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Simulation of laser beam melting of steel powders using the three-dimensional volume of fluid method

F.-J. Gürtler[a,b,*], M. Karg[a,b], K.-H. Leitz[a,b], M. Schmidt[a,b]

[a]*Chair of Photonic Technologies, University Erlangen-Nuremberg, Paul-Gordan-Str. 3, 91052 Erlangen, Germany*
[b]*Graduate school in advanced optical technolgies (SAOT) Erlangen, Paul-Gordan-Str. 6, 91052 Erlangen, Germany*

Abstract

A transient three-dimensional beam-matter-interaction model was developed to simulate the process dynamics of laser beam melting (LBM) of metals in the powder bed. The simulations were realized by the software OpenFOAM and modified solvers. Based on the continuity equation, the equation of heat conduction and the Navier-Stokes equation the laser material interaction is described. Furthermore, the volume of fluid method is used to characterize the free surfaces of the multi-phase system. These process simulations were performed for steel powders. The parameters were chosen according to those applied in industrial machines and the simulation results show good correlation to experimental data.

Keywords: selective laser melting; rapid prototyping; process simulation;

1. Introduction

In the last years additive manufacturing (AM) has become more and more important for many industry sectors. By the improvements of laser systems, especially the medium output power, the development from selective laser sintering over the direct metal laser sintering to the laser beam melting (LBM) was possible. In contrast to the two first mentioned methods, in LBM it is possible to use one metal component processing because the used powder is melted completely and no additional material is needed. The generated

* Corresponding author. Tel.: +49-9131-85-23239 ; fax: +49-9131-85-23234 .
E-mail address: Franz-Josef.Guertler@lpt.uni-erlangen.de .

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components show due to the complete fusing full density. Also due to the fusing process and the extremely high solidification rate, resulting to a fast cooling rate, the structure underlies a complete new formation.

In order to optimize the LBM process and to avoid unwanted porosity there is an increasing interest in understanding the process dynamics of laser beam melting, especially the mechanisms of defect formation. For the description of the process dynamics of LBM a simulation model is necessary which includes energy input, phase transition as well as thermo and fluid dynamics. Indeed some numerical models exist in this field of LBM, but they make strong simplifications regarding the geometry or the physicals effects [Wakai, 2006, Wang et al., 2002, Chen and Zhang, 2006 and Zaeh et al., 2009]. So a transient three-dimensional numerical simulation model was developed by using the volume of fluid method to elucidate the melting and resolidification problem of the LBM process by an explicit wetting.

2. Simulation Model

2.1. Physical Model

The simulations base on the computational fluid dynamics toolbox *OpenFOAM* (Open Field Operation And Manipulation, ©OpenCFD Limited) which is a C++ toolbox for the numerical solution of continuum mechanical dynamical problems. The software allows modifying standard solvers like for heat transfer and multiphase flow to model the specific physical phenomena of laser beam melting. During the last years specific solvers have been developed at the Chair of Photonic Technologies to simulate the interaction between laser and material for different material processing techniques [Geiger et al., 2009, Otto and Schmidt, 2010, Otto et al., 2011 and Leitz et al., 2012]. For this many physical effects had to be coupled. The energy flux in the fluid and solid phases are considered as a system of coupled nonlinear partial differential equations. The flow characteristic of the molten steel is described as an incompressible fluid by the Navier-Stokes equation [Versteeg and Malalasekera, 2006]. The free surface of the molten steel is described by the volume of fluid (VOF) method [Hirt and Nichols, 1981 and Ferziger and Peric, 2008]. The energy flux and the physics of the phase transformation are considered. The heat of melting and evaporation are included in the model [Ki et al., 2001]. By this rich in detail configured simulation model the shape of the melt pool and therefore the hydrodynamics can be determined. The most important parts of the laser beam melting are the heat flux, the surface and the interaction of the material with the laser which are described detailed by the following equations. The physical properties and process parameters are listed in Table 1 and Table 2.

Table 1. Process parameters

Process parameter	symbol	unit	value
Laser power	P_L	W	200
Focus radius	w_0	µm	50
Feed velocity	v_0	m/s	1
Wavelength	λ	nm	1064
Scan spacing	s	µm	100
Powder diameter	d	µm	30

Table 2. Physical properties

Physical property	symbol	unit	value
Density of steel	ρ	Kg/m^3	7840
Specific heat of liquid and solid steel	c_S / c_L	J/(Kg·K)	460
Thermal conductivity of steel	k	W/(m·Kg)	50
Kinematic viscosity of molten steel	v	m^2/s	$1 \cdot 10^{-6}$
Melting temperature of steel	T_M	K	1808
Vaporization temperature	T_V	K	3134
Enthalpy of fusion	H_M	KJ/kg	277
Enthalpy of vaporization	H_V	KJ/kg	6340
Surface tension coefficient	σ	N/m	1.79
Complex refraction index (λ = 1.064 μm)	$n+k \cdot i$	-	3.23 + 4.35·i

2.2. Governing Equations

The evolution of the temperature field is significantly influenced by the phase transitions. The fusion and resolidification of the metal is considered in the dynamic. To map the melting and evaporation enthalpy the heat conduction equation is formulated in the energy form [Dowden, 2009]:

$$\frac{\partial}{\partial t}(\rho \cdot H) + \nabla \cdot (\rho \cdot \vec{u} \cdot \mathrm{H}) - \nabla \cdot (\lambda \cdot \nabla T) = Q_A$$

The solution of this problem bases on an iterative method, in which the enthalpies are included more correctly at every calculation step [Kohl et al., 2012].

The fluid dynamic is based on a multi-phase fluid dynamic solver of *OpenFOAM* and is solved by the PISO (Pressure Implicit with Splitting of Operators) scheme and is described by the incompressible Navier-Stokes equation [Dowden, 2001 and Bristeau et. al, 1987]

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho \vec{u} \cdot \nabla \vec{u} = -\rho \nabla p + \eta \Delta \vec{u}$$

and mass conservation equation

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{u}) = 0$$

The flow of the solid phase is not possible, so the speed is constant zero.

The laser beam is simulated as a volume heat source with Gaussian distribution. The absorption coefficient depends on the angle of incidence and thus it is given by the Fresnel equations [Hügel, 1995]. The attenuation of the energy of the laser beam in the metal follows the Beer-Lambert law [Demtröder, 2006].

2.3. Specification of Geometry and Mesh of the Simulation

To reduce the complexity of the simulation a simple configuration of the process has been chosen. So the powder particles are represented by spheres with a uniform diameter of *30 μm*. Furthermore, the powder bed

is a face-centered cubic system. To reduce the relative density of the powder to a realistic scale (around *60%* content) some spacing between the particle spheres is introduced. For a realistic modeling of the powder geometry, the mesh on the powder surface is locally refined. The refinement degree is a trade-off between too angular powder particles and too large calculation time because of a high number of cells. So there are numerical connections of the spheres which increase the heat conduction between the particles. All this matches the characteristics of the used powders.

3. Results and Discussion

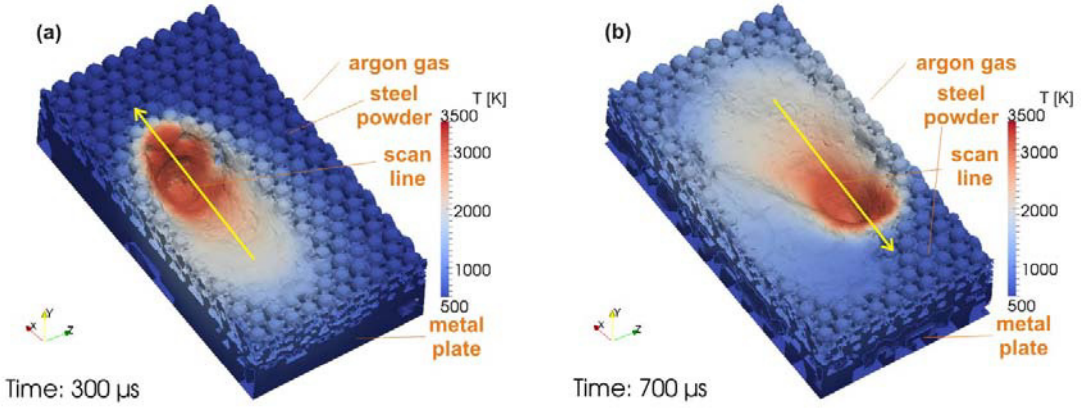

Fig. 1. (a) Overview of the process after a single scan line (*t = 300 µs)*;
(b) Overview of the process after a second scan line (*t = 700 µs)* in distance of *100 µm* to the first line;
The process parameters are: P_L = *200 W*, λ = *1064 nm*, w_0 = *50 µm*, v_0 = *1 m/s*.

For the simulation a small experimental setup is chosen to limit the calculation time. So a box (*600 µm x 320 µm x 200 µm*) is analyzed in which the relevant phenomena of the process can be seen. The boundaries are open for the material and energy flow, only the bottom side has a constant temperature of *T = 500 K* to model the influence of the pre-heated powder bed. In Fig. 1 an exemplary process at standard processing parameters is displayed at different time steps. The laser beam is moving along a line of *400 µm*. The line spacing is *s = 100 µm*, the feed rate is v_0 *=1 m/s*, the laser power is P_L *= 200 W*, the wavelength is

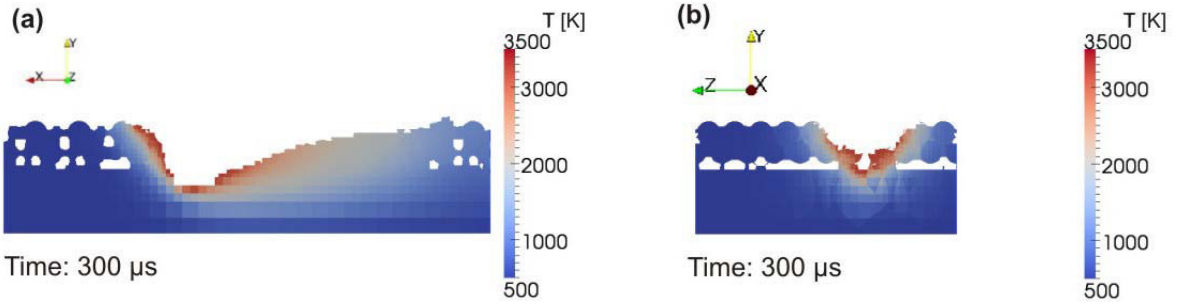

Fig. 2. (a) Slice of the powder bed along the laser feed direction through the focal spot (*t = 300 µs)*;
(b) Slice of the powder bed orthogonal to the laser feed direction through the focal spot (*t = 300 µs)*;
The process parameters are: P_L = *200 W*, λ = *1064 nm*, w_0 = *50 µm*, v_0 = *1 m/s,* s = *100 µm.*

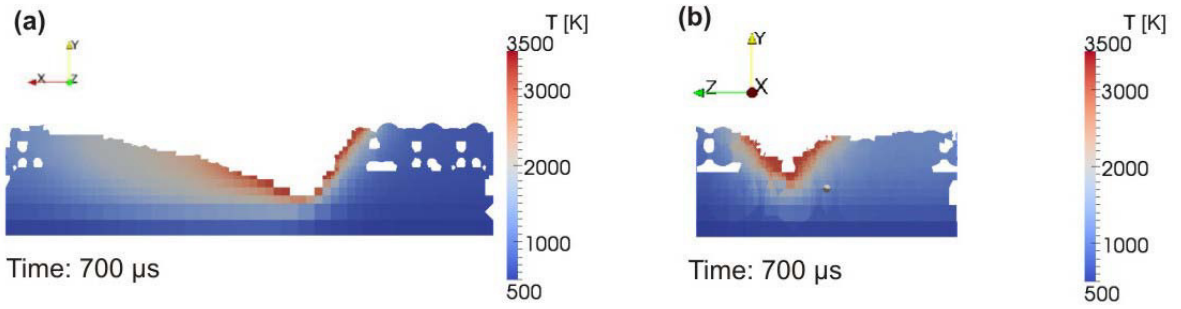

Fig. 3. (a) Slice of the powder bed along the laser feed direction through the focal spot ($t = 700\ \mu s$);
(b) Slice of the powder bed orthogonal to the laser feed direction through the focal spot ($t = 700\ \mu s$);
The process parameters are: $P_L = 200\ W$, $\lambda = 1064\ nm$, $w_0 = 50\ \mu m$, $v_0 = 1\ m/s$, $s = 100\ \mu m$.

$\lambda = 1064\ nm$ and the laser beam radius is set to $w_0 = 50\ \mu m$. The powder particles have a diameter of $d = 30\ \mu m$ and are located over a compact steel plate. To reduce the numerical connections because of the coarse mesh a separation distance of around $2\ \mu m$ is inserted in all directions.

Fig. 1 demonstrates that the simulation model can achieve realistic results. It displays the melting of the powder particles, the wetting of the liquid to the solid material and the solidification of the melt. After one scan (Fig. 1a) a significant coalescence of the powder and the plate already exists with a smooth surface. Fig. 1b shows the results of a second scan line. The maximum of the temperature field is limited by the evaporation. In the simulation the whole absorptance of the laser power in the material ranges between *60%* and *70%* in each time step. In both scans the metal plate has been molten for a deeper connection of the bead which can especially be seen in Fig. 2a and b. The slices of the box after the laser absorption are displayed in Fig. 3a and b. The compact layer has a realistic height of around *60%* of the powder layer. The bead of the second scan line is much deeper as the first one at the beginning. A reason can be the flow of the melt to the back of the heating area.

Also the simulation model can image defects. Fig. 4a displays a metallurgical grinding of porosity defects at false parameters. The simulation with too small power can produce similar defects (Fig. 4b). Here the fusing of the powder in the metal plate is not perfect. There are some holes between the scan lines, metal plate and powder.

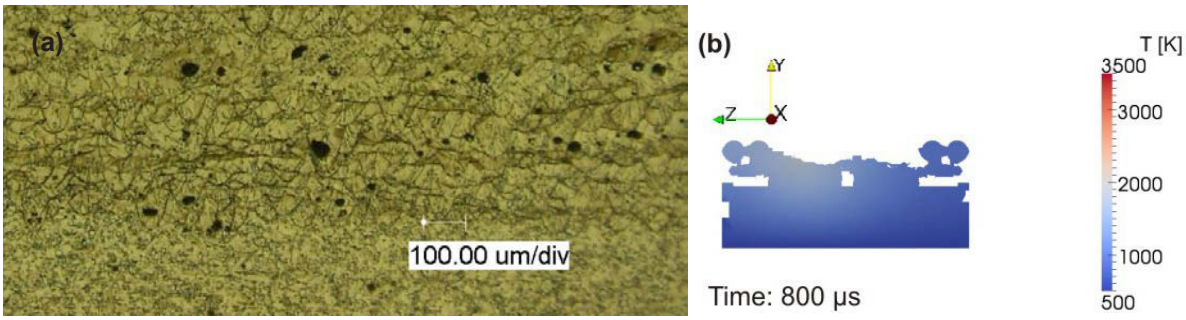

Fig. 4. Comparison of porosity in experiment and simulation:
(a) Experiment with $P_L = 75\ W$, $w_0 = 10\ \mu m$, $v_0 = 0.25\ m/s$, $s = 50\ \mu m$: Black areas are wholes without material;
(b) Simulation with $P_L = 100\ W$, $w_0 = 20\ \mu m$, $v_0 = 1\ m/s$, $s = 100\ \mu m$: White areas are wholes without material;
The other process parameters are: $\lambda = 1064\ nm$.

4. Summary and Outlook

In this contribution a numerical simulation model for LBM has been presented describing melting, wetting and solidification phenomena. The model is able to reproduce the fundamental properties of the laser beam melting process. The effects of the powder-layer thickness, moving heat source intensity, scan spacing and scanning velocity on the process dynamics can be shown. Realistic results for process dynamics in LBM are presented by using the parameters of industrial machines like the Renishaw AM125 or the Realizer SLM 50.

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