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Fundamental consolidation mechanisms during selective beam melting of powders

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Received 18 February 2013, in final form 30 August 2013
Published 8 November 2013
Online at stacks.iop.org/MSMSE/21/085011

Abstract
During powder based additive manufacturing processes, a component is realized layer upon layer by the selective melting of powder layers with a laser or an electron beam. The density of the consolidated material, the minimal spatial resolution as well as the surface roughness of the resulting components are complex functions of the material and process parameters. So far, the interplay between these parameters is only partially understood.

In this paper, the successive assembling in layers is investigated with a recently described 2D-lattice Boltzmann model, which considers individual powder particles. This numerical approach makes several physical phenomena accessible, which cannot be described in a standard continuum picture, e.g. the interplay between capillary effects, wetting conditions and the local stochastic powder configuration. In addition, the model takes into account the influence of the surface topology of the previous consolidated layer on the subsequent powder layer.

The influence of the beam power, beam velocity and layer thickness on the formation and quality of simple walls is investigated. The simulation results are compared with experimental findings during selective electron beam melting. The comparison shows that our model, although 2D, is able to predict the main characteristics of the experimental observations. In addition, the numerical simulation elucidates the fundamental mechanisms responsible for the phenomena that are observed during selective beam melting.

(Some figures may appear in colour only in the online journal)
1. Introduction

Beam and powder based additive manufacturing methods are relatively novel technologies that can build parts in layers from powder material by local melting with an electron or laser beam [1]. Examples of commercialized selective beam melting (SBM) processes are selective laser beam melting (SLM) and selective electron beam melting (SEBM). During SLM or SEBM, the surface of a powder bed is selectively scanned with a beam energy source to heat and eventually melt the powder. Thin molten tracks develop and are combined to form a 2D layer of the final part. After completion of one layer, the whole powder bed is lowered about 20 to 100 µm and a fresh powder layer is spread out on the building zone. The selective melting process is repeated until the component is completed.

Generally, for different materials different powder consolidation mechanisms are operative [2, 3]. For metal powders, melting and re-solidification are the underlying mechanisms to consolidate the powder particles to form a functional part. Typical material defects associated with SLM/SEBM are residual porosity, not molten powder or not fully connected layers. In addition, SLM/SEBM suffer from a high surface roughness which is much larger than expected from the mean powder particle diameter. Finding state-of-the-art processing parameters for a new material is still a trial-and-error practice, since a deep understanding of the consolidation process is yet incomplete.

SLM/SEBM is rather complex and involves many different physical phenomena [4]: absorption of the beam in the powder bed, melting and solidification, the dynamics of the melt pool, wetting of solid powder particles by the melt, diffusive and radiative heat conduction within the powder bed, diffusive and convective heat conduction in the melt pool, capillary effects, gravity, etc. The melt pool generated by the beam is highly dynamic. The movement is driven by the high surface tension in combination with the low viscosity of liquid metals. As a result, the consolidated surface shows a stochastic nature, i.e. it is irregular and looks corrugated. After finishing one layer, a new powder layer is applied on the corrugated surface leading to a new powder layer with strongly varying thickness which might result in the typical material defects mentioned above.

Finite element or finite difference methods based on a homogenized picture have been used in order to develop a better understanding of the underlying consolidation process [5–12]. These approaches are suitable for modeling the global temperature field and energy dissipation but are unsuitable to reproduce stochastic powder effects like wetting, variations of the local density of the powder bed, dynamic shrinkage, etc. The homogenized approaches always predict well defined melt pool geometries without the stochastic behavior that is experimentally observed [9] since they are not considering individual powder particles. That is, the existing numerical approaches are of little help to understand binding errors or rough surfaces and the influence of the process and material parameters on the consolidation process.

The aim of this paper is to gain a much better understanding of the fabrication process in layers during SLM/SEBM. In contrast to other numerical approaches in the literature, our approach is based on a lattice Boltzmann model [13–16] where the effect of individual powder particles is considered [17]. The beam is absorbed by the powder particles, which are heated and eventually become molten. After solidification, a new stochastic powder layer is applied on the rough surface consisting of powder and locally consolidated regions.

The paper is organized as follows: after a short introduction into the physical and numerical model, the algorithm for the generation of stochastic powder layers on a stochastic layer is explained in detail in section 2. Section 3 describes the experimental approach by SEBM and the physical and numerical parameters used. Section 4 is devoted to the influence of the process parameters (layer thickness, beam energy and beam velocity) on the appearance of walls. The
Figure 1. Additive manufacturing by SBM of powder.

numerical results are compared with analogous experiments from SEBM. Section 5 is devoted to discussing the underlying physical phenomena with the help of dimensionless numbers and the characteristic time scales of the process.

2. Physical model

SBM of powders involves many different physical processes [4], see figure 1. The beam is absorbed in the powder bed and heats the powder particles, which eventually start to melt and coalesce. The melt pool is highly dynamic, driven by capillary forces. Due to the hydrodynamic movement, the shape of the melt pool constantly changes during the process. Dependent on the parameters and environment, this reshaping can range from little deviations from a quasi-stationary melt pool shape to significant changes in geometry. Sometimes the disintegration of the melt pool into spherical droplets, called balling and commonly denoted as Rayleigh instability [18], is observed. In addition, the shape of the re-solidified melt pool is strongly dependent on the wetting characteristics of the melt with the powder particles [4]. After finishing one layer, a new powder layer is applied on the irregular and corrugated surface. Consequently, the thickness of the new powder layer is strongly varying which might result in typical process defects like binding faults [3, 4], see figure 1. To ensure that two consecutive layers form a sound bonding, sufficient remelting of the previous layer has to take place. In the following, the underlying physical model is described. The detailed numerical approach to solve this model, which is based on a lattice Boltzmann approach, is described in [17].

2.1. Geometry and beam definition

Since our numerical approach is 2D, the problem has to be reduced to 2D. Figure 2 shows the geometric situation. The buildup direction is denoted as $z$ and the building plane is defined by $x$ and $y$. The simulation plane is either spanned by the $x$ and $z$ coordinate or $y$ and $z$ coordinate. In the first case, (figure 2(b)), the beam is not moving and only the beam power is acting in a time span given by the $y$-velocity of the beam. In the second case (figure 2(c)), the beam is moving with the velocity of the beam. In this paper, we are only considering building situations as depicted in figure 2(b).

The electron beam can be described by a two dimensional Gaussian power distribution:

$$I(x, y, t) = \frac{P}{2\pi \sigma^2} \cdot \exp \left( -\frac{(x - v_x t)^2 + (y - v_y t)^2}{2 \sigma^2} \right),$$  
(1)
The line energy, $E_L$, is given by:

$$E_L = \frac{P}{v}. \quad (6)$$

The beam penetrates the powder bed. In the case of an electron beam, the energy is nearly completely absorbed at the position where it has first contact with the powder. The absorption process for laser radiation is more complex due to multi-reflection processes causing the radiation transport to have shadowed powder particles [19]. Our model does not take reflection processes into account but is able to handle the transient nature of the absorbing surface due to melting, see figure 1. Thus, this paper focuses on the simulation and validation of the electron
beam melting process, where reflection processes do not have to be taken into account. When the beam touches a powder particle, the energy absorption is modeled by the exponential absorption law,

$$\frac{dI}{dz} = \lambda_{\text{abs}} I,$$

(7)

where $\lambda_{\text{abs}}$ denotes the absorption coefficient of the radiation.

2.2. Energy transfer and conservation equations

The beam energy is absorbed in the powder bed, the powder temperature increases and the thermal energy spreads by heat diffusion. When the temperature exceeds the liquidus temperature of the metal, the solid–fluid phase transformation starts thereby consuming latent heat $L$. When the local liquid phase fraction exceeds a given threshold value, the solid starts to behave as a liquid. The liquid material is governed by the Navier–Stokes equations. Heat transport in the liquid is either by diffusion or by convection. Radiation and convection of heat from the liquid surface are neglected so that the excess heat of the liquid must be dissipated by heat conduction into the powder bed in order to re-solidify the melt pool. The neglect of convection is justified since the EBM process is under a vacuum. Radiation, vaporization and marangoni convection can have an essential effect and will be taken into account in a further work.

The underlying continuum equations of convection–diffusion transport are founded on an enthalpy based methodology. The single-phase continuum conservation equations to simulate thermo-fluid incompressible transport comprising melting and solidification are given by:

$$\nabla \cdot u = 0,$$

(8)

$$\frac{\partial u}{\partial t} + (u \cdot \nabla) u = -\frac{1}{\rho} \nabla p + \nu \nabla^2 u + g,$$

(9)

$$\frac{\partial E}{\partial t} + \nabla \cdot (u E) = \nabla \cdot (k \nabla E) + \Phi,$$

(10)

where $\nabla$ is the gradient operator, $t$ the time, $u$ the local velocity of the melt, $p$ the pressure and $\nu$ the kinematic viscosity. Gravity acceleration is denoted by $g$. Surface tension effects are taken into account via the boundary conditions at the free surface. Wetting effects between the melt and the solid phase are also taken into account. Details are described in [20]. The thermal diffusivity is designated by $k = k(E)$. The energy source $\Phi$ describes the energy deposited in the material by the beam. Viscous heat dissipation and compression work are neglected in this model. The thermal energy density $E$ is given by

$$E = \int_0^T \rho c_p dT + \rho \Delta H,$$

(11)

where $c_p$ is the specific heat at constant pressure, $T$ is the temperature and $\Delta H$ is the latent enthalpy of a computational cell undergoing phase change. For a multi component metal alloy, $\Delta H$ is a complex function of the temperature. In a simple approximation, it can be expressed as follows:

$$\Delta H(T) = \begin{cases} L, & T \geq T_i \\ \frac{T - T_i}{T_f - T_i} \cdot L, & T_i < T < T_f \\ 0, & T < T_i \end{cases}$$

(12)
with $T_i$ and $T_f$ representing the beginning and the end of the phase transformation, respectively. $L$ is the latent heat of the phase change. Denoting $\xi$ as the liquid fraction in a cell,

$$\xi(T) = \frac{\Delta H(T)}{L}$$

(13)

The latent enthalpy is taken up into an effective specific heat $\tilde{c}_p$:

$$E = \int_0^T \rho \, c_p \, dT + \rho \, \Delta H = \int_0^T \rho \, \tilde{c}_p \, dT$$

(14)

with

$$\tilde{c}_p = \begin{cases} 
    c_p, & T \geq T_f \\
    c_p + \frac{L}{T_f - T_i}, & T_i \leq T < T_f \\
    c_p, & T < T_i, 
\end{cases}$$

(15)

The thermal diffusivity $k$ is related to the heat conductivity $\lambda$ by:

$$k(E) = \frac{\lambda(E)}{\rho \, \tilde{c}_p(E)}$$

(16)

### 2.3. Boundary conditions and interface treatment

The surface between liquid and atmosphere is accounted for with the volume of fluids method. Dependent on the fluid motion, the fluid fraction of a volume element increases or decreases. When a cell is entirely filled or emptied, the surface moves accordingly, allowing for a freely moving surface. Thermally, the liquid-atmosphere surface is perfectly insulating. The effect of the surface tension is treated as a local modification of the gas pressure $p_G$ acting at the interface, i.e. the gas pressure is replaced by

$$p'_G = p_G - \kappa \cdot \gamma,$$

(17)

where $\kappa$ and $\gamma$ denote the curvature and the surface tension, respectively.

The dependence of the surface tension on the temperature and the high temperature gradients in the melt pool induce a hydrodynamic flow perpendicular to the surface. This phenomenon, commonly denoted as Marangoni convection, has not been taken into account for the simulations presented in this paper. This flow would lead to an increase of the transport of heat away from the center of the beam, increasing effective heat conduction and resulting in a different melt pool shape. Unlike in welding, the main effect leading to the growth of the melt pool in a powder bed is the wetting of neighboring powder particles. Hence, Marangoni convection can be regarded as a secondary effect increasing the melt pool life span and therefore its size. Due to the neglect of this phenomenon, the melt pool size in the simulation might be underestimated.

Thermally, the solid-atmosphere surface is perfectly insulating, while the solid phase is conductive. Hence, the thermal conduction between two powder particles is determined by the contact area between the individual particles, unlike in homogenized approaches.

The solid–liquid interface is treated as a hydrodynamic no-slip boundary condition. However, the solid phase is assumed to be immobile. Accordingly, the force resulting from the no-slip boundary condition is only applied to the liquid phase, not to the solid phase. For the SEBM process that this paper focuses on, solid movement can be neglected, as the powder is pre-sintered in the process, resulting in an immobile powder bed. For simulating SLM, a mobile solid phase might be necessary. Furthermore, wetting is included in the numerical model. Details of the algorithm and its validation are given in [20]. The wetting angle between fluid and solid is set to 0 for the simulations, assuming perfect homologous wetting.
Figure 3. Powder bed generation: (a) Rain model packing algorithm, (b) powder layer with a Gaussian size distribution, (c) powder layer with adapted relative density by removing a certain percentage of the particles, (d) local consolidation by melting, (e) generation of virtual particles (black dots) on the solidified melt and the surface particles, (f) generation of a new powder layer and (g) adaption of the relative density, see (c).

2.4. Layer upon layer random powder bed generation

The rain model packing algorithm [21] is used to generate the random powder bed. In this model, particles follow definable trajectories to find a resting place in the powder bed. Particles from a given size distribution (e.g. Gaussian distribution or a bimodal distribution) are placed one by one in randomly selected positions above the packing space, see figure 3(a)). The newly introduced particle falls downward until it comes into touch with a stationary particle. Subsequently, it attempts to minimize its vertical coordinate by rolling around the circumference of the stationary particle and any other particle that it comes into contact with. Movement ceases when no further downward movement is possible and the particle reaches the nearest local minimum. When no contacted particle is found, the particle is deposited on the basal line.

We use a 2D formulation of the rain packing algorithm, which results in a powder packing density much higher than in the experiments. In order to adapt the density of the new powder
layer (figure 3(b)) to the experimental density, a certain percentage of the particles is removed (figure 3(c)). Local melting of the particles leads to stochastic geometries of the solidified material (figure 3(d)). Virtual particles are generated on the surface of the consolidated material and the surface particles (figure 3(e)) and a new powder layer is applied (figure 3(f)). Again, the density is adapted (figure 3(e)).

3. Experimental approach and simulation parameters

In this section, a general description of the experimental procedure and the simulation parameters, which are identical for all simulations and experiments, are given.

3.1. Experiments

All experiments described in this work are carried out with the Arcam A2 EBM machine, which is based on SEBM. The SEBM process used for rapid component prototyping is operationally similar to the scanning of an electron beam in a scanning electron microscope and it can be considered as a variant of SLM. Similar to the SLM process, metal powders are selectively molten in paths traced by the electron beam gun. In all cases, the width of the Gaussian beam is 350 µm.

The SEBM machine consists of an evacuated building tank with an adjustable process platform, two powder dispensing hoppers and a rake system for spreading the powders. The electron beam is generated by heating a tungsten filament. The acceleration voltage of the electrons is 60 kV. The electrons are focused and deflected by electromagnetic lenses and release their kinetic energy to the powder particles, which causes them to heat.

The base material for the process is gas atomized pre-alloyed Ti–6Al–4V powder with a Gaussian particle size distribution between 45 and 115 µm. Vertical walls are deposited on a 10 mm thick stainless steel plate. The platform is first heated with the defocused electron beam to a temperature of 760 °C. Subsequently, a layer of Ti–6Al–4V powder is spread over the platform. Again, the entire powder bed on the platform is preheated by scanning with the defocused electron beam. During this procedure, the powder is sintered [17], increasing thermal and electrical conductivity and immobilizing the powder.

Following this preheating step, the beam scans the powder bed in order to melt the powder at predefined positions line after line. Here, perpendicular single line walls are produced. After completion of the layer, the platform is lowered by one layer thickness and the next layer of powder is applied. This process is repeated until the walls have reached their desired height.

A series of single line walls is manufactured with line energies of 0.5, 1.0 and 2.0 J mm⁻¹ using different combinations of beam power and scan speed, see table 1. Two different layer thicknesses, 70 and 100 µm, are considered. The samples are cross-sectioned, mounted and polished in order to compare the experimental results with the simulation.

3.2. Simulation parameters

The numerical simulation approach is based on the lattice Boltzmann method (LBM), which is an explicit finite difference method of second order accuracy in time and space [14]. The LBM is characterized by dividing the simulation space in cells, which all have the same size. All these cells have the same properties but may assume different kinds of states, e.g. solid, liquid or gas. The size of the cells defines the length scale. In addition, a mass scale Δm, a temperature scale ΔT and a time scale Δt have to be defined: Δx = 5.0 × 10⁻⁶ m, Δm = 5.0 × 10⁻¹³ kg, ΔT = 1.54 × 10³ K and Δt = 2.2 × 10⁻⁷ s. The scales have to be defined since the lattice
Table 1. Process settings for the multi-layer experiments and the equivalent simulation parameters.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process settings</td>
<td>Beam current (mA)</td>
</tr>
<tr>
<td>F2</td>
<td>2</td>
</tr>
<tr>
<td>F3</td>
<td>5</td>
</tr>
<tr>
<td>F4</td>
<td>10</td>
</tr>
<tr>
<td>F6</td>
<td>2</td>
</tr>
<tr>
<td>F7</td>
<td>5</td>
</tr>
<tr>
<td>F8</td>
<td>10</td>
</tr>
<tr>
<td>F10</td>
<td>2</td>
</tr>
<tr>
<td>F11</td>
<td>5</td>
</tr>
<tr>
<td>F12</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 2. Physical parameters of Ti–6Al–4V [22] and corresponding dimensionless parameters for the LBM simulation.

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Experiment</th>
<th>LBM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (liquid)</td>
<td>4000 kg m$^{-3}$</td>
<td>1.0</td>
</tr>
<tr>
<td>Viscosity</td>
<td>0.005 Pa s</td>
<td>0.011</td>
</tr>
<tr>
<td>Surface tension</td>
<td>1.65 N m$^{-1}$</td>
<td>0.15</td>
</tr>
<tr>
<td>Gravitational acceleration</td>
<td>9.81 m s$^{-2}$</td>
<td>10$^{-7}$</td>
</tr>
<tr>
<td>Thermal diffusivity of solid</td>
<td>7.83 \times 10^{-6} m$^2$ s$^{-1}$</td>
<td>0.068</td>
</tr>
<tr>
<td>Thermal diffusivity of liquid</td>
<td>9.93 \times 10^{-6} m$^2$ s$^{-1}$</td>
<td>0.087</td>
</tr>
<tr>
<td>Solidus temperature</td>
<td>1878 K</td>
<td>1.22</td>
</tr>
<tr>
<td>Liquidus temperature</td>
<td>1928 K</td>
<td>1.25</td>
</tr>
<tr>
<td>Preheat temperature</td>
<td>1023 K</td>
<td>0.664</td>
</tr>
<tr>
<td>Latent heat</td>
<td>0.37 \times 10^3 J kg$^{-1}$</td>
<td>0.3</td>
</tr>
<tr>
<td>$\lambda_{abs}$</td>
<td>0.4 $\mu$m$^{-1}$</td>
<td>2.0</td>
</tr>
<tr>
<td>Specific heat</td>
<td>700 J kg$^{-1}$ K$^{-1}$</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Boltzmann simulation uses dimensionless parameters. Thus, all material parameters have to be expressed in dimensionless form. Table 2 lists the physical parameters and their corresponding values used in the simulation.

The dimensionless quantities (marked with *) follow by multiplying the material parameters with the relevant scales, such as:

$$
\rho^* = \rho \frac{\Delta x^3}{\Delta m^3}, \quad v^* = v \frac{\Delta t}{\Delta x^2}, \quad \sigma^* = \sigma \frac{\Delta t^2}{\Delta m}, \quad g^* = g \frac{\Delta t^2}{\Delta x},
$$

$$
k^* = k \frac{\Delta t}{\Delta x^2}, \quad \text{etc.} \quad (18)
$$

The absorption depth for 60 kV electrons is about 10 $\mu$m. Since the size of a cell is 5 $\mu$m, most of the energy is absorbed within two cells.

4. Results

Figure 4 shows the layer by layer building process of a vertical wall. The first layer is generated directly on the building plate with the preheating temperature $T_0 = 760$ °C. The first powder
Figure 4. Formation of a single wall for different time steps from left to right during the formation of several layers. Melting of the powder takes place parallel to the exposure of the beam. (200 × 400 cells = 1 mm × 2 mm, beam width: 70 cells (350 µm), parameters: F6 (table 1), layer thickness: 20 cells = 100 µm).

layer is rather scarce since the total layer thickness is only 100 µm. The beam does not move and the resulting melt pool geometry has a stochastic nature. After solidification, the subsequent powder layer is applied on the previous solidified melt pool. In each layer, the appearance of the melt pool is completely different. Thus, the subsequent powder layer is applied upon a stochastic geometry, which might be either concave or convex. As a result, each new layer looks different. This stochastic behavior is essential for the resolution of the beam building process.

In the following, the influence of layer thickness, line energy and beam velocity on the appearance of vertical walls is investigated.

4.1. Influence of the layer thickness

The layer thickness is one of the main process parameters for layer based additive manufacturing processes. For SEBM, the layer thickness is typically varied between 50 and 150 µm; for SLM, the layer thickness is generally much smaller, between 20 and 50 µm, sometimes even less than 20 µm. In order to investigate the effect of the layer thickness on the resolution, different layer thicknesses between 35 and 150 µm are considered, see figure 5.

The quality of the walls decreases dramatically with increasing layer thickness. For layer thicknesses smaller than 70 µm, the surface quality is not further improved but the wall width increases due to the increasing total energy input with the increasing number of layers. This effect becomes clear comparing 70 µm with 35 µm walls.

In figure 6, the line energy is adapted to the layer thickness in such a way that the total energy input is the same for all layer thicknesses. That is, the line energy multiplied with the number of layers is constant. For 50 µm layers, the number of lines is doubled compared to 100 µm layers but the line energy is halved. As a consequence, the wall thickness and surface roughness is strongly increased for 100 µm layers. On the other hand, the comparison between the 70 and 50 µm layers reveals that the improvement of the surface roughness is eventually limited by the stochastic powder bed.
4.2. Influence of the beam line energy and velocity

Figure 7 shows the influence of the beam line energy and beam velocity for two layer thicknesses on the resulting walls. As expected, the results for the 70 µm layers are better than for 100 µm. This observation holds for the binding faults as well as the surface roughness. The mean thickness of the walls increases with an increasing line energy. At constant line energy, the appearance of the walls is also dependent on the velocity. With an increasing beam velocity, i.e. an increasing beam power, the wall thickness as well as the surface roughness increases. That is, the numerical results predict a dependence on the beam velocity. The slower the beam, the better are the results.

Figure 8 shows the buildup of the F7/100 µm/1 J mm\(^{-1}\) wall in 18 layers. In contrast to figure 4, beam velocity and beam power are increased by a factor of 2.5. Thus, the interaction time between beam and powder is reduced but the total energy input is the same. The first layers are still relatively defined but after 10 layers the building process gets more and more undetermined, especially between the 14th and 18th layer. Due to the strong geometry changes of the solidified melt pool, the new applied powder layer is sometimes much thicker than 200 µm, which we expect on average for a relative powder packing density of 50%.

4.3. Experiment versus numerical simulation

In order to verify the numerical results, experiments analogous to the numerical simulations of figure 7 were performed, see figure 9. The wall quality strongly increases by decreasing
the layer thickness. In addition, the wall quality decreases with an increasing beam velocity.

In order to have a quantitative measure available to compare simulation and experiment as a function of the process parameters, the mean wall thickness is determined. The wall thickness is measured geometrically for more than 60 points perpendicular to the wall center.
Figure 9. Wall formation as a function of beam velocity, line energy and layer thickness. Experimental results for Ti6AlV4.

Figure 10. Experimental and simulated wall thickness as a function of the scan speed for constant line energies. Powder layer thickness: 70 $\mu$m. Error bars indicate the standard deviation of the results.

line and the mean value is calculated. Figure 10 shows the mean value of the wall thickness for the 70 $\mu$m layer walls. The simulation results are in good agreement with the experiments.

5. Discussion

The experimental findings of figure 9 demonstrate in an impressive way the sensitivity of the results to the parameters. In addition, it becomes clear that the resulting surface roughness
is always much higher than expected from the mean powder particle diameter. An important question is what the origin of this high surface roughness is. At first glance, position accuracy and the quality of the beam are good candidates to cause the roughness. During wall building, the beam has to come back to its initial position in each layer. If this accuracy is bad or if the beam quality changes with time, the layers will be inaccurate resulting in a high roughness. Numerically, positioning accuracy as well as beam quality are perfect. Comparing the experimental results with the numerical ones, it becomes clear that there must be another mechanism that is responsible for the rough surface.

In the following, the fundamental mechanisms governing the consolidation process during SBM are discussed with the help of the relevant time scales. Material consolidation during SBM takes place on the micro-scale where surface forces dominate over volume forces. That is, the forces resulting from the surface tension are much larger than gravity or viscous forces. In order to get a more quantitative measure, it is instructive to consider dimensionless numbers. A measure to compare gravity and surface tension effects is the Bond number $Bo$,

$$\text{Bo} = \frac{\rho \cdot g \cdot L^2}{\sigma},$$  \hspace{1cm} (19)

where $\rho$, $g$, $L$, $\sigma$ denote the density, gravitational acceleration, the relevant length scale and the surface tension, respectively.

The Laplace number $La$ is used to characterize free surface fluid dynamics and represents the ratio of inertia and capillary effects to viscous forces,

$$La = \frac{\sigma \cdot \rho \cdot L}{\eta^2},$$  \hspace{1cm} (20)

where $\eta$ is the viscosity. For titanium, $Bo \approx 10^{-4}$ and $La \approx 10^5$. That is, during powder melting, the system is dominated by surface tension effects, gravity or viscous effect are small.

In order to gain a better understanding of the powder particle melting process and the evolution of the melt pool, it is instructive to introduce relevant time scales that allow one to compare different processes. The interaction time $t_{\text{int}}$,

$$t_{\text{int}} = \frac{D}{v},$$  \hspace{1cm} (21)

is a measure for the contact time of the powder layer with the beam with diameter $D$ and velocity $v$.

The diffusion time $t_{\text{diff}}$,

$$t_{\text{diff}} = \frac{d_l^2}{k},$$  \hspace{1cm} (22)

is the characteristic time necessary to transport heat over a distance $d_l$, the layer thickness, with the thermal diffusivity $k$. The capillary time $t_{\text{cap}}$,

$$t_{\text{cap}} = \frac{\eta \cdot L}{\sigma},$$  \hspace{1cm} (23)

is the time necessary for an interface to regain its equilibrium shape after a perturbation. The Rayleigh time $t_{\text{ray}}$,

$$t_{\text{ray}} = \sqrt{\frac{\rho \cdot L^3}{\sigma}},$$  \hspace{1cm} (24)

is the time scale which characterizes the relaxation of an interface perturbation under the action of inertia and surface tension forces $[23–25]$. 
5.1. Thermal diffusion time versus interaction time

During $t_{\text{int}}$, the beam heats the powder and eventually melts it. The characteristic time necessary for the deposited energy to reach and partly remelt the preceding layer is $t_{\text{diff}}$. If $t_{\text{int}} \ll t_{\text{diff}}$, energy distribution is diffusion limited. The surface gets strongly superheated and eventually evaporation starts. On the other hand, if $t_{\text{int}} \gg t_{\text{diff}}$, energy is lost by thermal diffusion and the melting process becomes ineffective. Thus, $t_{\text{int}} \approx t_{\text{diff}}$ is expected to be a reasonable choice for the interaction time:

$$v = \frac{D \cdot k}{d_1^2}. \quad (25)$$

For $d_1 = 100 \, \mu m$, the suggested beam velocity and the interaction time would be about $200 \, \text{mm s}^{-1}$ and $6 \, \text{ms}$, respectively. It is essential to realize that the optimal velocity is a function of $1/d_1^2$. For $d_1 = 20 \, \mu m$, a beam velocity of $5000 \, \text{m s}^{-1}$ is recommended. Thus, much higher velocities without the danger of overheating and evaporation can be realized with thinner layers.

5.2. Melting versus reshaping

An essential question is whether coalescence is governed by thermal diffusion and melting or reshaping due to the surface tension. The time scale for two molten powder particles to merge is determined by $t_{\text{ray}}$ if inertia or $t_{\text{cap}}$ if viscous forces dominate.

For a length scale of the order of 100 $\mu m$, the capillary time is about $10^{-7} \, \text{s}$, which is rather small in comparison with the Rayleigh time of about $10^{-4} \, \text{s}$. Thus, reshaping is governed by inertia effects rather than viscous ones.

Nevertheless, $t_{\text{ray}}$ is more than one order of magnitude smaller than the thermal diffusion time for 100 $\mu m$ layers. That is, coalescence of the powder particles follows the melting process nearly instantaneously. Thus, the consolidation is limited by thermal diffusion and not by hydrodynamics, which becomes visible in figure 11. In the time span between 680 and 1000 $\mu s$ the solid–liquid interface moves only a little, while the melt pool shape changes drastically due to coalescence and the movement induced by surface tension.

5.3. Surface beads and extrusions

The strong influence of the process parameters on the surface quality was demonstrated in section 4.3. Here, the fundamental mechanisms leading to the experimental observations are discussed.

The underlying principle of additive manufacturing is that the component is built layer by layer. Thereby it is assumed that layer consolidation is in the vertical direction. During
consolidation, the powder particles are molten, coalesce and the whole layer consolidates driven by the surface tension. This is a very vigorous process and does not necessarily lead to mere vertical movement, it might also result in a horizontal movement of the melt.

Figure 12 elucidates the evolution of beads and extrusions. In both cases, larger droplets form due to the surface tension and are accelerated to the left where they stick to powder particles as a result of the wetting conditions. Due to overheating of the droplets, powder particles far away from the range of the beam are also molten. For F7, the droplet is not able to regain contact to the rest of the melt pool and the bead sticks at the surface. The situation for F8 is different. Here, further melting eventually leads to the coalescence of the droplet with the lower melt pool. Nevertheless, although the surface tension pulls the melt downward, the dip further sticks to the powder particle and forms a pronounced extrusion.

Figure 12 reveals, as a cause for the development of the surface defects, a horizontal movement of the melt, which is triggered by the stochastic powder configuration in combination with the progression of the melt pool. In both cases, the powder configuration is such that the contact in the horizontal direction is better than in the vertical direction. The danger for horizontal movement increases with increasing the powder layer thickness, decreasing the relative density of the powder and increasing the power density of the beam. The thicker the powder layer is, the larger is the probability that there is no continuous contact of the powder particles in the vertical direction. This observation explains the strong influence of the layer thickness \( d_l \) on the surface quality of the walls. The number of superimposed powder particles for \( d_l = 100 \mu m \) is about 3–4, for \( d_l = 70 \mu m \) it is about 2. The decrease of the relative density has a similar effect as an increase of the powder layer thickness.

The dependence on the power density at constant line energy is more complex. In this case, the temporal evolution of the melt pool changes with increasing the power density. For low densities, the melt pool starts at the center of the beam and expands horizontally and vertically. For high power densities, melting starts all over the surface and the danger of a horizontal movement of the melt pool increases. In addition, overheating of the melt increases with increasing the power density. Thus, melt sucked into the surrounding powder bed will melt the neighboring particles and thus increase the horizontal deviation.
If the powder layer is reduced to a mono-layer of particles, the danger of horizontal movement is strongly reduced since the direct contact to the consolidated bottom drives the molten particles downward. Thus, we recommend choosing the mean powder diameter and the layer thickness in such a way that the applied powder layer is nearly a mono-layer. This means that for a mean powder diameter of 70 \( \mu m \), the layer thickness should be about 35 \( \mu m \).

6. Summary

This paper describes a numerical approach to simulate beam and powder bed additive manufacturing processes at the scale of individual powder particles. A numerical tool on the basis of a lattice Boltzmann method (LBM) was developed, which allows one to simulate layer by layer fabrication in 2D. The influence of the process parameters—beam power, beam velocity and layer thickness—on the resulting quality for vertical walls is investigated and compared with experimental results from selective electron beam melting (SEBM).

The numerical results demonstrate the nature of the buildup process, which is strongly determined by the stochastic nature of the powder bed in each layer. In addition, the numerical simulation reveals the underlying physical phenomena that govern the process. The high surface forces in combination with wetting of a stochastic, loosely packed powder bed are identified as the origin of the high roughness and the occurrence of binding faults. From the simulation results, we conclude that higher velocities at constant line energy are unfavorable since the overheated surfaces layer behaves in an unpredictable way. In order to increase building accuracy and velocity, we recommend adapting the powder size in such a way that mono-layers of particles are applied during building.

The powder-level simulation has turned out to be an essential means to reveal the mechanisms and parameters influencing consolidation during selective beam melting (SBM) of powders.

Acknowledgments

The authors gratefully acknowledge funding of the German Research Council (DFG) within the Collaborative Research Center 814 ‘Additive Manufacturing’, project B4 and within the framework of its ‘Excellence Initiative’ supports the Cluster of Excellence ‘Engineering of Advanced Materials’ at the University of Erlangen-Nuremberg.

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