressure on the saturation temperature will also be considered using the Clausius/Clapeyron equation. The effects of laser fluence, pulse width, initial temperature, and particle size on the solid-liquid-vapor phase change will also be investigated.

**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
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<tbody>
<tr>
<td>$h_f$</td>
<td>latent heat of fusion, $J \cdot kg^{-1}$</td>
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<tr>
<td>$h_v$</td>
<td>latent heat of vaporization, $J \cdot kg^{-1}$</td>
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<tr>
<td>$k$</td>
<td>thermal conductivity, $W \cdot m^{-1} \cdot C^{-1}$</td>
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<td>$q'$</td>
<td>heat flux, $W \cdot m^{-2}$</td>
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<td>$R_g$</td>
<td>gas constant, $J \cdot kg^{-1} \cdot K$</td>
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<td>$s_i$</td>
<td>solid-liquid interface location, $m$</td>
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<td>$s_l$</td>
<td>liquid-vapor interface location, $m$</td>
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<td>$t$</td>
<td>time, $s$</td>
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<td>$t_m$</td>
<td>time at which melting begins, $s$</td>
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<tr>
<td>$t_p$</td>
<td>half width of the laser beam pulse at $q'_0/2$, $s$</td>
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<tr>
<td>$t_r$</td>
<td>time at which melting and resolidification begins (when vaporization ends)</td>
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<tr>
<td>$t_s$</td>
<td>time at which solidification ends, $s$</td>
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<tr>
<td>$t_v$</td>
<td>time at which vaporization begins, $s$</td>
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<tr>
<td>$x$</td>
<td>coordinate measured from the particle surface, $m$</td>
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**Greek Symbols**

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<td>thermal diffusivity, $m^2 \cdot s^{-1}$</td>
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<tr>
<td>$\delta$</td>
<td>thermal penetration depth, $m$</td>
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<tr>
<td>$b_s$</td>
<td>thickness of thermal layer at the time at which solidification ends, $m$</td>
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<tr>
<td>$\gamma$</td>
<td>specific heat ratio</td>
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<tr>
<td>$\theta$</td>
<td>$(T - T_i)$, relative temperature, $^oC$</td>
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<td>$\rho$</td>
<td>density, $kg \cdot m^{-3}$</td>
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<tr>
<td>$\tau$</td>
<td>relative time, $nt_p$</td>
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**Subscripts**

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<tr>
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<td>$sat$</td>
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PHYSICAL MODEL

In this article, preheating, melting, vaporization, melting and resolidification, and thermalization of a single powder particle subjected to a nanosecond pulsed laser heating will be modeled. Temporal Gaussian heat flux of a laser beam is considered and the origin of time is chosen to be at the time when the heat flux is at its maximum (see Figure 1).

\[ q''(t) = q_0^0 e^{-\frac{\ln^2 2}{\gamma_p}} \]  

where \( q_0^0 \) is the maximum heat flux, and \( t_p \) is the half-width of the laser pulse at half maximum.

The diameter of the metal powder particle is much smaller than the diameter of the laser beam, which is in turn much smaller than the dimension of the final part. Since the laser radiation penetrates the powder bed over a distance of several powdersphere diameters, it can be assumed that multiple scattering of the radiation leads to a nearly homogeneous distribution of the heat flux within the optically penetrated layer [13]; this leads to an almost normal incidence of the radiation on the surfaces of the grains in the underlying layers. Figure 1 shows the physical model of solid-liquid-vapor phase change process under consideration. Because of symmetry of the spherical particle as well as the assumption of uniform heat flux distribution around the particle, the problem can be assumed to be 1-D in the \( r \)-direction. The heat flux at the particle surface, \( q'' \) (W/m²) can be related to the total energy flux by one pulse, or the laser fluence \( J \) (J/m²) by:

\[ J = \int_{-\infty}^{\infty} q''(t)dt = \int_{-\infty}^{\infty} q_0^0 e^{-\frac{\ln 2^2 \gamma_p}{\gamma_p}} dt = 2q_0^0 t_p \frac{\sqrt{\pi}}{\sqrt{\ln 2}} \]  

Providing sufficient pulse energy, a single power particle in the SLS process may undergo five stages: (1) preheating, (2) melting, (3) vaporization, (4) melting and resolidification, and (5) thermalization. The powder particle absorbs pulse

![Figure 1. The physical model.](image-url)
energy during the preheating stage to raise its surface temperature to the melting point. During the melting stage, the skin of the particle melts and forms a thin layer of liquid on the surface of the sphere. If the surface temperature of the grain reaches saturation temperature before the heat flux reaches its peak value, evaporation will occur at the liquid surface and process enters the third stage—vaporization. After the heat flux reaching its peak value, the liquid surface temperature begins to decrease. When the surface temperature decreases to the saturation temperature corresponding to the atmospheric pressure, the vaporization stage ends while melting may continue and the process enters its fourth stage—melting and resolidification. Melting continues for a while before resolidification occurs. The solid sphere interior acts as a heat sink, and the liquid phase solidifies. When the liquid layer is completely solidified, thermalization begins until the temperature becomes uniform throughout the particle.

The density change during melting is neglected and the melting point of the metal powder is constant in the entire process. The radiation and convection from the liquid skin of the particle are neglected, meaning that the excess heat of the liquid must be dissipated in the form of conduction into the powder grain for the melt layer to resolidify. Evaporated surface materials during the vaporization stage will be driven out and cannot condensate after this stage. All physical properties of the powder particle, such as conductivity, density and so on, are independent of temperature during all stages.

**Governing Equations**

**Preheating Stage \((t < t_m)\)** Heat transfer of the particle in the preheating stage can be described as a pure conduction problem. The heat conduction equation in the particle \((0 \leq x \leq r_0)\) is

\[
\frac{\alpha_s}{(r_0 - x)^2} \frac{\partial}{\partial x} \left( (r_0 - x^2) \frac{\partial \theta_s}{\partial x} \right) = \frac{\partial \theta_s}{\partial t}
\]

where \(\theta = T - T_i\) is the relative temperature. Equation (3) is subject to the following initial and boundary conditions

\[
\theta_s = 0, \quad 0 \leq x \leq r_0, \quad t \to -\infty
\]

\[
\frac{\partial \theta_s}{\partial x} = 0, \quad x = r_0
\]

\[
-k_t \frac{\partial \theta_s}{\partial x} = q^* (t), \quad x = 0
\]

**Melting Stage \((t_m \leq t < t_v)\)** The governing equation in the liquid phase \((0 \leq x \leq s_v)\) is

\[
\frac{\alpha_l}{(r_0 - x)^2} \frac{\partial}{\partial x} \left( (r_0 - x^2) \frac{\partial \theta_l}{\partial x} \right) = \frac{\partial \theta_l}{\partial t}
\]
which is subject to the following boundary condition

\[-k_l \frac{\partial \theta_l}{\partial x} = q^*(t), \quad x = 0\]  

(8)

Equations (3) and (5) are applicable in the solid phase \((s_s \leq x < r_0)\). The boundary conditions at the solid-liquid interface are

\[
\begin{align*}
\theta_s(x, t) &= \theta_l(x, t) = T_m - T_i, \quad x = s_s(t) \\
-k_l \frac{\partial \theta_l}{\partial x} + k_s \frac{\partial \theta_s}{\partial x} &= \frac{d s_s}{d t} h_d \rho_s, \quad x = s_s(t)
\end{align*}
\]

(9)\hspace{1cm}(10)

**Vaporization Stage** \((t_v \leq t < t_r)\) The energy balance equation for liquid-vapor interface is

\[
\rho_l h_l \frac{\partial s_l}{\partial t} - k_l \frac{\partial \theta_l}{\partial x} = q''(t), \quad x = s_l(t)
\]

(11)

The energy equation of liquid phase is still Eq. (7) but the boundary condition at the liquid surface becomes

\[
\theta_l(x, t) = T_{sat} - T_i, \quad x = s_l(t)
\]

(12)

It should be pointed out that the saturation temperature, \(T_{sat}\), corresponds to the recoil pressure created by vaporization. Equations (3) and (5) can be applied in the solid phase and the boundary condition at the solid-liquid interface are still Eqs. (9) and (10).

**Melting and Resolidification Stage** \((t_r \leq t < t_s)\) The governing equations of the melting and resolidification stage are the same with those of the melting stage. It is worth noting that the diameter of the particle \(r_0\) is decreased due to evaporation in the previous stage.

**Thermalization Stage** \((t > t_s)\) At the end of resolidification stage, the particle becomes a solid grain. While Eq. (3) is still valid for the thermalization stage, the initial temperature of this stage is the final temperature of the resolidification stage. Since the resolidification stage is not complete until several pulse widths after the peak heat flux at the surface occurs, the laser beam’s Gaussian distribution allows for the assumption that heat flux at the surface is negligible at this very late time in the simulation. The boundary condition at the surface of the particle becomes

\[
\frac{\partial \theta_s}{\partial x} = 0, \quad x = r_0, \quad t > t_s
\]

(13)

**INTEGRAL APPROXIMATE SOLUTION**

When the surface of the particle is exposed to a heat flux, heat will penetrate the surface and conduct inward. The depth to which the heat flux has penetrated is called
the thermal penetration depth, $\delta$, beyond which the temperature is equal to the initial temperature. The following two boundary conditions are valid for all stages.

$$\theta_s = 0, \quad x \geq \delta(t), \quad t > -\infty$$  \hspace{1cm} (14)

$$\frac{\partial \theta_s}{\partial x} = 0, \quad x \geq \delta(t), \quad t > -\infty$$  \hspace{1cm} (15)

**Preheating and Melting Stages**

The preheating and melting stages can be solved using an integral approximate method [14]. The thermal penetration depth during preheating can be obtained from

$$\frac{1}{60} \delta^4 e^{-\ln^2 2 \frac{x^2}{\rho}} - \frac{1}{12} \delta^3 r_0 e^{-\ln^2 2 \frac{x^2}{\rho}} + \frac{1}{6} \delta^2 r_0^2 e^{-\ln^2 2 \frac{x^2}{\rho}} - \frac{\alpha r_0^2 \tau_p \sqrt{\pi}}{2 \sqrt{\ln 2}} \left[1 + \text{erf} \left( \sqrt{\ln 2} \frac{t}{\tau_p} \right) \right] = 0$$ \hspace{1cm} (16)

which only has one root that is real and positive. The temperature distribution in the particle during the preheating stage is

$$\theta_s(x, t) = \frac{q_0^2 (\delta - x)^2}{2 k_s \delta} e^{-\ln^2 2 \frac{x^2}{\rho}}, \quad \delta < r_0, \quad t < t_m$$ \hspace{1cm} (17)

During the melting stage, the thermal penetration depth $\delta$ satisfies

$$\delta^3 + \delta^2 (-5r_0 + 2s) + \delta(10r_0^2 - 10r_0s + 3s^2)$$

$$+ \left[20r_0^2s - 15r_0s^2 + 4r_0^2 + 10r_0^2 \delta_m + 5r_0 \delta_m - \delta_m^3 - 60 \alpha_s \int \frac{(r_0 - s)^2}{(\delta - s)} dt \right] = 0$$ \hspace{1cm} (18)

where $\delta_m$ is the value of $\delta$ at the time of melting stage begins. The locations of the solid-liquid interface can be obtained from

$$s_s = \frac{q_0^2 r_0^2}{h_{sf} \rho_s} \int_{l_m}^{l} \frac{1}{(r_0 - x)^2} e^{-\ln^2 2 \frac{x^2}{\rho}} dt - \frac{2k_s (T_m - T_i)}{h_{sf} \rho_s} \int_{l_m}^{l} \frac{1}{\delta - s_s} dt$$ \hspace{1cm} (19)

The temperature distributions in the solid and liquid phases are

$$\theta_s(x, t) = \frac{(T_m - T_i)}{(\delta - s)^2} (\delta - x)^2, \quad t_m < t < t_s$$ \hspace{1cm} (20)

$$\theta_l(x, t) = \frac{q_0^2 r_0^2}{k_l} e^{-\ln^2 2 \frac{x^2}{\rho}} \left( \frac{1}{r_0 - s} - \frac{1}{r_0 - x} \right) + (T_m - T_i), \quad t_m < t < t_s$$ \hspace{1cm} (21)
Vaporization Stage

To get the solution of the vaporization stage, it is necessary to solve heat transfer in solid and liquid phases, as well as locations of liquid-vapor and solid-liquid interfaces.

**Heat Conduction in Solid Phase** Integrating both sides of Eq. (3) with respect to \( x \) from \( s_s \) to \( \delta \), and employing Eqs. (6), (14), and (15), one obtains

\[
\frac{\partial}{\partial t} \int_{s_s}^{\delta} \theta_s(r_0 - x)^2 dx + (T_m - T_l)(r_0 - s_s)^2 \frac{ds_s}{dt} = -\alpha_s (r_0 - s_s) \frac{\partial \theta_s}{\partial t} \bigg|_{x=s_s} \tag{22}
\]

Assuming the temperature profile of solid phase is a second degree polynomial function and invoking boundary conditions, Eqs. (6), (14), and (15), to solve the unknown coefficients, the temperature in the solid phase becomes

\[
\theta_s(x, t) = \frac{(T_m - T_l)(x - \delta)^2}{(s_s - \delta)^2} \tag{23}
\]

Substituting Eq. (23) into Eq. (22) gives

\[
\frac{d}{dt} \left(-10r_0^2s_s + 15r_0s_s^2 - 6s_s^3 + 10r_0^2\delta - 10r_0s_s\delta + 3s_s^2\delta - 5r_0\delta^2 + 2s_s\delta^2 + \delta^3\right)
+ 30(r_0 - s_s)^2 \frac{ds_s}{dt} = -60\alpha_s \frac{(r_0 - s_s)^2}{(s_s - \delta)} \tag{24}
\]

Integrating both sides of Eq. (24) with respect to \( t \) from \( t_v \) to \( t \), and collecting terms of \( \delta \), yielding

\[
\delta^3 + \delta^2(-5r_0 + 2s_s) + \delta(10r_0^2 - 10r_0s_s + 3s_s^2)
+ \begin{bmatrix}
20r_0^2(s_s - s_{sv}) - 15r_0(s_s^2 - s_{sv}^2) + 4(s_s^3 - s_{sv}^3) - 10r_0^2\delta_v + \\
10r_0s_{sv}\delta_v - 3s_{sv}^2\delta_v + 5r_0\delta_v^2 - 2s_{sv}\delta_v^2 - \delta_v^3 - 60\alpha_s \int_{t_v}^{t} \frac{(r_0 - s_s)^2}{(s_s - s_{sv})} dt
\end{bmatrix} = 0 \tag{25}
\]

where \( s_{sv} \) and \( \delta_v \) are the values of \( s_s \) and \( \delta \) at the time when the vaporization begins.

**Melting and Vaporization** Assuming the temperature distribution function is \( \theta_l(x, t) = A_l/(r_0 - x) + B_l \) and using Eqs. (9) and (12) to solve unknown coefficients, one obtains

\[
\theta_l(x, t) = T_{sat} - T_l + \frac{(T_{sat} - T_m)(r_0 - s_s)(x - sl)}{(r_0 - x)(sl - s_s)} \tag{26}
\]
Substituting Eqs. (1) and (26) into Eq. (11) and integrating the resulting equation with respect to \( t \) in from \( t_v \) to \( t \), one obtains

\[
sl = \frac{1}{\rho_l h_{lv}} \left[ \int_{t_v}^{t} q_0' e^{-\frac{h_{p0}}{R_g T_{sat}} T_{sat}'} dt + k_l \int_{t_v}^{t} \frac{(T_{sat} - T_m)(r_0 - s_l)}{(r_0 - s_l)(s_l - s_l)} dt \right] \tag{27}
\]

Substituting Eqs. (23) and (26) into Eq. (10) and integrating the resulting equation with respect to \( t \) in from \( t_v \) to \( t \), one obtains

\[
s_s = \frac{1}{\rho_s h_{sl}} \left[ 2k_s \int_{t_v}^{t} \frac{(T_m - T_s)}{(s_s - \delta)} dt - k_l \int_{t_v}^{t} \frac{(T_{sat} - T_m)(r_0 - s_l)}{(r_0 - s_l)(s_l - s_l)} dt \right] + s_{sv} \tag{28}
\]

where \( s_{sv} \) is the value of \( s_s \) at the time when the vaporization begins.

**Saturation Temperature and Recoil Pressure** The vaporization creates a recoil pressure around the particle sphere, which in turn increases the saturation temperature for vaporization. The dependence of saturation temperature on the surface heat flux can be obtained by using Clausius/Clapeyron equation and a gas dynamic model [17, 18]:

\[
\frac{\gamma + 1}{\gamma h_{lv}} \sqrt{\gamma R_g T_{sat}} \left( q'' + k_l \frac{\partial \theta_l}{\partial x} \right) = p_0 \exp \left[ \frac{h_{lv}}{R_g} \left( \frac{1}{T_{sat,0}} - \frac{1}{T_{sat}} \right) \right] \tag{29}
\]

where \( p_0 \) is atmospheric pressure, and \( T_{sat,0} \) is saturation temperature at this pressure.

Substituting Eqs. (1) and (26), into Eq. (29), one obtains

\[
T_{sat} = \frac{(s_l - s_s)(r_0 - s_l)}{k_l(r_0 - s_s)} \left\{ \frac{\gamma h_{lv} p_0}{(\gamma + 1) \sqrt{\gamma R_g T_{sat}}} \exp \left[ \frac{h_{lv}}{R_g} \left( \frac{1}{T_{sat,0}} - \frac{1}{T_{sat}} \right) \right] - q''_0 e^{-\frac{2h_{p0}}{R_g T_{sat}}} \right\} + T_m
\]

which must be solved iteratively because \( T_{sat} \) appears on both sides.

The vaporization stage is described by four nonlinear equations (25), (27), (28), and (30), for four unknowns: \( \delta, s_s, s_l, \) and \( T_{sat} \). They can be solved iteratively with underrelaxation.

**Melting and Resolidification Stage and Thermalization Stage**

Since the governing equations for the melting and solidification stage is the same as those of the melting stage, the solution for this stage is also the same as that of the melting stage except the radius of the particle is decreased due to surface evaporation. Heat transfer during the thermalization stage is a pure conduction problem with the final temperature of the melting and resolidification stage as its initial temperature. The integral approximate solution used in the preheating stage cannot be directly used
since the initial temperature of this stage is not uniform. The heat conduction problem during thermalization is divided into two subproblems: \( \theta = \theta_1 + \theta_2 \), where both \( \theta_1 \) and \( \theta_2 \) satisfy Eq. (3). At the power particle surface (\( x = s_{cv} \), where \( s_{cv} \) is the thickness of materials evaporated), the boundary condition are \( \partial \theta_2 / \partial x = \partial \theta_1 / \partial x = 2 (T_m - T_i) (\delta_s - S_{cv}) \) to ensure adiabatic condition at the surface. Both subproblems can be solved using an integral approximate solution and the temperature distribution can be obtained by summing solutions of two subproblems [14].

RESULTS AND DISCUSSION

The impacts of laser fluence \( J \), pulse width \( r_p \), initial temperature \( T_i \), and particle diameter \( r_0 \) on the phase change of a titanium powder particle will be investigated. Figure 2a shows the surface temperature during preheating stage of an 11-\( \mu \)m titanium particle under nanosecond laser heating. It can be seen that the particle surface reaches melting temperature at a very early stage of the first laser pulse. Figure 2b shows the location of the thermal penetration depth \( \delta \) during the same preheating stage. At the end of preheating stage, the thermal penetration depth is far from the particle center.

Figure 3 shows the effect of a change in laser fluence \( J \) on the temperature at the surface of the powder grain in all stages. Since the width of the laser pulse is fixed, the surface heat flux \( q'_0 \) increases with increasing laser fluence \( J \), as can be seen from Eq. (2). When laser fluence increases, the surface temperature increases significantly and the time it takes for the liquid skin of the particle to solidify also increases. The thermalization period becomes longer under higher energy fluence. Figures 4a and b show the effect of laser fluence on the locations of solid-liquid and liquid-vapor interfaces. It can be seen that increasing laser fluence shortens the preheating time,
increases melt thickness, and increases the amount of liquid evaporated. Since the latent heat of vaporization for titanium is one order of magnitude larger than that for melting, the thickness of evaporated powder surface is much less than that of liquid layer. Figure 5 shows variation of saturation temperature and recoil pressure for different laser fluence. Clearly, large laser fluence results in higher saturation

![Figure 3](image_url)

**Figure 3.** Effect of laser fluence on the surface temperature ($\tau_p = 50$ ns, $r_0 = 11$ $\mu$m, $T_i = 800$ K).

![Figure 4](image_url)

**Figure 4.** Effect of laser fluence on the locations of the solid-liquid and the liquid-vapor interfaces ($\tau_p = 50$ ns, $r_0 = 11$ $\mu$m, $T_i = 800$ K).
temperature and recoil pressure. The recoil pressure is much larger than atmospheric pressure in all cases, thus it is necessary to consider the effect of variation of saturation temperature versus recoil pressure.

Figure 6 shows the effect of laser pulse width, $t_p$, on the surface temperature of the particle while the laser fluence, $J$, is held constant. By observing Eq. (2) one sees that at the same relative time ($t/t_p$), the particle will receive identical heat flux. However, the surface temperature of the particle is higher with shorter pulse width than that with larger pulse width. The reason is that with decreasing pulse width, the changing rate of heat flux becomes faster, which results in thinner thermal penetration depth, and therefore absorbed energy per volume in thermal layer of the particle is increased. Figure 7 shows the effect of laser pulse width on the locations of solid-liquid and liquid-vapor interfaces. It can be seen that thicker liquid skin before vaporization and deeper liquid-vapor interface during the vaporization stage are obtained in the case of shorter pulse width. However, from the beginning to the ending of vaporization, the thickness of the liquid skin is decreased with decreasing pulse width. Since more energy is taken off by the surface evaporation in this case, and considering that laser fluence is held constant, the energy absorbed by liquid phase will be reduced, which leads to thinner liquid skin. Figure 8 shows the effects of laser pulse width on the saturation temperature and the recoil pressure, both of which increase significantly with decreasing laser pulse width.

The effects of the initial temperature of the particle on the heat transfer phase change are shown in Figures 9–11. When the initial temperature is increased, it will take less time for powder surface temperature to reach the melting point and the melting stage occurs earlier. Consequently, more energy will be absorbed during the melting and vaporization stages. The liquid skin becomes thicker and the amount of
the evaporated material also increases with higher initial temperature, as can be seen from Figure 10. The time it takes for particles to resolidify and cool down is longer for higher initial temperature. Considering that evaporated portion of power surface takes away part of the input energy, the final energy absorbed by the particle is not...
the same for different initial temperatures. Hence, the differences among the final temperatures are slightly less than that of initial temperatures. The saturation temperature and recoil pressure also increase with increasing initial temperature as shown in Figure 11.

Figure 8. Effect of laser pulse width on the saturation temperature and recoil pressure ($J = 12,000 \text{ J/m}^2$, $r_0 = 11 \text{ \mu m}$, $T_i = 800 \text{ K}$).

Figure 9. Effect of the initial particle temperature on the surface temperature ($J = 12,000 \text{ J/m}^2$, $\tau_p = 50 \text{ ns}$, $r_0 = 11 \text{ \mu m}$).
Figure 10. Effect of initial particle temperature on the locations of the solid-liquid and the liquid-vapor interfaces ($J = 12,000 \text{ J/m}^2$, $\tau_p = 50 \text{ ns}$, $r_0 = 11 \text{ mm}$).

Figure 11. Effect of initial particle temperature on the saturation temperature and recoil pressure ($J = 12,000 \text{ J/m}^2$, $\tau_p = 50 \text{ ns}$, $r_0 = 11 \text{ mm}$).
The effect of powder particle size on the heat transfer and phase change is shown in Figures 12–14. A smaller powder particle will reach a higher surface temperature than that of a larger one. The final temperature of the small particle is higher than that of a larger particle. A smaller sphere cools faster than a larger sphere because the heat has less material to penetrate. Figure 13a shows that the size of the powder particle does not have a significant effect on the time when melting begins; however, a smaller powder particle experiences longer melting period than that of a larger one and thus takes longer to resolidify. The vaporized thickness increases with decreasing particle size as can be observed from Figure 13b. Figure 14 shows the effect of particle size on the saturation temperature and the recoil pressure. It can be seen that both of them increase with decreasing particle size.

CONCLUSION

Solid-liquid-vapor phase change in a subcooled powder particle with temporal Gaussian heat flux during process of SLS was investigated analytically. It is obvious that the laser fluence is the most important processing parameter, which determines the energy absorbed by a particle. However, other parameters, such as pulse width, initial temperature, and particle diameter, also have an effect on the results of the phase change process. An earlier melting time, a higher surface temperature, more evaporated material, and a longer solidification time can result from a decrease in either particle radius or laser pulse width or an increase in either laser fluence or initial particle temperature. High recoil pressure around the particle during the vaporization stage is observed, and it is possible the reason for that SLS process can benefit from particles evaporation, and further study is needed for this stage. The physical model and results of this investigation pave the way for further modeling of SLS processes with a pulsed laser.
Figure 13. Effect of particle size on the locations of the solid-liquid and liquid-vapor interfaces ($J = 12,000 \text{ J/m}^2$, $\tau_p = 50 \text{ ns}$, $T_i = 800 \text{ K}$).

Figure 14. Effect of particle size on the saturation temperature and recoil pressure ($J = 12,000 \text{ J/m}^2$, $\tau_p = 50 \text{ ns}$, $T_i = 800 \text{ K}$).
REFERENCES


