Three-Dimensional Modeling of Laser Sintering of a Two-Component Metal Powder Layer on Top of Sintered Layers

A three-dimensional model of selective laser sintering of a two-component loose metal powder layer on top of previously sintered layers by a single-line laser scanning is presented. A temperature-transforming model is employed to model melting and resolidification accomplished by partial shrinkage during laser sintering. The heat losses at the top surface due to natural convection and radiation are taken into account. The liquid flow of the molten low-melting-point metal powders, which is driven by capillary and gravity forces, is also considered and formulated by using Darcy’s law. The effects of the dominant processing parameters, such as laser-beam intensity, scanning velocity, and number of the existing sintered layers underneath, are investigated.

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Introduction

Selective laser sintering (SLS) is a layered manufacturing technique that creates solid, three-dimensional objects by fusing powder materials with a moving laser beam [1]. During the SLS process, a thin (100–250 μm thick) powder layer is laser scanned to fuse the two-dimensional slice to an underlying solid piece, which consists of a series of stacked and fused two-dimensional slices. After laser scanning, a fresh powder layer is spread and the scanning process is repeated. Loose powder is removed after the part is extracted from its bin. A brief review of the basic principles of SLS machine operation, and materials issues affecting direct SLS of metals and the resultant properties and microstructures of the parts are discussed by Agarwala et al. [2]. An overview of the latest progress in selective laser sintering work as reported in various journals and proceedings is presented by Kumar [3].

Melting and resolidification are the mechanisms that bond metal powder particles to form a layer and also bond different layers together to form a functional part. Fundamentals of melting and solidification have been investigated extensively and detailed reviews are available in the literature [4–6]. In SLS process, particle melting by laser irradiation will result in formation of convective streams caused by surface tension and buoyancy force within the molten pool. The fluid flow plays an important role in the temperature distribution and the shape of the liquid pool. The existing models on laser processing of nonporous materials indicated that the effect of fluid flow on pool shape and temperature distribution is significant [7,8]. Kou and Wang [7] developed a three-dimensional convection model in the coordinate system that moves with the laser beam. Fluid flow driven by buoyancy force and surface tension gradient was considered. The model demonstrated that the surface tension temperature coefficient could significantly affect both the convection pattern and the penetration of laser-melted pool. Li et al. [8] studied the convection-diffusion phase-change process during laser melting of ceramic materials. Results by the pure heat conduction model, heat conduction model incorporating latent heat of fusion, and model involving both latent heat of fusion and fluid were compared. They demonstrated that the best prediction accuracy for the melt/solid interfaces can be achieved by considering both the latent heat of fusion and fluid flow in the melt pool.

The distinctive feature of laser-induced melting of the metal powders is that it is always accompanied by shrinkage due to the significant density change. When a single-component powder is used in the SLS process, the “balling” phenomenon caused by the use of inappropriate laser-processing parameters leads to the formation of spheres with diameters approximately equal to the size of the laser beam [9,10]. The adjustment of SLS parameters must be rather strict in order to prevent the “balling” phenomenon. There are several ways the balling phenomenon can be combated. As suggested by Bunnell [11] and Manzur et al. [12], one of which is to use a powder bed consisting of different types of metal powder, one with a significantly higher melting point than the other. If such a mixture is used, then the higher-melting-point powder will not melt, breaking up the surface tension forces and forcing out the interstitial gasses as desired. A molten liquid formed by melting the lower-melting-point powders infiltrates into the voids between the higher melting point powder particles and binds them together.

A one-dimensional thermal model of melting of the two-component powder bed was presented by Pak and Plumb [13], in which the liquid motion driven by capillary and gravity forces was considered but the shrinkage was neglected. Zhang and Faghri [14] analytically solved the one-dimensional melting of a semi-infinite two-component metal powder bed heated by a constant heat flux. Chen and Zhang [15] obtained the analytical solution for one-dimensional melting of a two-component metal powder bed with finite thickness subjected to a constant heat flux. Zhang and Faghri [16] simulated two-dimensional melting and resolidification of a subcooled two-component metal powder bed with a moving Gaussian heat source, with shrinkage accounted for but with the liquid flow of the low-melting-point metal neglected. A three-dimensional finite element simulation for temperature evolution in the SLS process was conducted by Kolossov et al. [17], who considered the nonlinear behavior of thermal conductivity and specific heat due to temperature changes and phase transformations. A three-dimensional thermal model of SLS of a two-component metal powder bed was presented by Zhang et al. [18], who considered the effects of the solid particle velocity induced by shrinkage of the powder bed and a liquid flow driven by capillary and gravity forces on the SLS process. The predicted tem-
perature history and the shape of the heat affected zone (HAZ) agreed fairly well with their experimental results with AISI 1018 steel as high-melting-point powder and nickel braze as low-melting-point powder.

The effects of processing parameters on the sintering process in a single loose powder layer with the complete shrinkage and the partial shrinkage were investigated numerically by Chen and Zhang [19,20]. Since SLS is a layer-by-layer process by which the sintering process occurs in a fresh loose powder layer on top of multiple sintered layers, it is necessary to study sintering of loose powder on top of sintered layers. A numerical solution of a three-dimensional quasi-steady state melting and resolidification problem in a two-component metal powder layer on top of multiple sintered layers subjected to a moving Gaussian laser beam will be presented in this paper. The effects of the volume fraction of the gas in the HAZ, laser scanning velocity and the number of the existing sintered layers on the shape of the HAZ will be investigated.

Physical Model

Figure 1 shows the physical model of the laser-sintering problem under consideration. The sintering process is modeled in a single loose powder layer on top of existing sintered layers. A moving Gaussian laser beam with the scanning velocity \( u_b \) is considered, and a moving coordinate, system is adopted. Part of the shrinkage model [20] that allows the fraction of the gas trapped in the heat affected zone (HAZ) to vary is employed. The HAZ is defined as the region where the low-melting-point powders went through melting and resolidification. Under the partial shrinkage model, the porosity \( e \) (defined as the volume fraction of the void, including the gas and low-melting-point liquid, \( \epsilon = e_{v} + \epsilon_{l} \)) in the liquid pool is no longer the same with that of the loose powder all the time, as it was in the case of complete shrinkage described in Ref. [19]. The volume fraction of the liquid of the low-melting-point powder \( \epsilon_{l} \) is zero when the powder is in the unsintered region and the porosity in this region is \( \epsilon = e_{v} \). When melting occurs, the increase of the volume fraction of the liquid will increase the porosity \( e \). Since a single-line scanning of the laser beam is considered, only half of the physical domain needs to be studied due to symmetry. The radius of the Gaussian beam measured at 1/e is much smaller than the length (in the \( x \) direction) and width (in the \( y \) direction) of the physical domain, and therefore, the length and width of the computational domain are treated as infinite and semi-infinite, respectively. The powder layer is treated as a continuum, since the size of the particles is small enough, compared to the diameter of the laser beam. The microscale effects can be neglected because a continuous wave laser is employed.

The physical model is formulated by a temperature transforming model [21], which converts the enthalpy-based energy equation into a nonlinear equation with temperature as the only dependent variable. In this methodology, the solid-liquid phase change is assumed to occur in the very small temperature range \( T_{0} - \Delta T \) to \( T_{0} + \Delta T \). It can successfully model a convection-controlled solid-liquid phase-change problem. The dimensionless governing equation in the moving coordinate system can be described as

$$
\nabla \cdot \left( \rho C_v \mathbf{V} (cT) \right) - \rho \frac{\partial}{\partial t} \left[ (\rho C_v + \rho L) T \right] + W_s \frac{\partial}{\partial z} \left[ (\rho C_v + \rho L) \right]
= \nabla \cdot \left( K \nabla T \right) - \left\{ \frac{\partial}{\partial t} \left[ (\rho c_v + \rho L) S_L \right] + \nabla \cdot \left( \rho \nabla S_L \right) + W_s \frac{\partial}{\partial z} (\rho c_v S_L) \right\}
$$

which can be derived by substituting the dimensionless enthalpy \( H = (\rho C_v + \rho L)(C_s T + S_l + \rho L)T \) into the energy equation in the enthalpy form. In the resolidified region at the left side of the liquid pool and underneath the loose powder layer, the volume fraction of the resolidified low-melting-point component is still represented by \( \epsilon_{l} \) (which differs from \( \epsilon_{v} \), which represents the volume fraction of the low-melting-point component before melting occurs). In other words, \( \epsilon_{l} \) is used to represent the volume fraction of the liquid in the liquid pool or volume fraction of the resolidified low-melting-point component in the resolidified region. The dimensionless shrinkage velocity \( W_s \), heat capacity of low-melting-point component \( C_s \), source term \( S_s \), and thermal conductivity \( K \) in Eq. (1) in the loose powder layer are different from those in the existing sintered layers below, which have been fully densified. In the loose powder layer,

$$
W_s = \begin{cases} 
0, & Z > S \\
1 - \frac{e_{l} - \epsilon_{l} - \epsilon_{v}}{1 - \epsilon_{l}} \left( \frac{\partial \eta}{\partial \tau} - \frac{\partial \eta}{\partial X} \right), & Z < S 
\end{cases}
$$

$$
C_s = \begin{cases} 
C_{sL}, & T < - \Delta T \\
C_{sL} \left( 1 + \frac{1}{2S_{s}} \right) - \Delta T < T < \Delta T \\
C_{sL}, & T > \Delta T 
\end{cases}
$$

$$
S_s = \begin{cases} 
0, & T < - \Delta T \\
C_{sL}, & - \Delta T < T < \Delta T \\
\frac{C_{sL}}{2S_{s}}, & T > \Delta T 
\end{cases}
$$

$$
K = \begin{cases} 
K_{eff}, & T < - \Delta T \\
K_{eff} + \frac{K_{l} - K_{eff}}{2 \Delta T} (T + \Delta T) - \Delta T < T < \Delta T \\
K_{l}, & T > \Delta T 
\end{cases}
$$

where \( K_{eff} \) and \( K_{l} \) are the dimensionless thermal conductivity of the loose powders and liquid pool, respectively [16]. In the resolidified region at the left of the liquid pool and the existing sintered layers,

$$
W_s = 0 
C_s = C_{sL} 
S_s = \frac{C_{sL}}{2S_{s}} 
$$
The dimensionless velocities of the liquid phase $V_L$ can be obtained by Darcy’s law. The dimensionless equation of Darcy’s law is [19]

$$V_L = \frac{eMa\phi^3}{\sqrt{180(1-\epsilon)^2 \psi}} \nabla P_e + \frac{e^2MaBo\phi^3}{180(1-\epsilon)^2 \psi} k$$

(11)

where

$$Ma = \frac{\gamma_{ml} \rho_R \rho_{m} \nu}{\sigma_{m} \mu}, \quad Bo = \frac{\rho_R \gamma_{ml} \rho_{m} \nu}{\gamma_{m} \mu}$$

(12)

are Marangoni and Bond numbers, respectively.

The dimensionless capillary pressure $P_c$ in Eq. (11) can be obtained by [22]

$$P_c = 1.417(1 - \phi_e) - 2.12(1 - \phi_e)^2 + 1.263(1 - \phi_e)^3$$

(13)

where the normalized saturation $\phi_e$ in Eq. (11) is obtained by

$$\phi_e = \begin{cases} \frac{\phi - \phi_{ir}}{1 - \phi_{ir}}, & \phi > \phi_{ir} \\ 0, & \phi \leq \phi_{ir} \end{cases}$$

(14)

where $\phi_{ir}$ is the irreducible saturation, below which liquid does not flow. Equation (11) satisfies the dimensionless continuity equation of the liquid in the moving coordinate system, which is obtained by

$$\frac{\partial \phi_e}{\partial \tau} - U_b \frac{\partial \phi_e}{\partial X} + \nabla \cdot (\phi_e V_L) = \Phi_L$$

(15)

The continuity equations for the solid phase of the low- and high-melting-point powders, assuming shrinkage occurs in the $Z$ direction only, are

$$\frac{\partial \phi_s}{\partial \tau} - U_b \frac{\partial \phi_s}{\partial X} + \frac{\partial (\phi_s \omega_s)}{\partial Z} = - \Phi_L$$

(16)

$$\frac{\partial \phi_{st}}{\partial \tau} - U_b \frac{\partial \phi_{st}}{\partial X} + \frac{\partial (\phi_{st} \omega_{st})}{\partial Z} = 0$$

(17)

and the following relationship is valid in all regions:

$$\epsilon + \phi_s + \phi_{st} = 1$$

(18)

Combining Eqs. (16)–(18), the volume production rate $\Phi_L$ of the liquid phase is obtained as

$$\Phi_L = -\frac{\partial (1 - \epsilon)}{\partial \tau} + U_b \frac{\partial (1 - \epsilon)}{\partial X} - \frac{\partial}{\partial Z}[(1 - \epsilon) W_s]$$

(19)

where the porosity $\epsilon$ is no longer a constant during the sintering process under the partial shrinkage model. Since $\epsilon$ is defined as the volume fraction of voids that can be occupied by either gas or liquid, the value of the porosity depends on the volume fraction of the gas $\phi_{g,t}$ in the loose powders or HAZ. The porosity in the loose powder layer $\epsilon_s$ is equal to the initial volume fraction of the gas in the powders $\phi_{g,t}$. The porosity in HAZ can be calculated from $\epsilon_{st} = \phi_s + \phi_{g,t}$. The heat loss at the surface of the powder bed due to the irradiation and convection was investigated by Zhang and Faghri [16], who concluded that its effect on the SLS process is not negligible. With the convective and radiative heat loss accounted for, the boundary conditions of Eq. (1) at the top of the powder bed are

$$-K \frac{\partial T}{\partial Z} = N_i \exp(-X^2 - Y^2) - N_g(T + N_j)^4 - (T_s + N_j)^4$$

$$-Bi(T - T_s) = \eta_g(X, Y)$$

(20)

The other boundary conditions of Eq. (1) are

$$\frac{\partial T}{\partial Z} = 0, \quad Z = \Delta_s + N\Delta_e$$

(21)

$$\frac{\partial T}{\partial Y} = 0, \quad Y = 0 \quad or \quad Y \to \infty$$

(22)

If the dimensionless sintered depth $\eta_s$ is less than the dimensionless thickness of the loose powder $\Delta_s$, then the location of the liquid surface $\eta_s$ is related to $\eta_s$ and the porosity in the liquid phase $\epsilon_s$. Once the entire loose powder layer is melted, the location of the liquid surface $\eta_s$ is related to dimensionless thickness of the loose powder $\Delta_s$ and the porosity in the liquid phase $\epsilon_s$ as

$$\eta_s(X, Y) = \begin{cases} 1 - \epsilon_s - \phi_{st}, & \eta_s(X, Y) < \Delta_s \\ \frac{1 - \epsilon_s}{1 - \epsilon} \Delta_s, & \eta_s = \Delta_s \end{cases}$$

(24)

**Numerical Solutions**

The fabrication of a functional part in the SLS process is achieved using a layer-by-layer fashion. For strong mechanical properties, the newly sintered layer should integrate tightly with the existing sintered layers underneath. The appropriate processing parameters, e.g., laser power intensity and scanning velocity, should be chosen to obtain an ideal sintering depth, which is beyond the bottom surface of the loose powder layer. In order to obtain the expected sintering depth, the optimum combination of dimensionless laser-beam intensity and scanning velocity is required.

The governing equation with the false transient term in the moving coordinate system is solved by the finite volume method, and the converged steady-state solution is declared when the temperature distribution does not change with the false transient time, i.e., maximum temperature difference between the temperature at the current time step and at the previous time step is $<10^{-3}$. The grid number used in the numerical simulation was $92 \times 37 \times (22 - 42)$, depending on the number of the existing sintered layers, and the false transient time step is 0.12. The distribution of grids in the $z$ direction is uniform grids in the loose powder layer with an arithmetic progress in existing sintered layers underneath. Smaller time steps and finer grids were also used in the simulation, but no noticeable difference was found. The dimensionless thickness of the loose powder layer is 0.25. The dimensionless thickness of the existing sintered layers underneath can be derived by the shrinkage rate. Since the shape of the physical domain is irregular due to the movement of the top surface, a block-off technique [23] is used to simplify the computation. The thermal conductivity in the empty space created by the shrinkage is assumed to be zero.

The computation for each scanning velocity $U_b$ starts from a lower dimensionless laser power intensity $N_i$ which is then gradually increased at small increments in order to obtain the expected sintering depth. The computation is stopped when the width of the HAZ at the interface between the new layer and the existing layer $(Z=\Delta)$ is 50% of the width of the HAZ at the top $(Z=\eta_s)$. A portion of the existing sintered layers must be remelted to achieve
firm binding between the newly sintered layer and the existing layers. The numerical simulation is carried out using a computer program developed by the authors.

Results and Discussions

The effects of the volume fraction of the gas in the liquid \( \varphi_{g,l} \), the scanning velocity of the moving laser beam, and the number of the existing sintered layers underneath on the formation of the heat affected zone (HAZ) are investigated. The powder mixture with nickel braze (BNi-2) as a low-melting-point powder and AISI 1018 steel as a high-melting-point powder are considered. The dimensional properties of AISI 1018 and BNi-2 are summarized in Table 1. The average diameters of nickel braze and AISI 1018 steel are 45 \( \mu \text{m} \) and 68 \( \mu \text{m} \), respectively. The dimensionless parameters that are used in the numerical simulation are shown in Table 2. The dimensionless processing parameters used in simulations correspond to the dimensional laser intensity ranging in \( 2 \times 10^7 \) \( \text{W/m}^2 \) and laser scan speed varying within 1–2 mm/s.

The three-dimensional shape of the HAZ sintered by a moving laser beam with a different volume fraction of the gas in the solid \( \varphi_{g,s} \), liquid pools \( \varphi_{g,l} \), and with one existing sintered layer underneath \( (\mathcal{N}=1) \), are shown in Fig. 2. The shrinkage, shown by a depression in the top surface of the HAZ, becomes less significant when the volume fraction of gas in HAZ increases. The overlap region of the liquid pool is the remelt region of the existing sintered layers below \( (Z>\Delta=0.25) \), which ensures the metallic bonding of the newly sintered layer to the existing layers. For the extreme case, there is no shrinkage when the volume fractions of gas in HAZ and the loose powder are equal \( (\varphi_{g,s}=\varphi_{g,l}) \) because the gas trapped in the void among the powder particles is not released. A higher-moving laser-beam intensity is needed for the sintering process with a higher volume fraction of the gas in the liquid pool in order to obtain the expected sintering depth. The magnitude of laser-beam intensity increases by \( \sim 1.1\% \) and \( 2.5\% \) for cases with one existing sintered layer below, as \( \varphi_{g,s} \) increases from 0 to 0.2 and 0.42, respectively. This is because the higher volume fraction of gas in the liquid pool causes a smaller rate of shrinkage and thicker existing sintered layers below. In addition, the thermal conductivity of the existing sintered layers is much higher than that of the loose powder layer. The higher thermal conductivity will result in a lower temperature. To compensate the higher thermal conductivity, the laser energy input was increased, which resulted in a higher surface temperature. The increase in the volume fraction of gas in the HAZ also causes an increase in the porosity in the HAZ. The increasing porosity in the HAZ will

Table 1 Summary of thermal properties of AISI 1018 and BNi-2

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<thead>
<tr>
<th></th>
<th>AISI 1018</th>
<th>BNi-2</th>
</tr>
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<tbody>
<tr>
<td>( \rho_H )</td>
<td>7892 kg/m(^3)</td>
<td>8257 kg/m(^3)</td>
</tr>
<tr>
<td>( k_H )</td>
<td>48.3 W/m K</td>
<td>14.65 W/m K</td>
</tr>
<tr>
<td>( c_{pl} )</td>
<td>451.8 J/kg K</td>
<td>462.6 J/kg K</td>
</tr>
<tr>
<td>( \alpha_H )</td>
<td>1.3546 ( \times 10^{-5} ) m(^2)/s</td>
<td></td>
</tr>
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Table 2 Sintering parameters applied in the numerical simulation

| Bi        | 2.94 \( \times 10^{-4} \) | \( N_y \) | 4.2 \( \times 10^{-4} \) |
| Bo        | 5.3 \( \times 10^{-3} \)  | \( Sc \)  | 1.38 |
| CL        | 1.07                      | \( T_m \) | –1.0 |
| \( K_f \) | 5.38 \( \times 10^{-4} \) | \( \varphi_{g,s} \) | 0.42 |
| \( K_L \) | 0.2                       | \( \varphi_{g,l} \) | 0.0, 0.2, 0.42 |
| Ma        | 1042.0                    | \( \rho_{\gamma} \) | 0.08 |
| \( N_f \) | 1.19 \( \times 10^{-3} \) | \( \Delta T \) | 0.001 |
| \( N \)   | 1.3                       |          |     |

Fig. 2 Three-dimensional shape of the HAZ \( (\Delta_z=0.25, \ U_b=0.1, \ N_y=0.3198, \ N=1) \)
decrease the density of the sintered part and increase the dependency of the post-processing process through liquid metal infiltration.

The temperature distribution on the surface of the powder layer at quasi-steady-state during the sintering process is shown in Fig. 3. The temperature distributed on the top surface of the overlap region of the liquid pool is higher than that of other locations on the top surface, since the high thermal conductivity of the existing sintered layer causes more energy input to induce the remelting of the existed sintered layers, and then results in higher surface temperature.

The effect of scanning velocity on the sintering process, with respect to the specific fraction of the gas in HAZ, can be illustrated by the longitudinal and sectional plots of HAZ. Figures 4–9 show the longitudinal view in plot “a” and the sectional view in plot “b.” Figure 4 shows the effect of the dimensionless scanning velocity on the sintering process for the case with the complete shrinkage ($\varphi_{A,f}=0.0$). The top surface location at $y=0$ after shrinkage is $\eta_0=0.0997$. A larger value of the laser-beam intensity is needed when the scanning velocity increases (represented by the dotted line in the Fig. 4) in order to achieve the desired sintering depth and overlap. The shapes of the HAZ are similar, but the liquid pool is a little narrower when the scanning velocity increases. That is because the time of the interaction between the moving laser beam and the powder layer is shorter. It can be seen that the overlapped region of the liquid pool has reached the bottom of the physical domain when quasi-steady state is achieved. The effects of the dimensionless scanning velocity on the sintering process for the case with partial shrinkage ($\varphi_{A,f}=0.2$) and without shrinkage ($\varphi_{A,f}=0.42$) are shown in Figs. 5 and 6, respectively. The top surface locations at $y=0$ for $\varphi_{A,f}=0.2$ and $\varphi_{A,f}=0.42$ are $\eta_0=0.0687$ and $\eta_0=0$, respectively. It can be seen that the shrinkage decreases with increasing $\varphi_{A,f}$. The shrinkage diminishes when $\varphi_{A,f}=\varphi_{A,f}$. A larger value of the laser-beam intensity is needed when $\varphi_{A,f}$ increases. A similar phenomenon as occurred in Fig. 4 can also be observed.
The number of the existing sintered layers underneath is also one of the important processing parameters because it can dramatically affect other processing parameters. Figures 7–9 show the effect of the dimensionless scanning velocity on the sintering process for the cases with complete shrinkage \( \psi_{g,t}=0.0 \), partial shrinkage \( \psi_{g,t}=0.2 \), and without shrinkage \( \psi_{g,t}=0.42 \) when the number of the existing sintered layers is increased to 3. It can be seen that the required laser-beam intensity increases significantly when the number of existed sintered layers below increases. For cases with three existing sintered layers below, the magnitude of the required laser-beam intensity increases by 9% when \( \psi_{g,t} \) increases from 0 to 0.2, compared to cases that have one existing sintered layer below and cause 1.1% increase of the magnitude of laser-beam intensity. When \( \psi_{g,t} \) increases from 0 to 0.42, the magnitude of the required laser-beam intensity increases by 14% for the case of three existing layers, which is much higher than a 2.5% increase for the cases with one existing sintered layer below. For the case without shrinkage, the bottom of the overlapped region of the HAZ is not flat, since the required overlap between the newly sintered layer and existing sintered layers has been achieved before it reaches the bottom surface of the physical domain. The increase in number of existing sintered layers underneath, combined with increasing \( \psi_{g,t} \), demands a much higher laser-beam intensity. Therefore, an increase in shrinkage is anticipated in order to achieve both a highly densified sintered part while simultaneously lowering the laser-beam intensity. However, increasing shrinkage results in poor geometric representation of features; thus, this may be an impractical solution for actual usage. One possible solution to obtain higher final density without significant shrinkage is to increase the initial packing density by using mixture of large high-melting-point particles with small low-melting-point particles [24].

**Conclusion**

A three-dimensional sintering process of a two-component metal powder for a single line scanning induced by a moving laser beam interacting with a loose powder layer on top of existing sintered metal layers is investigated. Partial shrinkage and liquid metal flow, driven by capillary and gravitational forces are taken into account in the physical model. The results demonstrate that the shape of the HAZ is significantly affected by the fraction of the gas in the liquid pool. The optimized combination of processing parameters, such as the laser-beam intensity, scanning velocity, and the number of the existing layers underneath, is needed to satisfy the required overlap between newly sintered and existing sintered layers.

**Acknowledgment**

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**Nomenclature**

- \( Bi \) = Biot number, \( hR/k_H \)
- \( Bo \) = Bond number, \( \rho c_p R d_p / \eta \rho \)
- \( C \) = dimensionless heat capacity, \( C^0 / C_H^0 \)
- \( C_{LIH} \) = heat capacity ratio, \( C_L^0 / C_H^0 \)
- \( C^0 \) = heat capacity, \( \rho c_p (1 / \text{m}^3 \cdot \text{K}) \)
- \( c_p \) = specific heat (J/kg K)
Fig. 8 Effects of laser intensity and scanning velocity on the sintering process ($\varphi_{x} = 0.42$, $N = 3$)

$d_p$ = diameter of the powder particle (m)
$g$ = gravitational acceleration (m/s$^2$)
$h$ = convective heat transfer coefficient, (W/m$^2$ K)
$h_{ef}$ = latent heat of melting or solidification, J/kg
$i$ = unit vector in the $x$ direction
$I_0$ = laser intensity at the center of the laser beam (W/m$^2$)
$j$ = unit vector in the $y$ direction
$k$ = thermal conductivity (W/m K)
$k$ = unit vector in the $z$ direction
$K$ = permeability ($m^2$), or dimensionless thermal conductivity, $k/k_H$
$K_{rel}$ = relative permeability
$Ma$ = Marangoni number, $\gamma_0 d_p/\alpha H u$
$N$ = number of existing sintered layers
$N_i$ = dimensionless laser intensity, $\alpha H/[k H (T_m^0 - T_i^0)]$
$N_R$ = radiation number, $e_o (T_m^0 - T_i^0)/R H$
$N_f$ = temperature ratio for radiation, $T_m^0/(T_m^0 - T_i^0)$
$p$ = pressure (Pa)
$P_c$ = dimensionless capillary pressure, $p/c_0 (T_m^0 - T_i^0)$
$(K)$ is permeability
$R$ = radius of the moving laser beam at $1/e$ (m)
$s$ = solid-liquid interface location (m)
$S$ = dimensionless solid-liquid interface location
$s_0$ = location of surface (m)
$s_{st}$ = sintered depth (m)
$S_c$ = subcooling parameter, $C^0 Ls (T_m^0 - T_i^0)/(\rho S h_{ef})$

$T$ = dimensionless temperature, $(T^0 - T_m^0)/(T_m^0 - T_i^0)$
$t$ = false time (s)
$T^0$ = temperature (K)
$u_b$ = laser-beam moving velocity (m/s)
$U_b$ = dimensionless heat source moving velocity, $u_b R/\alpha_H$
$v$ = velocity vector, $u + v_\perp + v k$
$V$ = dimensionless velocity vector, $v R/\alpha_H$
$\forall$ = volume (m$^3$)
$w_s$ = shrinkage velocity (m/s)
$W_s$ = dimensionless shrinkage velocity, $w_s R/\alpha_H$
$x, y, z$ = coordinate, (m)
$X, Y, Z$ = dimensionless moving horizontal coordinate, $(x, y, z)/R$

Greek Symbols

$\alpha$ = thermal diffusivity (m$^2$/s)
$\alpha_b$ = absorptivity
$\gamma$ = surface tension (N/m)
$\gamma$ = dimensionless surface tension, $\gamma^0/\gamma_m$
$\gamma_m$ = surface tension of the low-melting-point metal at melting point (N/m)
$\delta$ = loose powder layer thickness (m)
$\Delta$ = dimensionless loose powder layer thickness $\delta R$
$\Delta T^0$ = one-half of phase-change temperature range (K)
$\Delta T$ = one-half of dimensionless phase change temperature range, $\Delta T^0/(T_m^0 - T_i^0)$
\[ \varepsilon = \text{porosity}, (\nabla \phi + \nabla \psi)/(\nabla \phi + \nabla \psi + \nabla \mu) \]
\[ \varepsilon_s = \text{emissivity of surface} \]
\[ \eta = \text{dimensionless location of the solid-liquid interface, } s/R \]
\[ \eta_0 = \text{dimensionless location of the surface, } s_0/R \]
\[ \eta_m = \text{dimensionless sintered depth, } s_m/R \]
\[ \rho = \text{density (kg/m}^3) \]
\[ \sigma = \text{Stefan-Boltzmann constant, } 5.67 \times 10^{-8} \text{ W/(m}^2 \text{K}^4) \]
\[ \tau = \text{dimensionless false time, } \alpha \mu t/R^2 \]
\[ \varphi = \text{volume fraction} \]
\[ \Phi_L = \text{dimensionless volume production rate of the liquid} \]
\[ \psi = \text{saturation, } \varphi_L/\varepsilon \]
\[ \nabla = \text{dimensionless gradient operator, } i(\partial/\partial X) + j(\partial/\partial Y) + k(\partial/\partial Z) \]

**Subscripts**
- \( c \) = capillary
- \( g \) = gas(es)
- \( \text{eff} \) = effective
- \( H \) = high-melting-point powder
- \( i \) = initial
- \( \ell \) = liquid or sintered region
- \( L \) = low-melting-point powder
- \( m \) = melting point
- \( p \) = existing sintered region
- \( s \) = solid

**References**